The processing and properties of aluminium-silicon alloys containing graphite

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THE PROCESSING AND PROPERTIES OF
ALUMINIUM-SILICON ALLOYS
CONTAINING GRAPHITE

BY

P.R. GIBSON.

A Doctoral Thesis

Submitted in partial fulfilment of the
requirements for the award of Doctor of Philosophy
of the Loughborough University of Technology.

ABSTRACT

THE PROCESSING AND PROPERTIES OF ALUMINIUM-SILICON ALLOYS CONTAINING GRAPHITE

by P.R. GIBSON.

Cast aluminium-silicon alloys containing graphite particles are reported to offer the potential for use as bearing and cylinder block materials due to low friction and wear characteristics, good thermal conductivity and resistance to corrosion. However, a fundamental problem exists in dispersing graphite particles because liquid aluminium alloys do not wet graphite and so particles are rejected by the melt.

The first section consists of a literature survey which examines the potential for graphite aluminium alloys, and reviews various methods for dispersing graphite particles. The potential for the use of recently developed methods of casting semi-solid alloys as a means of retaining graphite particles in melts is then considered.

The second section reports on an investigation into the production of aluminium-silicon alloys which contain graphite particles and an evaluation of the mechanical and tribological properties of the composites produced with various silicon and graphite contents. Processing semi-solid alloys produced an even dispersion of graphite particles without segregation, agglomeration or rejection. Solidification under pressure (squeeze casting) was used to optimise the mechanical properties of the composites.

The evaluation of mechanical and tribological properties showed that strength and ductility were reduced in alloys which contained graphite. Wear tests showed that graphite additions provided increased load carrying capacity, reduced coefficient of friction, reduced steady running temperature and reduced damage to mating components. There was no evidence of a deterioration in corrosion from corrosion tests and machinability tests showed that machinability was greatly improved by the addition of graphite particles.
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# CONTENTS

<table>
<thead>
<tr>
<th>Introduction</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION A - LITERATURE SURVEY AND REVIEW</strong></td>
<td></td>
</tr>
<tr>
<td><strong>CHAPTER 1 : Bearing Materials</strong></td>
<td>5</td>
</tr>
<tr>
<td>2 : Aluminium Alloy - Graphite Particulate Composites</td>
<td>40</td>
</tr>
<tr>
<td>3 : The Production and Casting of Aluminium Alloys Containing Graphic Particles</td>
<td>63</td>
</tr>
<tr>
<td>4 : Summary and Conclusions</td>
<td>72</td>
</tr>
<tr>
<td>5 : Possible Areas for Investigation</td>
<td>75</td>
</tr>
<tr>
<td><strong>SECTION B - EXPERIMENTAL WORK</strong></td>
<td>79</td>
</tr>
<tr>
<td><em>Objectives, Equipment, Procedures</em></td>
<td></td>
</tr>
<tr>
<td><strong>CHAPTER 6 : Composite Alloy Production</strong></td>
<td>81</td>
</tr>
<tr>
<td>7 : Composite Alloy Evaluation</td>
<td>116</td>
</tr>
<tr>
<td><em>Results</em></td>
<td></td>
</tr>
<tr>
<td>8 : Results - Composite Alloy Production</td>
<td>148</td>
</tr>
<tr>
<td>9 : Results - Composite Alloy Evaluation</td>
<td>164</td>
</tr>
<tr>
<td><em>Observations of Results</em></td>
<td></td>
</tr>
<tr>
<td>10 : Observations - Composite Alloy Production</td>
<td>204</td>
</tr>
<tr>
<td>11 : Observations - Composite Alloy Evaluation</td>
<td>212</td>
</tr>
<tr>
<td><em>Discussions</em></td>
<td></td>
</tr>
<tr>
<td>12 : Discussion - Composite Alloy Production</td>
<td>226</td>
</tr>
<tr>
<td>13 : Discussion - Composite Alloy Evaluation</td>
<td>241</td>
</tr>
<tr>
<td>14 : Conclusions</td>
<td>259</td>
</tr>
<tr>
<td>15 : Suggestions for Further Work</td>
<td>261</td>
</tr>
<tr>
<td>16 : References</td>
<td>264</td>
</tr>
<tr>
<td>17 : Appendices</td>
<td>279</td>
</tr>
<tr>
<td>18 : Figures</td>
<td>324</td>
</tr>
</tbody>
</table>
INTRODUCTION

The increase in the cost of energy is providing the automotive industry with a strong impetus to produce lighter, more energy-efficient products. Aluminium alloy castings are playing an increasingly important role in the drive to reduce weight and provide bearing materials with good friction characteristics, high thermal conductivity and resistance to corrosion. In particular, aluminium-silicon alloys fulfil these requirements, in combination with good casting characteristics. However, a limitation exists in their tribological performance in the form of a tendency to scuff in conditions where lubrication is sparse or intermittent.

The inclusion of evenly dispersed graphite particles in these alloys has been reported to have improved tribological properties by providing continuous solid lubrication. However, the production of aluminium-silicon alloys containing dispersed graphite particles presents difficulties because liquid alloys will not wet graphite, with the result that particles tend to be rejected from liquid alloys. Several methods have been proposed to overcome this limitation such as injection onto an inert gas stream, and mechanical stirring. These methods are slow and cumbersome and usually require an expensive metallic coating on the particles to aid wetting.

The principal aim of this research was to utilise newly-developed technology of processing partially-solid alloys as a means of dispersing uncoated graphite particles in aluminium-silicon alloys. Having evaluated the optimum conditions for the dispersion and retention of particles in the alloys, the use of squeeze casting provided a
means of producing castings with the minimum deterioration in mechanical properties caused by additions of graphite particles.

The second aim of the research was to obtain information and data on the mechanical and tribological properties of aluminium-silicon alloys containing graphite particles. Although data has been published on graphite aluminium alloys, researchers have not been consistent in either their methods of production or evaluation. Consequently, it has been difficult to make valid conclusions about their work. Therefore, it was considered essential to comprehensively evaluate the materials produced in this research. The tribological properties were evaluated by using techniques established by the Tribology Group at Brunel University in their study of aluminium-silicon alloys.
SECTION A

LITERATURE SURVEY AND REVIEW

CHAPTER 1 - BEARING MATERIALS.

1.1 Requirements of Bearing Materials.
1.2 Bearing Material Types.
1.3 Methods used in the Production of Bearings.
1.4 Assessment of Bearing Materials.
1.5 Wear Mechanisms in Bearing Materials.
1.6 Characteristics and Applications of Bearing Materials.
1.7 The Effect of Material Type on Wear Mechanisms.

CHAPTER 2 - ALUMINIUM ALLOY - GRAPHITE PARTICULATE COMPOSITES.

2.1 Potential for Aluminium-Silicon Alloys Containing Dispersed Graphite as Bearing Materials.
2.2 Production of Aluminium-Silicon Alloys Containing Dispersed Graphite.

CHAPTER 3 - THE PRODUCTION AND CASTING OF ALUMINIUM ALLOYS CONTAINING DISPERSED GRAPHITE PARTICLES.

3.1 Rheocasting and Compocasting.
3.2 Methods of Casting Components.

CHAPTER 4 - SUMMARY AND CONCLUSIONS.

4.1 Bearing Materials.
4.2 Aluminium-Alloy Particulate Composites.
4.3 The Production and Casting of Aluminium Alloys Containing Dispersed Graphite Particles.

CHAPTER 5 - POSSIBLE AREAS FOR INVESTIGATION.

5.1 Introduction.
5.2 Suggested Programme.
CHAPTER 1

BEARING MATERIALS

1.1 REQUIREMENTS OF BEARING MATERIALS.

A bearing may be defined as a machine element which transmits loads and reaction forces to and from another machine element moving in contact and relative to it.

In a properly lubricated bearing a film of oil separates the moving parts and the bearing material is of no great importance. In starting and stopping and severe running conditions however, this film cannot always be maintained and the material must be able to withstand direct contact without damage or rapid deterioration.

The properties required of the material therefore may be listed as follows:

(i) Antiseizure and antigalling characteristics.
(ii) Good friction properties.
(iii) Good corrosion resistance.
(iv) Good fatigue resistance.
(v) Sufficient strength to resist loads imposed.
(vi) Deformability to allow running in and embedability of foreign particles.
(vii) Shock resistance.

(i) Antiseizure or Antigalling Characteristics.

When two metals are rubbed together in contact, friction results in heat generation thereby raising surface temperatures. Ultimately,
temperatures become high enough to cause intermittent welding of the materials. The bearing then becomes scored or in severe cases seized resulting in the machine becoming stalled.

At one time, it was thought necessary for a bearing to have two constituents to exhibit antiseizure. Experiences with single phase materials such as silver or nickel have shown that this is not necessarily the case.

(ii) **Friction Properties.**

Bearings must exhibit low coefficients of friction when in contact and moving relative to their mating materials. This is to avoid excessive heat generation and so delay the onset of galling and seizure.

(iii) **Corrosion Resistance.**

There are two factors to be considered in avoiding excessive corrosion; a corrosive lubricant or environment and/or a bearing material which is corroodable under operating conditions.

Corrosive lubricants can result from additions of other compounds and acidic formations resulting from oxidation. In multiphase materials corrosion may attack various constituents selectively. Corrosion resistance tends to decrease with increasing temperatures.

(iv) **Fatigue Resistance.**

Fatigue has been a common cause of bearing failure. Bearings are subject to both wear and fatigue and so there are many factors which may influence the fatigue limit resulting in difficulty in
predicting a fatigue failure in a specific application.

Fatigue performance can only be evaluated in the actual application or in a simulation which faithfully reproduces operating conditions. Resistance to bearing fatigue is distinctly different from more usual fatigue resistance. Attempts to increase fatigue life by increasing strength or hardness may have no effect in bearing applications.

(v) **Strength.**

Strength is important when loads are sufficient to cause plastic flow or extrusion of the bearing material. Many bearing materials are used in thin layer form bonded to a high strength backing to enable higher loads to be carried however there is no correlation between increased strength and temperature or fatigue life.

(vi) **Deformability.**

Many mating components are slightly flexible with imposed load. Such conditions cause heavy bearing pressure in localised areas which can result in galling or seizure of these areas. Therefore it is useful for the material to yield sufficiently to take care of misalignment and allow the couple to "run in".

Secondly the material should have the ability to deform enough to embed dirt. In general, where dirt is embedded wear rate increases but, damage to mating components is minimal. Hardness may be used as a measure of embedability.

(vii) **Shock Resistance.**

Machine elements running on bearing materials are often
subjected to shock loading. Bearing materials must be able to withstand shock loads such that they can be transmitted safely to the main load bearing areas of the machine.

1.2 BEARING MATERIAL TYPES.

Bearing materials can be classified into four groups:

(i) White metal type: Hard particles are dispersed in a soft matrix. The hard particles acting as the wear resisting load carrying element with the soft matrix allowing deformability and flow of lubricant.

(ii) Soft material distributed throughout a hard matrix:
The soft material becoming smeared over the hard matrix and acting as a solid lubricant film.

(iii) Single metals or single phase alloys.

(iv) Non metallic types.

(i) White Metal Type.

White metal materials fall into two main groups. Tin base (Babbits) and Lead base.

Tin base materials consist substantially of tin, antimony and copper. The soft matrix is a solid solution of antimony and tin throughout which hard particles of the intermetallic compound Cu₆Sn₅ are dispersed.

The most common Babbit (BS 3322/1) contains 3-4% copper and 7-8% antimony. This material offers an outstanding resistance to seizure and galling, often to the extent where even in conditions of oil starvation the bearing will suffer no more damage than
highly localised melting of the surface. Larger amounts of copper and antimony increase hardness but reduce ductility.

Dirt embedability is good, allowing unhardened mating components to be used without danger of scoring.

Fatigue resistance at higher temperatures is limited to the extent where Babbit materials are not suitable for use above 130°C(1). In many commercial applications tin base materials are used with a steel backing which has been found to increase fatigue life by a factor of approximately 2 or 3. Typical Babbit thicknesses range from .05 mm to .125 mm(2,3).

There is little doubt that Babbits would offer performance superior to most bearing materials if its fatigue performance at higher temperatures could be maintained to the standard set at room temperature. For this reason many sources appear to evaluate bearing materials by using Babbit metals as a benchmark(1,3-7).

Lead base materials (also known as Lead Babbits) can be considered in two categories, these being; alloys of lead, tin, antimony or arsenic and alloys of lead, tin, calcium and the alkaline earth metals.

Alloys of lead and tin have been used since the eighteenth century as bearing materials. The addition of arsenic is comparatively recent.

When arsenic is not included, the microstructures consist of cuboid shaped primary crystals of SnSb or of antimony embedded in a ternary mixture of PbSbSn in which lead forms the matrix. As the antimony content is increased the amount of cuboids tends to increase. Contents of over 14% antimony are not considered because
the amount of hard constituents makes the material unsuitable for bearing applications.

Arsenic improves the mechanical properties, particularly fatigue limit at higher temperatures. One of the most common alloys is SAE 15 which contains about 1% arsenic.

Lead-base bearing materials were once thought to be only a low cost substitute for tin-base materials. However, when used with a steel backing they have been shown to equal or surpass tin-base materials\(^{(1,3,5)}\). Although there is little difference in anti-seizure characteristics a higher fatigue limit allows lead-base alloys to be used in bearing applications where tin-base materials may fail.

Lead-base materials which contain calcium and alkaline metals offer similar properties to arsenical lead Babbits but with impaired fatigue resistance. Acidic oils also tend to cause premature corrosion failures.

(ii) **Soft Material Distributed Throughout a Hard Matrix.**

This group of materials includes; copper-lead alloys, aluminium-tin alloys, aluminium-lead alloys, tin bronzes and cast irons.

Copper lead alloys are usually used in steel back form. A typical example is SAE 48 (67-74% Cu and 25-32% Pb). The actual amounts of copper and lead are not thought to be critical\(^{(3)}\) and so SAE 480 (60-70% Cu, 30-40% Pb) has evolved with deliberately wide tolerances so that it can replace various compositions now in use.

In general, lead lowers fatigue resistance but increases antifriction characteristics, therefore a compromise must be made.
Silver and tin may be substituted for part of the copper as a means of increasing fatigue resistance but these alloys suffer corrosion in certain oils.

Corrosion can be a major problem with copper-lead alloys under certain conditions \(^{(1,8)}\). Overlay plating is claimed to help alleviate corrosion \(^{(3)}\).

The fatigue resistance of copper lead is approximately double that of white metal which has allowed the development of high performance machines where bearings operate under arduous conditions \(^{(2,9,10)}\).

Abrasive particles which may be present in lubricants have been found to result in accelerated wear of components mated with copper-lead \(^{(2)}\). This is due to the inability of the copper matrix to embed particles and has resulted in the need for hardened mating components.

Aluminium-tin alloys have become increasingly important since 1945. A divergence of practice exists between America and Europe. In America, alloys such as SAE 780 containing 6% tin have been in common use, either as a bearing in unbacked form or more recently as a thin layer with a lead-tin overlay on a steel strip.

In Europe, means of bonding alloys of higher tin content have been developed resulting in a 20% tin alloy becoming more common \(^{(11)}\). The use of the higher tin content makes overlays unnecessary without significantly affecting wear on mating components because the tin acts as a metallic lubricant. Bearings of this type offer good fatigue resistance, (approximately three times that of white metal), and are immune to oil corrosion and highly resistant.
to cavitation (9,11).

The limitations of low tin content alloys arise through their hardness and poor conformability which means very hard mating components with good surface finish are required. A further problem which arises with solid bearings is a high coefficient of expansion which makes fitting difficult and results in the need for relatively large cold clearances.

It has been shown that 20% cold work deforms the aluminium matrix producing drawn out films of tin rich eutectic. Subsequent annealing at 500°C for 1 hour breaks up the tin structure into small interconnected pools, producing a net like recticular structure (12). Using this method 50% tin can be incorporated without impairing mechanical properties so that a compromise between surface properties and fatigue resistance can be achieved without the need for hardened mating components having fine surface finishes.

**Aluminium-lead alloys:**

Attempts have been made to replace the expensive tin in aluminium-tin alloys with lead.

Lead has very limited solubility in aluminium, only going into solution at very high temperatures. As the alloy is cooled, lead is progressively precipitated and immediately segregates through molten aluminium under the influence of gravity, the large difference in the two densities making segregation a problem. However, a good unsegregated structure is possible (11), a typical example containing 10% lead.

Fatigue life and wear resistance are claimed to be similar
to aluminium-tin but corrosion resistance and dirt embeddability are slightly inferior. Aluminium-lead bearings are usually bonded to a steel backing.

Tin-bronzes are alloys of copper to which 5-20% tin is added and a small percentage of phosphorus. These alloys are usually referred to as phosphor bronzes.

When 2-6% zinc is substituted for phosphorus, the alloy is referred to as gun-metal.

Phosphor-bronze is a useful bearing material where load-carrying capacity at low speeds is of paramount importance whilst gun-metal is specified where complicated castings are required and difficulties may be encountered in the foundry with phosphor-bronze.

Typical phosphor bronzes contain 79% copper, 20% tin and 1% phosphorus and are suitable for bearings on railway turntables and movable bridges.

Gun-metal has a typical composition 88% copper, 8% tin and 4% zinc and offers excellent casting characteristics. Excellent strength, toughness, friction properties and resistance to corrosion in sea water are offered by this combination.

Leaded-tin-bronzes have a typical composition of 88% copper, 6% tin, 4% lead and 2% zinc. These alloys are also known as "wrist-pin bushing" and are suitable for low or moderate bearing pressures in many types of machinery. The lead content giving good machinability whilst reducing hardness and strength in comparison to gun-metal.

Grey cast-iron is used as a bearing material in applications
where boundary lubrication is common. Close grained iron with uniformly distributed graphite is found most suitable. Phosphate coatings are often used to improve antiseizure characteristics and help retain oil. The material offers poor dirt embeddability and so it is necessary to use mating components with hard highly finished surfaces. Bearing pressures are usually fairly low.

**Zinc base alloys** were developed in Germany during the second world war due to a shortage of copper. These materials gave superior friction characteristics to bronzes but tended to seize and gall when mated with components made from ferrous materials. This resulted in the need for very low bearing pressures but corrosion resistance was excellent.

(iii) **Single Metals or Single Phase Materials.**

**Silver** is used in electroplated form on a steel backing. The bearing is machined to very close tolerances, precision plated with a lead overlay and then with indium or tin-lead alloy. This bearing offers the most superior fatigue resistance and load carrying capacity of all bearing materials. For optimum properties silver must be of the highest purity.

Overlays are necessary because the silver itself possesses poor surface characteristics. Load carrying capacity is claimed to be a factor of ten times that of tin Babbit\(^3\).

Fatigue limit on silver bearings is so high that used bearings can be reclaimed by simply replacing the overlays.

The high cost of these bearings limits their use to only a few specialised applications.
Nickel or nickel-silicon carbide deposited electrolytically in very thin layers has been used with great success in similar applications to those where grey cast iron has been used. Friction properties are claimed to be excellent.(13).

Sintered carbides offer high modulus of elasticity, high thermal stability and high resistance to abrasion. This results in the ability to run with very small working clearances. Dirt and grit are unable to penetrate the bearing and high hardness leaves the surface highly resistant in the result of lubrication failure.

A typical example is sintered tungsten carbide which also offers excellent corrosion resistance.

Many single phase materials offer potential in bearing applications provided they possess bearing properties as well as other desirable properties for specific applications.

(iv) Non Metallic Materials.

Nylon is limited to applications below 120°C due to its low melting point but offers excellent friction characteristics.

Graphite, molybdenum disulphide and other fillers may be added to improve bearing properties.

P.T.F.E. (Teflon) is used because it is chemically inert and it possesses a very low coefficient of friction. However, use is limited by low thermal conductivity and high thermal expansion. At very low speeds, teflon can operate under loads normally encountered where silver bearings are used.

Filled teflon has been shown to possess greatly superior
wear resistance to both lead and aluminium.

**Carbon-graphite** offers very good wear characteristics especially at high temperatures and is suitable for applications in water and petroleum. The material is very brittle and so is most suitable for steady continuous loads.

*Wood* impregnated with oil is used in some applications. Lignum wood has been used as a lining for underwater bearings where metal corrodes severely.

**Rubber** usually backed with a steel shell, offers excellent shock resistance and wears well. The material is used in underwater applications.

**Asbestos cloth reinforced phenolic** offers high compressive strength and can be used lubricated or unlubricated as there is a certain amount of porosity. Some bearings of this type also contain dispersed graphite to improve friction properties further.

P.T.F.E. overlays can be used with asbestos cloth reinforced phenolics allowing a very strong high load bearing.

**Asbestos yarn reinforced cresylic** gives good dimensional stability in aqueous environments. Deformability is claimed to be very high, being about forty two times that of bronze bearing materials. This being a useful feature where mating component inaccuracies are to be accommodated. The material finds uses in maritime applications.

**Asbestos flock reinforced phenolics** can be moulded accurately and require no machining, and offer a cheap moderately high load carrying bearing.

**Cotton cloth reinforced phenolics** have high strength but
exhibit a high friction coefficient. The material is used for high load, dirty applications with water lubrication.

Acetal Co-polymer with Entrapped Mineral Oil gives similar properties to P.T.F.E. but is very much cheaper. Injection moulding enables high quantities to be produced at low cost.

In general, plastic bearings, especially thermosets, are used in high load, arduous conditions.

Plastic bearings are still in their formative stages but offer great potential as they are easily formed and can be tailored to suit various bearing requirements.

There is also a possibility that plastic bearings may eventually replace metal journal bearings in automotive engines and other applications (11,14,16).

1.3 METHODS USED IN THE PRODUCTION OF BEARINGS.

Whilst it is important that a bearing material must exhibit the properties required of it for a particular application it is equally important that there must be a production process suitable for economic manufacture of the bearing. Plain bearings may consist of solid castings or more commonly may be thin layers supported by a stronger backing.

White metals, both tin and lead base are soft and so must be supported by a strong backing - usually steel, cast iron, or bronze.

In order to obtain a satisfactory bond, it is first necessary to tin the backing material to form a thin layer to which the white metal will become bonded. Tinning is achieved by dipping the backings in a bath of molten tin.
The strip is then passed beneath a stream of molten white metal which solidifies onto the strip and cools at a rapid rate.

Graphite has to be removed from cast iron strip surfaces prior to tinning to ensure a high integrity bond. This is achieved by shot blasting or electrolytic treatments (1,17).

Large white metal bearings may be produced by centrifugal casting techniques. The backing is machined to size and tinned in the normal manner. White metal is then deposited by centripetal force onto the backing. Segregation can be a problem due to the differing densities of the constituents of white metals. This is overcome by careful control of spinning speeds and times, cooling rates and the amounts of the constituents themselves.

A more recent technique involves adhering the white metal to its backing using an epoxy resin (18). This is mainly confined to larger bearings. The technique though not widely used is claimed to give a bond strength equivalent to that of traditional methods.

Overlay platings, where necessary, are applied to the bonded backing and white metal, usually by electro deposition techniques. The bearing is then ready for forming and fabrication. In the case of half shell bearings the first operation is blanking to the required size followed by forming into semi-circular shells. Where oil holes and grooves are required they are punched or drilled and broached respectively.

Manufacture of white metal bearings has been subject to automation which has resulted in large scale manufacture, thus helping to control unit costs of a product made from comparatively
expensive materials.

Copper lead alloys are also used almost exclusively in backed form. The backing, usually of steel, is continuously coated in a similar manner to that of white metal materials. Subsequent forming and fabrication operations are also similar.

Copper-lead bearings may also be produced by applying a copper-lead alloy powder to a steel strip which is passed through a furnace where the mixture is simultaneously sintered and bonded to the strip\(^3\). Using this method it is possible to obtain a homogeneous equiaxed structure rather than the dendrites of copper perpendicular to the strip surface which occur in cast bearings.

 Aluminium-tin bearings containing 6% tin are occasionally produced in solid form, as permanent mould castings. In some cases it is also possible to continuously cast aluminium-tin bearing stock, producing a uniform, fine grained structure free from porosity, oxides and dross.

Most aluminium-tin bearings, in common with white metal and copper-lead materials, use a steel backing for production of shell bearings for the automotive industry.

This material is usually made into bearings with the use of "roll bonding" techniques. Surfaces must be very clean because a lack of integrity of the bond can have a catastrophic effect on fatigue life.

European techniques have centred on the use of an interlayer between the alloy and the steel backing. This gives a stronger bond and allows a tin content of 20% tin to be used. American techniques do not use an interlayer which has resulted in the
need to limit tin content to 6 or 7\% to ensure sufficient bond strength\(^{(5)}\).

In the European process commonly adopted today, aluminium foil is first roll-bonded onto a steel strip, followed by a second roll bonding, at a temperature below 230\(^\circ\)C, of this composite onto a second steel strip.

A modification has been described\(^{(17)}\) whereby pure aluminium is roll bonded onto both faces of the aluminium-tin prior to bonding to the steel. When the finished strip is finally annealed the protective outer coating of aluminium prevents tin migrating and exuding from the surface of the aluminium-tin alloy.

Aluminium-lead bearings are also used in steel backed form, but are produced in a similar manner to white metal bearings and so, may offer economic advantages over aluminium-tin as roll bonding is not necessary. However, the wide acceptance of aluminium-tin bearings has restricted the use of lead bearings.

Tin bronze bearings are normally produced by casting. There is a trend towards continuous casting techniques which are claimed to give better surface finish, strength and fatigue resistance\(^{(19)}\).

Centrifugal casting is used to produce larger bearings and cast liners\(^{(1)}\). Tin bronzes may also be used in steel backed form, the alloy being cast onto the strip.

Thin layers have also been produced by sintering tin-bronze powder onto the surface of the backing. The process is carried out by initial partial sintering, followed by rolling and then fully sintering to give a strong dense lining.

Cast iron may be cast into the bearing shape required and
then finish machined, or may be machined from solid where small quantities are required. Many iron castings have no separate bearings and simply allow mating components to run directly in the casting itself.

Silver is electrolytically plated onto its backing and then machined to very close tolerances. Overlays may then be applied. Annealing usually follows to allow diffusion.

Nickel can be electrolytically applied or electroless plating may be used to allow more complicated shapes to be evenly plated. Sintered carbides are usually made into bearings using a powder metallurgy route.

Reinforced thermoset resin bearings are usually produced using compression moulding and finished, where necessary, by machining.

Thermoplastic bearings may be produced by injection moulding in large quantities, and other common plastic moulding techniques.

1.4 ASSESSMENT OF BEARING MATERIALS.

A number of approaches have been used in evaluating the performance of bearing materials. This has led to problems in comparing the properties of different materials.

Forrester\(^{(5)}\) summarises the problem;

"Our basic knowledge of the behaviour of sliding surfaces now rests on firm foundations well laid down by ingenious work from a number of sources. Unfortunately the available information concerning the actual performance in service of different materials and their comparative usefulness is by
no means always so reliable. Much of the published information is a matter of opinion rather than scientific data. Many investigators have neither added to our fundamental knowledge nor afforded practically useful comparisons between bearing materials". The problem has arisen due to a lack of working standards. At the time of writing the International Organisation for Standardisation (I.S.O.) working group TC123/SC2/WG6 is engaged in formulating and standardising suitable test methods by which the tribological behaviour of bearing materials can be characterised. Bearing materials should have a number of properties to ensure that the function of the bearing is maintained under various operating conditions. These properties are interdependent and also they depend on the properties of the mating component, lubrication (if any), and on operating conditions. This makes it difficult to design adequate standard test methods and has led to the situation summarised by Forrester. Before the I.S.O. establishes suitable test methods to assess tribological properties of bearing materials it became first necessary to determine which tribological properties were to be assessed. The following were laid down.

1. Coefficient of friction and wear rate under conditions of boundary lubrication.

2. Contact parameter under conditions of boundary lubrication.

3. Behaviour at nominal speed and complete breakdown of lubricant supply.
4. Rate of erosive wear under conditions of hydrodynamic lubrication.

5. Cavitation erosion under conditions of hydrodynamic lubrication.

6. Surface fatigue under conditions of hydrodynamic lubrication.

Various proposals have been and are being put forward as suitable means of assessing these properties. However, a problem of consistency of results appears to exist. As yet, no firm recommendations have been made. Some of the means of assessment and test methods available for consideration are outlined below.

(P.V.) Value. (Pressure-velocity product).

Attempts have been made to classify performance in terms of a P.V. value, which is the product of pressure and linear velocity. This is of little practical use in view of the number of unaccounted for variables and speed dependent properties in bearings. Nevertheless, the analysis is widely used in bearing literature and applied in many bearing configurations.

ZN/P Evaluation.

Use of the quantity ZN/P is also widely used as a criterion, where Z = lubricant viscosity, N = rotational speed and P = bearing pressure. In theory this relationship produces a straight line passing through the origin. However, the relationship is valid only to a certain level, below which the coefficient of friction increases sharply due to the breakdown of the lubricant film. Below this the bearing becomes unstable because increased coefficient of friction causes increased temperature which in turn decreases
the viscosity value and further increases the coefficient of friction.

The minimum value of \( ZN/P \) changes with the material in question. Softer materials tend to give lower values. In practice, differences in material may be swamped by differences in bearing design\(^{(5)}\). Low \( ZN/P \) is useful for starting when hydrodynamic lubrication may not be adequate. In these cases the minimum value of \( ZN/P \) must inevitably be passed through.

A wear test which appears to be in widespread use for obtaining the quantity \( ZN/P \) is the "Hohman Wear Test\(^{(22,23)}\). The principle of the test is shown in Fig. 1 and the type of result obtained is shown in Fig. 2.

The whole device is immersed in an oil bath of given viscosity. Referring to Fig. 2, the sudden increase in coefficient of friction can be seen as demonstrated by Forrester\(^{(5)}\). This is in the region of boundary lubrication where fluid film is breaking down and the qualities of the bearing material are most important. Unfortunately the analysis is not reliable in this region.

**Independent Assessments.**

Many research workers in tribology have realised that little standardisation in bearing test methods exists and that most established methods of assessment are limited. A few such workers have therefore embarked upon their own research projects using methods of test and assessment which have evolved and been found to offer suitable comparisons within individual projects.

Two approaches of this type are described below:
1. Neyman (24).

Four basic tests were evolved as a means of comparing four bearing materials. The materials compared were three different steel backed bronzes and one aluminium-tin alloy without backing. The tests consisted of:

A: Radially loading the bearing in increments until a transition from hydrodynamic to mixed lubrication was reached (Load capacity test).

B: Constant radial load, but with an incrementally applied lateral load.

C: As test 1 except the lubricant contained iron powder. This test was stopped when the bearing temperature reached 90°C.

D: Constant frictional torque was applied under mixed lubrication conditions. Load, bush temperature and frictional torque were continuously monitored until steady state conditions were obtained. A curve was then drawn for load v time and hence a comparative running in characteristic obtained.

To summarise the results, the bronzes exhibited superior performance to the aluminium tin alloy in all but test A. Here, the aluminium-tin alloy gave results similar to the most superior bronze (which was in fact a copper-lead alloy with 70% copper).

These results appear to conflict with claims from other sources (3,11,25) but may not be directly comparable as the aluminium-tin was not used in backed form. However, few reports give such detailed experimental data, but tend to rely on subjective discussion rather than quantitative results.
2. **Brunel University Tribology Group.**

The Tribology Group in the Metallurgy Department of Brunel University has established a number of interests in the field of tribology. One such interest is in the development of bearing materials, with a particular interest in aluminium alloys.

To assess bearing materials, two principal methods are used, these being the **reciprocating diamond scratch test** and the **pin on disc test**. The **reciprocating diamond scratch test** is described by Razavizadeh and Davies (26) and was designed to simulate wear by abrasion and delamination. A single point diamond Rockwell indentor with an included angle of 120° is used to produce tracks of various lengths. The speed of the diamond can be changed by adjusting motor speed. Tests can be carried out with different loads and different numbers of passes.

Assessment of performance is then carried out by comparing scratch widths with the aid of a travelling microscope. A formula may then be applied to convert scratch width into abraded wear volume.

Data is usually presented graphically in the form of graphs of wear volume vs. applied load and wear volume vs. number of passes. Wear rate may also be computed.

The test is usually supplemented with the use of scanning electron microscope (S.E.M.) examination to show the amount of plastic flow, delamination and abrasion which may explain changes in wear volume.

The **reciprocating diamond scratch test** is shown schematically in Fig. 3.
The pin on disc test is used extensively in bearing materials research and has been described by Shivanath et al. (27).

The test is shown schematically in Fig. 4. A pin of bearing material is loaded in contact with the flat surface of a hardened steel or cast iron disc. The speed of the disc is carefully controlled to ensure a constant linear sliding velocity. Change in wear distance, (i.e. the length of pin lost) is continuously recorded with the aid of a linear displacement transducer. This can give useful indications of wear rate and also the point at which any transition may have occurred.

Coefficient of friction measurements may be obtained by accurately measuring the deflection of the pin in the direction of rotation of the disc. The force required to cause such a deflection is determined and from this the coefficient of friction is calculated. The values obtained are not absolute because coefficient of friction is dependent on speed (21) but provided speed is controlled values are comparable between tests.

Further data may be obtained from temperature measurements obtained by attaching thermocouples to the pin.

Scanning electron microscopy is used to provide supporting evidence about modes of wear and indications of the reasons behind any transitions which may have occurred and been indicated by transitions in wear distance, coefficient of friction or temperatures. There are many wear mechanisms present in pin on disc testing, and so the test may be considered to be a simulation of the types of conditions which may be met in service. The S.E.M. has been instrumental in identifying and explaining wear mechanisms present (28).
Fatigue Testing.

Fatigue is a very common mechanism of bearing material failure. Various machines are available to test bearing fatigue life, a typical example being the Glacier fatigue tester. This consists of a shaft running in bearings under test, with an eccentric weighting applied to induce cyclic stresses.

In common with other methods of assessing bearing materials standardisation of fatigue testing does not exist and so results from different sources are not comparable. Standardisation of test conditions is particularly important when evaluating the fatigue life of any material.

Corrosion Testing.

For the results to be relevant, corrosion testing should take place under the conditions in which the bearing is likely to operate. Bearing materials must be tested in likely lubricants and coupled with the materials with which they will be in contact under operating conditions. Common means of evaluating corrosion performance, such as salt spray tests, have little relevance to bearing applications.

1.5 Wear Mechanisms in Bearing Materials.

Wear has been defined as "the progressive loss of substance from the operating surface of a body, occurring as a result of relative motion of the surface". (O.E.C.D.)

No single universally held view of wear mechanisms exists, but a great deal of progress has been made since earlier views that there were two basic wear types: adhesive and abrasive.
Today it is believed that there are few material failure mechanisms which do not play a part in wear behaviour. Literature now contains reference to: adhesion; abrasion; erosion; fatigue; impact; plastic deformation; fracture and corrosion. It can be seen, therefore, that virtually every physical, mechanical or chemical characteristic of a material may play some part in its wear behaviour.

Eyre (32) has reviewed some of the more common mechanisms of wear.

**Abrasive Wear.**

Abrasive wear occurs when hard particles penetrate a surface and displace material in the form of chips or slivers. The wearing surface becomes roughened by fairly regular grooves. The damage caused is often referred to as scoring, galling, scratching or gouging. Abrasive wear can occur with varying degrees of severity.

In practice, abrasive wear occurs under two conditions. The first operates under low stress conditions and the latter under high stress conditions. Under low stress conditions particles are transported across the surface with little breakdown in particle size of abrasive. Under high stress conditions particles are reduced in size or are trapped between two bearing surfaces. In both cases only a very small fraction of the particles cause wear due to a variation in angle of attack and particles which roll or slide cause no abrasive wear. Particles may be the result of detachment from the bearing couple materials or may be due to the ingress of foreign particles.

Volume of wear (volume of material lost from the operating surface) usually increases linearly with both load and sliding
distance. If deviations do occur they are usually due to a reduction in particle size, clogging of the surface or changes in surface conditions at the interface.

Abrasive wear is claimed to account for 50% of wear in industrial situations (32).

Adhesive Wear.

Adhesive wear occurs when surfaces slide against each other, and the pressure is high enough to cause local plastic deformation and adhesion. Adhesion is favoured by clean surfaces, non oxidising conditions, and by chemical and structural similarities between the bearing couple. With increasing motion, the size of asperities increases, transfer of material from one surface to the other usually then results as the asperities rupture at their weakest points.

Adhesive wear increases where the contact area is larger - usually soft materials. Chemically clean surfaces cause bonding and welding and so result in increased wear particularly when the couple is mutually soluble. Transferred material may become considerably harder due to strain hardening and phase hardening which may cause associated abrasive wear.

Adhesion is claimed to depend on the ability of pure metals within a bearing couple to form solid solutions (33). Lead, for example has a very low solubility in iron and therefore would represent a good choice for a counterface. Other constraints must however be considered, the low strength of lead making it unsuitable for bearings other than in alloyed or mixed form. Adhesive wear should in theory be avoided where a metal slides against a non-metal, such as a ceramic or polymer. The solid
solution theory is difficult to apply in practice because information is available only for pure metals under certain sliding conditions.

Variations in load and speed have been found to bring about marked changes in wear behaviour. Transitions from mild wear to severe wear have been found to result in the breakdown of an oxidised surface at the sliding couple\(^{(26,34)}\). The transition has become referred to as the oxidative to metallic transition. The oxidative layer helps prevent adhesion.

Adhesive wear is claimed to account for 15% of wear in industrial situations.

**Fretting.**

Fretting is defined as: "A wear phenomenon occurring between two surfaces having oscillatory relative motion of small amplitude\(^{(32)}\). Fretting usually appears as a dish brown debris on ferrous materials. Surfaces are rarely completely out of contact due to the small amplitude of oscillations and so there is little opportunity for the products of the action to escape. This can result in blockage of lubrication and may even cause seizure. Two main processes appear to be present in fretting:

(a) A mechanical action which removes oxide films resulting in rapid reoxidation followed by further removal of oxide with each successive cycle.

(b) The removal of fine particles by mechanical abrading or by the formation and subsequent shearing of welds at points of contact. The particles are then broken up by direct shearing or fatigue.
Fretting usually occurs where there is vibration and therefore can be eliminated by removal of that vibration. Surrounding the area with lubricant improves damping, reduces the coefficient of friction and prevents contact to some extent which helps prevent fretting. Surface coatings have also been found to offer solutions to particular fretting problems by reducing adhesion.

Corrosive Wear.

With the introduction of high sulphur fuels and lubricants a considerable increase in the wear of internal combustion engine components was recorded. This has been attributed to acidic formations. Modern lubricants have been developed which contain amounts of free alkalis, which neutralise acidity. The problem of corrosive wear in modern engines is not serious and is usually only evident after a long operating life.

Increases in wear rate due to corrosion are difficult to describe in a specific sense. No set corrosion model can be applied universally to bearing situations. A typical individual example of impaired wear resistance occurs in white metal bearings, where the formation of tin oxide, by corrosion can seriously reduce the strength of the bearing. The presence of hard tin oxide particles also increases abrasive wear.

Corrosion can also be reduced by changes in the structure and composition of the bearing couple materials.

Fatigue.

Fatigue occurs on bearing surfaces which come into repeated contact at stresses in excess of the specified fatigue stress for
the materials concerned. This type of damage is particularly common in cams, ball bearings and gear teeth. Damage may be initiated at or near the surface, in both cases resulting in a pitted mating surface. Corrosion or defects within the body of the material may promote early fatigue failures.

Fatigue problems can be seen as striations extending radially from the source of fatigue. Fatigue striations may become obscured by products of corrosion or where surfaces continue to rub against each other after the initiation of fracture.

Surface treatments such as shot peening, which increase hardness and leave the surface in a condition of residual compressive stress are used to improve fatigue failure resistance.

**Delamination.**

Delamination is a recently characterised mechanism of wear thought to occur in "scuffing" in internal combustion engines. It is also thought to be present in many other bearing applications and is indicated by the production of plate-like debris. Discovery of delamination followed observations that the debris produced in many situations did not have the appearance of debris produced in abrasion or adhesion (35).

Wear debris from delamination appears as plate-like debris with a length to thickness ratio in excess of 10:1. Cylinder liners previously thought to fail by abrasion have been shown to fail by delamination (36).

Delamination is indicated by a ploughed surface appearance. Both flat and coiled plates of debris may be produced. The effects
of deformation are highly localised and it is sometimes possible
to see plates originating at discontinuities in material structures.

1.6. CHARACTERISTICS AND APPLICATIONS OF BEARING MATERIALS.

In comparing different bearing materials, a problem arises
in predicting the performance of one material in comparison to
another. This is due to the wide variety of properties a bearing
material may possess and the varying degrees in which these
properties are present.

In general, a new bearing material's performance cannot be
completely assessed until it is used in the actual application
for which it was intended. (For example, the replacement of
Babbit metals in automotive bearings by copper-lead and aluminium-
tin alloys).

In the absence of established standards for bearing material
comparison, the literature contains data of a subjective nature
which makes comparisons of data from different sources difficult.

Table 1 attempts to classify bearing material characteristics
and applications together with a rough indication of the maximum
load carrying capacity of each material. Load carrying capacity
is speed dependent and so it has been attempted to ensure that
data for comparison has been obtained by similar experimental
methods.

Information has been compiled from a number of sources (1-3,
5-7, 9, 14-16, 24, 37, 38).
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MAX LOAD (MN/m²)</th>
<th>CHARACTERISTICS</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin base Whitemetal</td>
<td>1.0 - 1.75 (limited by fatigue resistance at higher temperatures)</td>
<td>Good fatigue resistance below 130°C. Good corrosion resistance. Good seizure resistance.</td>
<td>Low loads, Electric motors, Pumps.</td>
</tr>
<tr>
<td>Lead base Whitemetal</td>
<td>1.0 - 9.0</td>
<td>As tin base, but better fatigue performance at higher temperatures and more wear resistant.</td>
<td>Automobile engines and transmissions - light cyclic loads.</td>
</tr>
<tr>
<td>Tin-bronzes</td>
<td>Upto 70.0 (at very low speeds)</td>
<td>Good strength. Good friction characteristics. Good toughness. Very good corrosion resistance. Poor fatigue resistance.</td>
<td>Slow speeds - Railway turntables, Bridges, Uses at sea.</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>MAX LOAD (MN/m²)</td>
<td>CHARACTERISTICS</td>
<td>APPLICATIONS</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Silver</td>
<td>28.0 - 42.0</td>
<td>Exceptional fatigue resistance and load carrying capacity.</td>
<td>Mainly limited to high speed applications in aircraft gas turbines due to high cost.</td>
</tr>
<tr>
<td></td>
<td>(at very high speeds)</td>
<td>Corrosion resistance very poor with sulphur lubricants.</td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>3.5 max.</td>
<td>Low melting point. Good friction characteristics. Cheap.</td>
<td>Low loads. Slow speeds.</td>
</tr>
<tr>
<td></td>
<td>(at low temperatures)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.T.F.E.</td>
<td>30.0 - 40.0</td>
<td>Excellent coefficient of friction. Chemically inert.</td>
<td>Many applications - usually used as low friction coating. Slow speeds.</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>MAX LOAD (MN/m²)</td>
<td>CHARACTERISTICS</td>
<td>APPLICATIONS</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Asbestos cloth reinforced phenolic</td>
<td>70.0 +</td>
<td>High compressive strength. Good friction characteristics with P.T.F.E. overlay.</td>
<td>Heavy duty applications. Sliding crane jibs. Suspension ball sockets.</td>
</tr>
<tr>
<td>Asbestos yarn reinforced-cresylic</td>
<td>30.0 (approx)</td>
<td>High resilience and good deformability. Good corrosion resistance.</td>
<td>Water lubricated propellor shafts on ships and submarines.</td>
</tr>
<tr>
<td>Asbestos flock reinforced phenolics</td>
<td>40.0 (approx)</td>
<td>Good deformability. Random fibres - no directional properties.</td>
<td>Automotive steering gear bearings.</td>
</tr>
<tr>
<td>Cotton cloth reinforced phenolics</td>
<td>70.0 (approx)</td>
<td>High strength High coefficient of friction unless water lubricated.</td>
<td>Heavy duty. Steel rolling mills.</td>
</tr>
<tr>
<td>Acetal copolymer with entrapped mineral oil</td>
<td>30.0 (approx)</td>
<td>Similar to P.T.F.E. but cheaper.</td>
<td>Similar to P.T.F.E.</td>
</tr>
</tbody>
</table>
1.7 THE EFFECT OF MATERIAL TYPE ON WEAR MECHANISMS.

Four structures of bearing material have been identified. (See 1.2). These are:

(i) Hard particles dispersed in a soft matrix (eg. white metal types).

(ii) Soft material dispersed throughout a hard matrix.
     (eg. copper-lead).

(iii) Single metals or single phase alloys (eg. silver).

(iv) Non metallic materials (eg. thermoset types).

The construction of bearing materials has a major influence on their dominant mechanisms of wear.

Where hard particles are present in a softer matrix, for example, iron phosphide or vanadium carbide in steels, the particles act as a load carrying element which resists abrasive wear. This is due to hard particles standing proud of the matrix which allow a differential wear process to occur. Abrasive wear resistance is inversely proportional to overall hardness\(^{(32)}\). The greater the number of hard particles, the greater the resistance to abrasive wear. However, work hardening may also have some effect. Cast irons do not work harden and so there is a good correlation between hardness and abrasive wear. Some steels, for example, Hadfield's manganese steel, offer better abrasive wear resistance above certain loads, when surface pressure is high enough to drastically work harden the surface.

Resistance to abrasive wear is also dependent on the hardness of the abrasive particles. Aluminium alloys are comparatively soft and so in the presence of hard abrasive particles tend to suffer a
high rate of abrasive wear. However, few wear interface conditions produce sufficient particles to cause major problems. Softer materials also allow a small number of abrasive particles to be embedded without major abrasive wear damage.

Adhesive wear in materials is caused to contacting asperities by a process of deformation and welding. Adhesive wear is encouraged if the wear couple is mutually soluble. Bearing materials which consist of a soft material dispersed throughout a hard matrix resist adhesive wear by allowing the soft material to smear over the hard matrix. The softer material, (eg. lead in copper lead alloys) forms a layer of material which is not mutually soluble with the material of the mating component and so adhesive wear is avoided. This, in turn, can also reduce abrasive wear by preventing the formation of small particles of debris which may abrade the mating surfaces. Bearing materials which operate in this manner are also associated with sharp transitions in wear behaviour. For example, some aluminium alloys tend to wear at a mild rate due to the formation of an insoluble oxide layer on the surface. However, above a certain load, the layer breaks down and wear becomes considerably more severe. The use of tin in aluminium-tin alloys is a similar example.

Single phase materials are used to produce bearings which are tough and resistant to fatigue, allowing high loads to be carried at high speeds. The lack of secondary phases helps to prevent the initiation of cracks which may eventually cause the material to become fragmented. This helps prevent wear by abrasion and delamination. However, single phase materials may be soluble with the material of their mating components, which can result in adhesive wear. Therefore, an insoluble overlay is
usually required. (eg. the use of lead on silver.)

The use of non-metallic bearings usually eliminates adhesive wear because they are rarely soluble in metals. However, their low hardness and strength can result in severe abrasive wear and delamination.
The excellent potential as a bearing material for aluminium alloys containing dispersed graphite particles has been noted by a number of sources. Some of the earliest recorded work on the subject was published by Badia and Rohatgi (39) in 1969. In this work, graphite was incorporated by the use of nickel coated graphite particles injected into the melt using a nitrogen gas stream. The size of the graphite particles ranged from 60 - 400 μM. The Hohman wear tester (Fig. 1) was used to evaluate the materials with the use of the bearing parameter ZN/P.

The performances of graphitic and non-graphitic alloys were compared. To summarise the results, it was found that the presence of graphite in the alloys almost eliminated the onset of abrasive wear. The higher the graphite content, the lower the prospect of galling. None of the ungraphitised alloys were found to operate without galling under boundary lubrication conditions (ZN/P < 3). Graphite allowed the alloys to run without galling above a coefficient of friction of 0.1 whereas galling occurred without the use of graphite at a coefficient of friction of 0.025. A further finding was that silicon, nickel and graphite additions gave superior galling resistance to an alloy with silicon and
graphite only. This was probably due to a stronger base alloy and is a finding confirmed by an alternative source \(^{(40)}\).

In attempting to explain the superior galling resistance of the alloys which contained graphite particles, Badia and Rohatgi suggested three possible mechanisms which have operated under boundary lubrication conditions:

(i) A thin graphite layer spread over the mating surfaces, providing a layer of solid lubricant and preventing metal to metal contact.

(ii) The graphite may have been transferred to the lubricant thus providing superior lubrication conditions.

(iii) Voids, which were formed as a result of graphite vacating the surface, may have provided tiny reservoirs of lubricant.

Badia and Rohatgi and others \(^{(4,41)}\) have shown (ii) and (iii) not to be the case by running alloys containing graphite in similar tests which were completely unlubricated. Similar alloys containing no graphite were also run under identical conditions. The graphitic aluminium alloys allowed the test to be conducted without lubrication with no signs of galling. In contrast the alloys without graphite galled almost instantaneously.

The authors concluded that graphitisation of aluminium alloys improved their galling resistance to the extent that they could become useful bearing materials. They hypothesised that improved galling resistance was due to the flow of graphite over the aluminium matrix surface and that any depletion of surface graphite was replenished.
by a flow from the subsurface. The hypothesis was supported by photomicrographs.

Badia and Rohatgi made no comparisons with established bearing materials, but the publication does indicate that graphitised aluminium alloys may offer solutions to the problems encountered with aluminium silicon alloys which tend to gall when lubrication is sparse, for example, aluminium-silicon cylinders in internal combustion engines.

Gorbunov et al. (4) evaluated "aluminium-graphite antifriction alloys" by comparisons with a phosphor-bronze bearing material and a lead Babbit. The aluminium alloys were graphitised by a technique involving the use of ultrasonic vibrations and surface active elements in the melt, the graphite particles were uncoated. Wear testing was carried out on an "M.I.1" wear tester which consists of placing the material under test under a hardened steel roller with pressure applied.

The authors state that the friction characteristics of the graphitised aluminium were superior to those of the phosphor bronze and approximately equal to those of lead Babbit. However, load carrying capacity did not approach that of the Babbit material. Information regarding the actual compositions of all the materials evaluated is not given, but it should be noted that Babbit materials are not generally considered to offer sufficient load carrying capacity and fatigue resistance for the high temperatures and loads encountered in modern internal combustion engines. The reference states that graphitised aluminium bearings have been successfully employed in hydraulic pump bearings to replace phosphor-bronze
and that this resulted in a significant cost saving. The authors stated that, from the manufacturers point of view, the alloys can be recommended for the production of plain monolithic bearings for use under boundary lubrication.

This is a conclusion reiterated by Biswas et al.\(^{(44)}\) who also stated that graphitised aluminium alloys were found to offer a superior bearing performance to a phosphor-bronze.

Suwa et al.\(^{(42)}\) investigated strength and wear resistance of graphitised alloys using nickel coated particles of graphite. The optimum range of graphite content for the highest wear resistance, was stated as 5 - 10\% by weight. In common with previous sources\(^{(4,39)}\) this report stated that unlubricated and lubricated graphitised alloys possessed friction characteristics similar or better than lubricated alloys without graphite and that wear resistance increased with increased graphite contents. The particular alloy matrix used also had an effect on strength and wear. The stronger the base alloy, the stronger was the composite and this provided associated improvements in wear resistance. Alloys with higher strength were able to tolerate a higher graphite content for a given strength.

These findings were emphasised by Rohatgi and Pai\(^{(43)}\). In common with previous work\(^{(39)}\), their investigation centred on the Hohman wear tester. In general, both reports gave similar results from wear tests. The latter work extended the investigation to consider variations in graphite content, shape and particle sizes. Graphite shape investigations were restricted to spheroidal and flake graphites.

The authors claimed that unlike cast irons, graphite shape
and size had no effect on wear and seizure resistance. However, higher contents were claimed to delay the onset of wear. The explanation given for this was that the aluminium alloy matrix yielded at low yield stresses and deformed extensively which in turn accentuated the deformation and fragmentation of surface and subsurface graphite particles. Thus a continuous graphite film was deposited on the mating surface, which gave solid lubrication and prevented seizing. If the graphite layer became damaged in any way, then deformation and fragmentation of subsurface graphite caused it to come to the mating surface, thus maintaining a continuous film.

The evidence presented suggests that this explanation is fairly sound, in which case graphitised aluminium alloys may be considered as type (ii) bearing materials (see Chapter 1). (i.e. A soft material becoming smeared over a hard matrix and acting as a solid lubricant film). Tokisue and Abbaschian (47) have also made claims about the properties and potential of graphitised aluminium alloys which reflect the conclusions outlined above.

**Load Carrying Capacity and Fatigue Life.**

Load carrying capacity of graphitised alloys does not appear to be well documented. This is partly due to there being no standardised method of evaluation available (see Chapter 1). Biswas et al. (44) have quoted a PV value of $73 \times 10^6$ Nm m$^{-2}$ min$^{-1}$ but this may be of little significance due to the limitations of PV values (see Chapter 1).

In general, the literature states that load carrying capacity
is a function of tensile and compressive strengths and to a lesser extent hardness or resistance to deformation. Gorbunov\(^{(4)}\) gave the following data with regard to these properties. (Table 1).

**TABLE 1 : PROPERTIES OF GRAPHITISED ALUMINIUM ALLOYS**\(^{(4)}\).

<table>
<thead>
<tr>
<th>% Graphite (by-volume)</th>
<th>Tensile Strength (MN/m(^2))</th>
<th>Compressive (MN/m(^2)) Strength</th>
<th>Linear coef. of expansion (\times 10^{-6}/^\circ C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>167</td>
<td>549</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>147</td>
<td>343</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>118</td>
<td>294</td>
<td>14</td>
</tr>
</tbody>
</table>

From Table 1, it can be seen that graphite content tended to reduce tensile and compressive strength, but if limited to around 5\% by volume (approx. 4\% by weight) then tensile and compressive properties compare very favourably with the published values for S.A.E. 770, an aluminium-tin alloy\(^{(3)}\),

i.e. Tensile strength 148 MN/m\(^2\)
Compressive strength 441 MN/m\(^2\).

Therefore, according to Gorbunov et al., the properties which are likely to influence load carrying capacity are similar to those of a high performance bearing material however, Gorbunov et al. state that a Babbit material, which is widely believed to have a lower load carrying capacity than aluminium-tin materials, offers higher load carrying capacity than graphitised aluminium alloys. This may be the result of poor fatigue performance,
Gorbunov et al. may have limited the loads carried by the graphitised aluminium alloy in an attempt to compensate deficiencies in fatigue performance.

Little published information on the fatigue performance of graphitised aluminium alloys exists. Therefore, it has been attempted to surmise on the fatigue properties from the data available.

Fatigue cracks tend to grow from small surface irregularities or discontinuities. The presence of voids vacated by graphite may have a detrimental effect in this respect. In some cases, non-metallic inclusions just below the surface may act as starting points for cracks. Easily deformed inclusions may reduce fatigue life slightly but hard inclusions can have a catastrophic effect\(^{(45)}\). Therefore graphite may not have a significant effect in terms of fatigue defects initiated from the subsurface.

Hardness and impact values appear to have little influence on fatigue life and so reported losses in such properties\(^{(4)}\) are not likely to be of any consequence.

Alloys which form unstable precipitates often suffer relatively poor fatigue strengths in relation to their static strengths. Aluminium alloys graphitised by the use of either copper or nickel coated particulate may form precipitates which cause poor fatigue properties.

Aluminium alloys containing dispersed graphite have been found to offer high damping capacity\(^{(46)}\). This property may help damp out cyclic forces, helping to prevent fatigue problems.
From the above, it is not possible to make conclusions on the fatigue performance of graphitised aluminium alloys. One of the most important areas of bearing application is fatigue performance, and so it is important that bearing fatigue properties of graphitised aluminium alloys are investigated. Many excellent bearing materials, for example, tin Babbit, now have limited bearing applications due to low load carrying capacity caused by poor fatigue properties.

**Dry Wear Properties.**

Graphitic aluminium composites have been claimed to be good anti-seizure and anti-friction materials. Most of the literature available makes these claims from the results obtained from lubricated tests. These properties are claimed to make the material suitable for boundary lubrication conditions where lubricant is scarce or non-existent. The investigation of "dry wear" properties is therefore of particular relevance.

The work of Suwa et al.\(^{(42)}\) showed that under dry conditions, the wear resistance of aluminium-graphite, (nickel coated) composite, increases with increasing graphite content. Tests were conducted on a reciprocating pin on plate type machine.

Biswas and Pramila Bai\(^{(48)}\) published findings which contradicted Suwa et al. Tests conducted under unlubricated conditions were claimed to show that wear characteristics deteriorated with the addition of graphite. The results were repeated through a range of loads and sliding distances, conducted on a pin on disc wear testing machine. Microstructural and
microhardness studies of the worn subsurface and debris analysis showed that decreases in ductility and strength of the composite due to graphite particle addition, may have been the most likely causes of deterioration of the dry wear characteristics of the composite material.

In general, the results published by Biswas and Pramila Bai do not reflect findings in previous research from many different sources, and so the area of dry wear testing requires further investigation so that firm conclusions can be made.

Internal Combustion Engine Components.

Smith\(^{(49)}\) has outlined a case for an "all aluminium engine" but points to a problem also outlined by Patton\(^{(54)}\). For many engineering applications such as piston and cylinder arrangements, it is desirable to run aluminium alloys, particularly aluminium-silicon, in sliding contact with each other. However, unless lubrication conditions are ideal, they tend to seize or gall. The problem becomes more intense in conditions of boundary lubrication. Such conditions can occur in almost all cases of sliding contact. Various solutions have been tried to solve this problem. They have included the development of surface treatments and coatings\(^{(51)}\) and alloys of intrinsically high hardness. Whilst some treatments have been proved to be effective, most have proved to be too expensive for large volume production.

Hypereutectic Aluminium-silicon alloys with silicon contents of 16 - 20 wt % have been developed for aluminium cylinder blocks\(^{(51)}\). The material requires a special chemical treatment to expose
primary silicon on the bore surface, and pistons require a wear resistant coating. Bearing properties are excellent under conditions of good lubrication but abrasive wear and delamination can occur with cold starts and poor lubrication. "Running in" characteristics are also limited. Damage has frequently occurred leading to failure of the component and loss of confidence by the automobile manufacturers.

For this reason an alternative approach is under development by Bruni and Iguera (52) whereby solid lubricant (graphite) is incorporated into the aluminium-silicon alloy. Cylinders have been manufactured from hypereutectic aluminium-silicon alloys with dispersed graphite particles. Components normally made from cast iron, have been substituted by the composite cylinders. Applications included a complete cast cylinder barrel for a 125 cc Hiro two stroke engine and replacement of cast iron wet liners in a 1300 cc Alfa Romeo engine and 3 litre Ferrari formula 1 racing engine. All components were finished using a standard diamond boring operation with no special chemical treatments required. Pistons and rings were identical to those used with cast iron components.

The authors state that the graphitised aluminium alloys displayed superior wear and friction characteristics in all cases. Scuffing tests were carried out and it was found that the properties of aluminium-graphite cylinders allowed the tests to be extended to three times their normal duration. A further observation was that average power outputs were increased as a direct result of improved friction properties. The material has not been adopted by a motor manufacturer for a production engine. Bruni and Iguera found a
slight problem with piston ring wear and recommended that chromium plated rings were essential to prevent oil blow-by at the end of test sequences. However, Ferrari did adopt the material for their formula one racing engines.

Adoption in production engines may not have occurred as a result of difficulties in manufacturing components from graphitised aluminium-silicon alloy. Methods at present available for dispersing graphite may not be suited to volume production. Bruni and Iguera stated that a mechanical stirring technique was used. Previous research indicated that die casting, preferably with pressure applied, was required to ensure a sound casting was produced in graphitised aluminium alloy with good distribution of graphite. Therefore, it can be seen that two separate processes are required for the production of castings from graphitised aluminium alloys. This is likely to increase manufacturing costs of components when compared with the cost of manufacturing similar quantities of the same components from cast iron.

Krishnan et al. (53) have described the performance of an aluminium-silicon-graphite particle composite piston in a diesel engine. Tests with a 5 hp single cylinder Diesel engine have shown that aluminium-silicon-graphite particle composite pistons could withstand an endurance test of 500 hours without any apparent deterioration. The use of the aluminium-silicon-3% graphite piston also resulted in reductions in specific fuel consumption, considerable reduction in the wear of the piston rings, reduction in the wear of the piston and a reduction in frictional horsepower losses as determined by the motoring test (53). It is stated that these
reductions were due to increased lubrication from the graphite particles which were smeared on the bearing surface, higher damping capacity of the composite pistons and reduced coefficient of thermal expansion. The authors state that the results indicate that aluminium-graphite particle composites offer a promising material for automotive pistons.

High Damping Applications.

Graphitised aluminium-alloy castings have been shown to possess remarkable damping capacity as a result of their dispersed graphite\(^{(46,54)}\). The damping capacity for a given weight was in fact found to be superior to cast iron. This suggests applications such as machine tools and structures where vibration and wear must be minimised.

The use of the material for jig and tool applications may also be feasible. The reduction in weight over cast iron and excellent wear properties could be very useful in combination with high damping capacity. However a compromise may be necessary due to increased cost.

Coefficient of Expansion.

The inclusion of graphite appears to reduce coefficient of expansion. Gorbunov et al. have published figures to support this (see Table 1). Krishnan et al.\(^{(53)}\) have also published such a finding. A reduction in coefficient of expansion may be a desirable advantage in comparison with aluminium-tin alloys. One of the few disadvantages of aluminium-tin bearings is that they require large working clearances to account for expansion at operating temperature. This can cause knocking and fretting in large Diesel engines when starting.
Corrosion Resistance.

Aluminium base bearings have become renowned for their resistance to corrosion. This property may not be reflected in aluminium alloys containing dispersed graphite because graphite is known to be a highly effective cathode in electrochemical terms. Therefore it may be found that the aluminium alloy will corrode.

Chandrashekar and Rohatgi\(^{(55)}\) investigated the electrochemical and stress corrosion compatibility of aluminium-graphite particulate composites. They found that the corrosion potential shifted to the noble side as graphite content in the composite was increased. The corrosion resistance was found to be better than an aluminium base piston alloy (LM13). Similarly, when composites were coupled with iron, galvanic corrosion was found to be negligibly small. The authors concluded that these composites offered a high potential for use in automobile engines.

2.2 PRODUCTION OF ALUMINIUM-SILICON ALLOYS CONTAINING DISPERSED GRAPHITE.

The most direct route for the production of graphitic particulate aluminium composites would seem to be to add graphite powder to the molten metal and cast the resulting composite melt. The major difficulty with such an addition has been reported to be the lack of wetting between graphite and aluminium, leading to the rejection of graphite as soon as it is introduced into the melt\(^{(56)}\). The angle of contact of aluminium with graphite is \(160^\circ\) and has been reported to remain unchanged from the melting point of aluminium to \(1050^\circ\)C.
Several approaches have been tried as a means of dispersing graphite particles in aluminium alloy melts.

These include:

a) Injection into the melt of nickel coated graphite powder in a stream of nitrogen gas\(^{39,57}\).

b) Stirring the melt to create a vortex into which coated graphite particles could be placed and so dispersed. Nickel\(^ {66}\) and copper\(^ {59}\) coatings have been used. Later investigations found that heat treating the graphite precluded the need for coatings\(^ {60}\).

c) Immersion of a pellet compact consisting of base alloy powder and coated graphite powder\(^ {61}\).

d) Use of ultrasonic vibrations and surface active elements to disperse uncoated graphite\(^ {4}\).

e) Reacting nickel coated graphite powder with aluminium at an elevated temperature to form a briquette consisting of graphite and the matrix alloy. The briquette then being immersed to disperse graphite particles in the melt\(^ {123}\).

f) Infiltration of coated powder by molten aluminium alloy\(^ {62}\).

A further means of including particulate material is that of "Compocasting" described by Mehrabian et al.\(^ {63}\). This has not been reported as a means of including graphite in aluminium alloys for bearing purposes but offers potential in this area, because the introduction of anthracite particulate has been reported.

Review of Processes for the Production of Graphitised Aluminium Alloys.

a) Injection into the melt of nickel coated graphite powder in a
stream of nitrogen gas:

This method was first described by Badia et al. (57) in 1969. A nickel coated powder was used which allowed nickel to be wetted by molten aluminium alloy. A special gun was developed with a hopper to contain coated powder and allow it to fall by gravity into a nitrogen gas stream. The melt was stirred whilst the nozzle of the gun was placed beneath the melt surface. The authors described a mechanism whereby a nitrogen bubble formed in the melt. The bubble rose slowly to the surface whilst its size increased due to the decreasing pressure head. Coated graphite particles came into contact with the bubble-melt interface and either dispersed into the melt or were rejected. Transfer of graphite took place if conditions were energetically favourable and if graphite came to the interface. The necessary condition for transfer was said to be a function of surface energy and density. After transfer, the nickel dissolved in the molten aluminium, at which point stirring the melt vigorously was necessary to ensure that the graphite did not float. Permanent moulds were found to be essential to ensure a high cooling rate and so prevent graphite flotation. Badia gave examples of automobile pistons which were cast in this way and indicated with photographs, a regular deposition of graphite. He went on to state that castings could be remelted but graphite tends to be lost after successive remelts. The nitrogen stream had a useful secondary effect in degassing the melt. However, chlorine degassing resulted in rejection of graphite.

The authors claimed that stirring and mixing were sufficient
to ensure that graphite did not segregate, however, subsequent publications did not confirm such a finding \( (54,64,65) \). Later work reported that the gas injection method led to a large proportion of rejected graphite \( (66) \) and the use of nickel coated particulate resulted in the formation of an intermetallic \( (\text{Ni Al}_3) \) within the casting which caused embrittlement \( (59) \).

b) Stirring the melt to create a vortex into which coated graphite could be placed and so dispersed:

Further work published in 1971 carried out by Badia et al. \( (66) \) concerned the development of the "Vortex Method" and also the use of copper coated graphite particles. The process for copper coating was described by Pai et al. \( (40) \).

The "Vortex Method" consisted of heating aluminium alloy to a completely liquid temperature. Stirring was then carried out using an impeller powered by an electric motor. The driving shaft of the impeller was usually inclined at an angle of 20° to accentuate the formation of a vortex within the liquid. Graphite powder, normally nickel coated, was then deposited into the vortex and was pulled down into the melt and subsequently dispersed evenly throughout the melt by the stirring action.

To optimise the performance of the impeller a simulation was used which involved using a mixture of red polypropylene powder in water. These two substances offered a similar density relationship to liquid aluminium alloy and graphite. The extent of mixing could be easily seen because the powder was red.

Examples were given of pistons, bearings and other components,
all having been cast in permanent moulds. The Vortex Method was claimed to offer better recovery of graphite than gas injection and also the impeller could be controlled to ensure predictable graphite content and dispersion. Graphite segregation, due to flotation, could be put to good use to provide areas of high graphite content within a casting which would also contain more ductile, graphite-free, areas. This could be achieved by control of cooling rates and mould orientation.

Surappa et al. (59) published details of the use of copper coated graphite for the production of graphitised aluminium alloys. Advantages of copper coated particles were:

i) Copper was cheaper than nickel.

ii) Copper was more easily coated on graphite.

iii) Nickel formed a brittle intermetallic compound Ni Al₃ which reduced ductility.

Two disadvantages were:

i) Corrosion resistance was impaired by copper.

ii) As-cast tensile strengths were reduced. However, the inclusion of copper allowed the alloy to become heat-treatable, so that tensile strength and hardness could be improved but with some loss of ductility.

Surappa et al., in contrast with Badia et al., claimed that the use of chlorine degassing was possible. Problems of segregation and flotation were not acknowledged, it was stated that distribution of graphite was quite uniform and that pouring temperatures of 973 - 1073°K gave the best conditions for a good graphite
distribution. A later development of the vortex technique was described by Krishnan et al. (60) in 1981 and termed the UPAL process. The mixing technique was similar to that described above, but the graphite did not require a metallic coating because a special heat-treatment made this unnecessary. This consisted of heating the graphite particles to 400°C for one hour prior to stirring and was thought to remove all traces of moisture from the graphite surface and in so doing, improve wettability. Further wetting improvements were achieved with the use of surface active elements. Examples of cast pistons and liners were shown which were produced by this technique. The U.P.A.L. process was claimed to offer reductions in cost and has been used widely in subsequent research.

c) Immersion of a pellet compact consisting of base alloy powder and coated graphite powder (61):

This method was put forward by Pai and Rohatgi in 1978. The authors stated that both the gas injection method and the "Vortex Method" suffered a problem during the transfer of the graphite particle from air or gas bubble into the bath of molten metal. Using the pellet method this problem was overcome since the pellet was already under the surface of the molten metal, being held there with a plunger.

The pellets were prepared by producing powder compacts of aluminium and coated graphite powders, in the ratio of 1:2, with a green density of between 2.4 and 12.6 g cm⁻³. The pellets, 20 mm in diameter and 50 mm in length, were produced at a pressure between 3 and 5 kg mm⁻².
Several pellets were plunged into the melt using an inverted cup whilst stirring. Expanding gases entrapped between the powder particles and expanding aluminium powder became heated to the melt temperature resulting in disintegration of the pellet and dispersion of graphite throughout the melt. Aluminium alloys containing silicon were found to give higher recoveries of graphite probably as a result of silicon forming a metastable phase with graphite, or alternatively, silicon may have become absorbed on the surface of the graphite reducing its flotation rate. The authors state that occasionally places in castings were found where graphite was not evenly dispersed, perhaps due to incomplete disintegration of the pellets.

It was concluded that the pellet technique was suitable for use in foundries because less skill was required and good results were obtained.

d) Use of ultrasonic vibrations and surface active elements to disperse uncoated graphite:

This method has been widely used for the production of aluminium alloy graphite fibre composites (67) and stems from the idea that graphite will not be wet by aluminium alloys due to the effects of absorbed oxygen and water on the surface of the graphite.

Gorbunov et al. (4) subjected the melt to ultrasonic vibrations using a probe 2-5 mm below the surface oscillating at a frequency of 15-20 kHz. Uncoated graphite was placed on the melt surface at a temperature 20-25°C above the liquidus temperature resulting in a pasty mix. The temperature was then increased whilst the ultra-
sonic probe was slowly lowered to full depth. The melt was simultaneously stirred for 2-3 minutes. Wetting was thought to be due to the combined action of cleaning by ultrasonic vibrations and surface and interface active elements, resulting in the formation of strong bonds. The graphite particles were claimed to be free from absorbed gases and various impurity films, and so the contact angle was reduced.

Temperature of the composite had to be limited to ensure that graphite remained suspended within the melt which may have limited viscosity because it was stated that the most effective means of forming was semi-liquid stamping or pressure die casting with an enlarged ingate.

e) Reacting nickel coated graphite powder with aluminium-alloy at an elevated temperature to form a briquette:

General Motors Corporation of U.S.A. have patented a method for producing graphitic-aluminium castings which consisted of reacting nickel coated graphite particles with aluminium alloys at elevated temperatures in a non-oxidising environment to form a briquette consisting essentially of graphite particles and a discrete nickel-aluminium intermetallic phase in an aluminium matrix. The briquette was then immersed in an aluminium alloy melt where it melted and the graphite particles became suspended in the molten aluminium alloy.

f) Infiltration of coated powder by molten aluminium alloy:

The Teikoku Piston ring company of Japan has patented a method of making "lubricated" aluminium alloys. In this
method, graphite or boron nitride powder coated with nickel or copper by vapour deposition or electroless plating was infiltrated with molten aluminium and solidified to make "self lubricated aluminium alloys".

Rheocasting.

The methods described above, all required coated graphite particulate or special treatments to melts and particles. This has led to processes which are excessively time consuming and complicated for large scale production of components made from graphitised aluminium alloys. Coated graphite particles are expensive to produce. (Nickel has been coated by a process of decomposition of nickel carbonyl directly onto the particle surface. Copper has been coated by electroless plating.)

At the Massachusetts Institute of Technology Flemings and his group developed a compocasting technique from their investigations into rheocasting. They found that metal alloys held at a temperature between solid and liquid which were vigorously agitated exhibited an unusual non-dendritic structure (68). Alloys in this condition could be cast at a temperature lower than their melting points. Compocasting (63) was a development in which particulate non-metallic material could be added to, dispersed and retained in a semi-solid alloy slurry. Reports make no specific reference to the inclusion of graphite particles in aluminium-silicon alloys by compocasting but it has been claimed that anthracite, a carbon based material, can be included and so this method may offer a potential means of graphitisation. The advantage
of there being no need to use coated or specially treated particles could be offered together with the established advantages of rheocasting (68).

**Principles of Semi-solid Processing.**

When a conventional casting alloy solidifies, it forms a dendritic primary phase which is surrounded by eutectic on final solidification. Each dendrite has a fir tree-like branched structure which traps interdendritic eutectic between its branches. On reheating such a structure to a temperature between its liquidus and solidus, the eutectic melts but the dendrites offer resistance to flow. If the material is sheared fracture occurs through the liquid phase. This has become known as hot shortness.

If the alloy in this state is vigorously agitated, the structure tends to degenerate, converting the material into a low viscosity slurry. The dendrites are broken down and globularised to form rounded particles which are rather coarse. If these are held without further agitation, they form agglomerations surrounded by liquid phase which become fairly rigid. That is, the stationary slurry viscosity rapidly increases and can be handled as a solid. If it is put under pressure by shearing, the bonds between the rounded particles are disturbed and the metal will flow as a viscous liquid without the body of the metal fracturing. Viscosities of slurries become lower with increasing shear rates; that is, they are thixotropic. In the stationary state, they can be handled and fed into a die-casting machine. When forced by the ram into the die, the metal flows like ball bearings in syrup and readily fills the die.
CHAPTER 3

THE PRODUCTION AND CASTING OF ALUMINIUM ALLOYS
CONTAINING DISPERSED GRAPHITE PARTICLES

3.1 RHEOCasting AND COmpocasting.

Rheocasting, as described by Flemings (68), has been developed as a means of utilising the rheological properties of vigorously agitated semi-solid slurries.

Flemings achieved vigorous agitation by stirring semi-solid alloys in such a manner that they became "sheared". The simple rheocasting process is shown in Fig. 5. Rheocast slurry has been produced continuously at fractions solid ranging up to 70%. The semi-solid slurry was fed directly into a casting machine such as a cold chamber die casting machine and formed into parts. A development from the rheocasting process which has become known as "thixocasting" (68, 69) is shown in Fig. 6. The metal was fully solidified after leaving the rheocasting machine and could be cut into convenient lengths or shapes for reheating. When the metal was required to be formed, it was simply necessary to reheat to the required semi-solid temperature, retaining the non-dendritic structure, where the material could be handled as a solid. Without any need for agitation or heating to a temperature above the liquidus, the material could be placed directly into a cold chamber die casting machine and formed.

Fundamental work on vigorously agitated, partially solidified alloys has shown that the structure and rheological behaviour of an alloy slurry are a function of three process variables. These
variables are the average shear rate, (i.e. rate of agitation); the average cooling rate during primary solidification; and the volume fraction solid within the slurry (69).

The general trends established, relating process variables to structure and viscosity of partially solid alloys, were found to be:

1. Increasing the rate of agitation (average shear rate) generally reduced the amount of entrapped liquid in solid particles resulting in a corresponding decrease in viscosity. This was also illustrated by a reduction in primary particle size.

2. Increasing the average cooling rate during primary solidification reduced the size of primary solid particles, but increased the amount of entrapped liquid in the primary solid particles. This resulted in increased volume fraction solid in the slurry and hence increased viscosity.

3. As the volume fraction solid in a slurry increased viscosity increased also.

4. For a given average shear rate (assuming constant cooling rate), the relative viscosity ($\eta_r$) of a partially solid alloy at volume fractions solid higher than 20% could be described by the relationship

$$ \eta_r = A e^{B g_s} $$

where $A$ and $B$ are constants,

$g_s$ is volume fraction solid,
and \[ \eta_r = \frac{\eta_a}{\eta_o} \]

\[ \eta_a = \text{apparent viscosity of suspension} \]

\[ \eta_o = \text{viscosity of the liquid.} \]

5. Metal slurries were thixotropic (their viscosity decreased with increased shear rate and was time dependent and reversible) and showed a thixotropic hysteresis loop phenomenon similar to other well known thixotropic systems (Fig. 7). The area of thixotropic hysteresis loops increased with time at rest indicating an increase in thixotropy.

Table 2 below summarises these findings.

**TABLE 2 : EFFECTS OF INCREASING SHEAR RATE.**

<table>
<thead>
<tr>
<th>Initial Shear Rate</th>
<th>Isothermally Held Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>When INCREASED</td>
<td>1. Apparent viscosity decreased.</td>
</tr>
<tr>
<td></td>
<td>2. Primary particle size decreased.</td>
</tr>
<tr>
<td></td>
<td>3. No change in volume fraction solid.</td>
</tr>
</tbody>
</table>

Thixotropic hysteresis loops were obtained by increasing shear rate continuously whilst torque (which reflected viscosity) was measured. At some point, shear rate was maintained constant and then reduced in the exact reverse to the increase in speed. The down curve was then obtained. If the two curves did not coincide, behaviour was thixotropic.
Compocasting would appear to offer a potential means of dispersing graphite particles in aluminium alloys. Mehrabian and Flemings (70) stated that "Particulate or fibrous non-metallic substances could be added to and retained in vigorously agitated slurries. Development of abrasion resistant and low friction materials or perhaps dilution of expensive metals are possible areas of application".

In general, when adding non-metals to partially solidified vigorously agitated slurries, it appeared that the high effective viscosity of the slurry prevented particles floating, settling or agglomerating. Increasing the mixing time promoted interaction between particles and the semi-liquid matrix and so improved bonding. Particles of silicon-carbide, aluminium oxide, magnesium oxide, boron, mica and anthracite have been dispersed by this method. Particle sizes varied from sub-micron up to 0.1 mm. The resulting composite could be cast when partially solid or after allowing to completely solidify and then reheating to above the liquidus temperature.

Compocasting was thought to bring the alloy close enough to the non-metal surface to permit bond formation by continuous agitation of the liquid portion of the slurry despite the fact that the metal did not wet the non-metal by simple contact (68). The type of bond was stated to be one of five types classified by Metcalfe (71) but was thought to be peculiar to the composite system, conditions, time and temperature. The five bond types were: dissolution and wetting bond; reaction bond; exchange reaction bond; and mixed bonds.
This process may be particularly economical if it is desired to manufacture strip for bearings. Here, the thixocasting\(^{(68)}\) route would appear to offer advantages. If the partially solid material is held at a constant temperature after shearing a large increase in viscosity takes place as a result of growth and welding of the primary particles in the liquid. At this stage the composite could be handled as a solid with tongs. Research has been carried out into rolling the material in this state\(^{(72)}\) to produce a strip. Therefore, an aluminium alloy containing graphite particles in a thixotropic state may be in a useful form for roll bonding onto a steel backing prior to forming of bearings.

Rheocasting operations in aluminium graphite bearing production are attractive for the following reasons:

1. No need for expensive metallic coatings on graphite powder.
2. Useful material form for bonding to steel strip, no need for two casting operations.
3. Lower casting temperature, therefore lower energy usage.
4. Less problems with graphite rejection and segregation.

However, West\(^{(73)}\) reported that rheocasting tended to have an adverse effect on fatigue life which may be undesirable in terms of bearing performance.

### 3.2 METHODS OF CASTING COMPONENTS

Having dispersed and retained graphite within an aluminium alloy melt or slurry, the next stage to be considered is the manufacture of actual castings.
Published work on graphitised aluminium alloys appears to refer to bearings which were cast and machined into the shape in which they were used. However, for bearing production to be as economical as possible casting may not be viable. Most shell bearings are produced by blanking and forming operations. Thus if aluminium-graphite bearings are found to exhibit useful bearing properties, it is likely that special attention will have to be given to production by this method.

Krishnan et al. (65) have shown that centrifugal casting is a viable technique for producing circular bearings. The density difference between aluminium alloy and graphite particles was put to good advantage because the graphite particles tended to segregate at the inner bearing surface, resulting in a high graphite content at the bearing surface with a stronger, more ductile backing. Centrifugal casting of aluminium alloys with graphite particles may prove to be an economical means of producing bearing shapes, especially if it can be shown that graphitised aluminium alloys offer similar properties to centrifugally cast tin Babbit whose constituents are considerably more expensive. The authors also gave data concerning optimum particle size, casting temperatures and spinning speeds.

Squeeze Casting.

This process has evolved to impart many of the properties of a forging to a casting, in one single pressing operation. The process has been shown to be a viable technique for producing strong high integrity castings such as automobile and military
tank wheels and Diesel pistons in aluminium alloys. Squeeze casting is now a production process used commercially by companies which include GKN (UK)(77), Gould (USA)(78) and Toyota (Japan).

The process consists of pouring molten metal into a heated die and then applying pressure during solidification (Fig. 8). The pressure being applied by either a simple punch pushing down on the melt surface or by a punch which also serves to force molten metal into more intricate die shapes, thus allowing the production of more complicated casting shapes.

Kaneko(74) claimed that the process offered increases in tensile strength, compressive strength and Charpy impact values over more conventional die casting techniques. Surface finish and accuracy were stated to be excellent and possibly as good as any precision casting technique. Components such as motor car wheels required no machining or polishing.

A form of squeeze casting has been patented(75,76) as a means of casting alloys which are held at semi-solid temperatures, below their melting points. The process has also become known as "thixoforging". In such cases, it may become necessary to inject the agitated slurry into the die because high apparent viscosity may preclude pouring by gravity. Alternatively, the liquid alloy may be allowed to cool to semi-solid before applying pressure.

Squeeze casting is very attractive with regard to the production of components from aluminium-graphite. The inclusion of graphite has been shown by many sources to reduce the strength of the composite in comparison with the base alloy. It is possible that
Squeeze cast graphitised aluminium alloys may possess similar tensile strength to similar alloys without graphite which have been produced by gravity die casting. In this way, it may be possible to improve fatigue life and other properties of graphitic aluminium alloys. The technique has been claimed to be suitable for many of the types of components whose performance may benefit if they were manufactured from graphitised aluminium alloys. Examples include pistons, cylinder liners, connecting rods, suspension arms, and even cylinder blocks.

Production of discontinuous 'slugs' from thixotropic material has been found to be feasible by Flemings et al. but there does not appear to be any publications with regard to continuous production of thixotropic bar or strip. (Fulmer Research Institute, UK, are known to be investigating the production of continuous thixotropic aluminium alloy bar). This may prove feasible by feeding the output from a rheocasting unit through rollers rather than using a process similar to pressure die casting for the production of thixotropic shot or slugs.

Production of half shell bearings by squeeze casting semi-solid thixotropic strips may be possible. This operation could perhaps also be combined with the formation and bonding of a steel backing strip. The method illustrated in Fig. 9 is proposed. Die construction would be similar to that of a form tool used in the production of conventional press formed shell bearings. The thixotropic aluminium-graphite strip would be fed into the die in precut lengths on to a preformed steel shell. The punch would then apply pressure to form and bond the thixotropic aluminium graphite strip to the steel shell.
The semi-solid state of the graphitised aluminium alloy would offer a useful means to promote bonding.

However, this process may not offer an economical means of producing shell bearings because two pressing operations are required where one is normally used. Further, the squeeze casting operation is slower than conventional press forming because time is required for the alloy to solidify whilst pressure is applied. Therefore, a further technique is suggested. (Fig. 10). This could be termed continuous squeeze casting. Strip produced would require cropping and forming into shells. In this operation, continuous thixotropic strip could be produced in strip form and then rolled onto a continuous steel strip to form a bimetallic strip suitable for cropping and forming into half shell bearings.
CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1. BEARING MATERIALS.

Bearing materials must exhibit many material properties in addition to good wear resistance and friction characteristics. Requirements may vary according to application.

The types of bearing material may be broadly classified by mode of operation. There are four basic types:

i) White metal type,
ii) Soft material in a hard matrix,
iii) Single phase materials,
iv) Non-metallic materials.

Methods used in the production of bearings vary according to design and material. Many materials are used with a steel backing to improve performance. Processes employed include casting, rolling, hot and cold forming, powder metallurgy and electrolytic plating.

There are problems in assessing and comparing the performances of bearing materials. Standardization of assessment has proved difficult to apply in view of the large number of failure mechanisms in bearing applications which may vary according to design and application of bearing material. Many researchers have evolved independent means of evaluation which has led to data which cannot be usefully compared from different sources.

Most material failure mechanisms are applicable to bearing materials. The Scanning Electron Microscope is proving an essential tool in identifying and characterising failure mechanisms.
4.2 ALUMINIUM ALLOY GRAPHITE PARTICULATE COMPOSITES.

In plain bearing applications, aluminium alloy-graphite particulate composites have been found to offer resistance to seizing and galling, low coefficient of friction and resistance to wear. Load carrying capacity has been indicated to be similar to bronze materials. The composites offered outstanding performance in conditions of boundary lubrication due to a thin layer of graphite becoming smeared on bearing surfaces.

Aluminium-silicon alloys containing dispersed graphite particles have been shown to offer an outstanding performance when used for pistons and cylinders in reciprocating internal combustion engines. The composites may offer an economical solution to lubrication problems encountered in the all-aluminium engine.

Special techniques are required to disperse and retain graphite in aluminium alloys because the former will not be wet by the latter. Several techniques have been developed to solve this problem which involve the use of coated or specially treated graphite particles.

4.3 PRODUCTION AND CASTING OF ALUMINIUM ALLOYS CONTAINING DISPERSED GRAPHITE PARTICLES.

Research has shown that particulate material may be dispersed in aluminium alloys by addition to vigorously agitated semi-solid slurries. This method is a branch of "rheocasting" which has become known as "compocasting" and may be applicable to dispersing graphite in aluminium-silicon alloys.

Squeeze casting of semi-solid aluminium alloys containing graphite particles may provide high integrity castings with good
mechanical properties. The thixotropic properties of semi-solid slurries offer potential use in the production of plain bearings manufactured from graphitised aluminium-silicon alloys.
5.1 INTRODUCTION.

Methods involving completely liquid alloys, described by various sources, for the preparation and casting of graphitised aluminium alloys appear to suffer from the following limitations:

a) Special treatments have been required either to melts or graphite particles (or both) in order to ensure that wetting and bonding takes place. Metal coated graphite particles are very costly to produce, and melt treatments may result in means of production which are too time-consuming and expensive for industrial exploitation. In addition, some methods, for example injection on a gas stream and the pellet method, apparently suffer some degree of particle rejection which could result in a lack of reproducibility.

b) Additional processes have been required, such as mechanical stirring or gas injection, after primary melting, which has probably resulted in high production times and a need to maintain alloys liquid for long periods. This again, could result in higher production costs.

c) Liquid alloys have required superheat to allow graphite introduction and pouring into gravity die casting moulds. This led to very low viscosity liquids which contained particles of lower density. Constant stirring has been widely reported to be necessary to ensure that graphite particles remain evenly dispersed. This appears to be an attempt to avoid segregation and agglomeration.
due to flotation of the graphite. Permanent mould casting techniques have been widely adopted by researchers to ensure rapid cooling rates so that solidification occurs before movement of particles can take place. However, in a completely liquid alloy some movement of particles by flotation may well be inevitable due to the significant difference in the density of the two constituents.

d) The use of metal-coated particles of graphite has resulted in additional metallic elements in the melt. This may not be desirable in bearing materials because intermetallic phases which are hard and abrasive may be precipitated in the composite.

e) The inclusion of graphite in aluminium-silicon alloys which have been gravity die cast has been widely claimed to reduce strength in comparison to similar alloys without included graphite particles. In bearing materials, a need has been established to optimise mechanical properties in order to obtain good load carrying capacity and fatigue properties. Therefore, there may also be a need to ensure that the casting process used for the production of components manufactured from graphitised aluminium alloys allows high casting integrity so that mechanical properties are not impaired by inherent casting defects.

f) Published data on mechanical and tribological properties of graphitised aluminium alloys apparently does not include a fundamental appraisal of the effects of graphite content and the effects of alloying elements. Many sources have reported results
of graphite additions to aluminium alloys. However, graphite contents investigated and base aluminium alloys used, have varied widely. There appears to be a requirement to produce fundamental knowledge on the mechanical and tribological performance of graphitised aluminium alloys with particular reference to the effects of various graphite contents, in particular aluminium-silicon base alloys.

5.2 FINALISING THE PROGRAMME OF WORK.

The following was proposed:

a) The use of "Compocasting" as a means of incorporating graphite particles. Although there appears to be no specific reference to the inclusion of graphite particles, compocasting is likely to offer:

   i) No need for specially treated or coated graphite particles and no extraneous elements introduced.

   ii) Dispersion without rejection, flotation, agglomeration or segregation.

   iii) Lower casting temperatures resulting in improved die life and lower heat input.

   iv) The potential for taking advantage of the rheological benefits of rheocasting and thixocasting (e.g. improved die filling properties) in commercial processing of the composites.

However, there were also possibilities of the following disadvantages:
i) Critical control of parameters required in handling the semi-solid composites in order to ensure reproducibility of casting viscosity structure and properties.

ii) Alloys with long freezing ranges are desirable to allow sufficient volume solid to facilitate control of rheological properties.

iii) Special equipment required to be designed with provision to minimise air entrapment during dispersion.

iv) Pressure induced solidification required to ensure solid castings and good mechanical properties.

b) The use of "Squeeze Casting" as a means of solidifying composites so that the following might be achieved:

i) High casting integrity resulting in minimised loss of mechanical properties due to graphite inclusions.

ii) The use of a process suitable for industrial production of components which might benefit by manufacture from semi-solid aluminium alloys with dispersed graphite particles. (e.g. automotive pistons and bearings).

c) The production of specimens by the above techniques and a comprehensive evaluation to promote understanding and knowledge of mechanical and tribological properties of graphitised aluminium-silicon alloys in comparison to similar ungraphitised alloys in terms of:

i) Strength, ductility and hardness.

ii) Wear properties and mechanisms.

iii) Fatigue, corrosion and machinability properties.
SECTION B

EXPERIMENTAL WORK

CHAPTER 6 - COMPOSITE ALLOY PRODUCTION.

6.1 Objectives.
6.2 Equipment.
   6.2.1 Vortex Introduction Equipment.
   6.2.2 Compocasting Equipment Design.
   6.2.3 Gravity Die Casting Equipment.
   6.2.4 Squeeze Casting Equipment.
   6.2.5 Manufacture, Evaluation and Design Modification of Compocasting Unit.
6.3 Materials.
6.4 Experimental Procedure.
   6.4.1 Vortex Experiments.
   6.4.2 Composite Production by Compocasting.
   6.4.3 Graphite Rejection.
   6.4.4 Castings Produced to Assess Repeatability of Composite Alloy Production.

CHAPTER 7 - COMPOSITE ALLOY EVALUATION.

7.1 Objectives.
7.2 Equipment.
   7.2.1 Microstructures and Macrostructures.
   7.2.2 Tensile Testing.
   7.2.3 Hardness Testing.
   7.2.4 Wear Testing.
   7.2.5 Electron Optical Techniques.
   7.2.6 Quantitative Analysis of Elements.
   7.2.7 Fatigue Testing.
   7.2.8 Corrosion Testing.
   7.2.9 Machinability Testing.
7.3 Experimental Procedures.
   7.3.1 Microstructures and Macrostructures.
7.3.2 Tensile Testing.
7.3.3 Hardness Testing.
7.3.4 Wear Testing.
7.3.5 Electron Optical Techniques.
7.3.6 Quantitative Analysis of Elements.
7.3.7 Fatigue Testing.
7.3.8 Corrosion Testing.
7.3.9 Machinability Testing.
CHAPTER 6

COMPOSITE ALLOY PRODUCTION

6.1 PROGRAMME.

a) To evaluate the vortex technique for the dispersion of nickel coated graphite particles in aluminium alloys.

b) To design a compocasting unit suitable for the introduction of uncoated graphite particles into vigorously agitated semi-solid slurries.

c) To manufacture a compocasting unit to the design specification, evaluate its performance, and make modifications where necessary.

d) To illustrate the effects of the introduction of graphite, in terms of distribution, dispersion and retention.

e) To characterise the relationship between shear rate, graphite content and viscosity.

f) To squeeze cast the partially solid composite and determine optimum squeeze pressure and die temperature.

g) To produce squeeze castings with various silicon and graphite contents from which mechanical and tribological properties could be determined.

h) To investigate and solve if possible, any problems which may occur in the experimental programme.

i) To produce additional castings which enabled the reproducibility of composite alloy production to be assessed.
6.2 EQUIPMENT.

6.2.1 Vortex Method.

The equipment designed was similar to that described by Badia et al. (57). This consisted of:

1) A Morgan electrical resistance crucible furnace with 0 – 1000°C Eurotherm contact breaker type controller.

2) A Fisons 1.S/lt 5851/14H variable speed stirring motor.

3) An Impeller, similar to that used in publication (57) (Fig. 12), manufactured in mild steel and refractory coated.

4) A Framework for attachment of stirring motor to furnace.

5) A Chute to aid particle introduction.

6) A Salamander A4 crucible. (See Fig. 11).

6.2.2 Compocasting Equipment Design.

The design of the compocasting equipment was developed by gaining information from three sources:

i) Literature.

ii) Industrial liaison.

iii) Experimentation.

Literature:

In early publications rheocasting equipment was described as simple stirring paddles, bobs or rotors which were rotated by an electric motor in a crucible containing the semi-solid alloy. Much fundamental work was carried out using systems of this type. At Massachusetts Institute of Technology, (MIT),

...
Spencer et al. (80), made many discoveries which enabled characterisation of the rheocasting process using a high temperature viscometer based on a simple design (Fig. 13).

Later designs became more sophisticated with multiple contra-rotating stirring paddles. Campbell, at Fulmer Research (81) and Mehrabian et al. at M.I.T. (63, 82) reported similar designs of this type which allowed larger quantities of semi-solid alloy to be sheared. Early work on compocasting was carried out using designs of this type. The design used by Mehrabian et al. for compocasting is shown in Fig. 14.

As research in rheocasting moved towards production of components from semi-solid material, design of equipment progressed towards machines which were more practical in terms of the amounts and quality of material produced. Ramati et al. (024) reported a design for continuous production of rheocast material. The equipment was designed with commercial exploitation in mind. The production, at high speed, of rheocast ingots was required. The design is shown in Fig. 15. The alloy was continuously cooled from above the liquidus and agitated as it passed through lower semi-solid temperature zone. The liquid zone in the equipment allowed a continuous supply of liquid metal to be added to the machine and prevented contact of the semi-solid zone with air. In previous designs, air became entrapped as a result of the semi-solid becoming agitated in direct contact with air. The upper liquid zone remained undisturbed and so prevented air penetrating the semi-solid in this design, which was developed at the University of Illinois.
In later work, at Fiat SpA, Italy, the continuous rheocaster was thought to be limited in maximum volume fraction solid which could be achieved due to limitations in rotor speed. High rotor speeds resulted in segregation of solid particles due to density differences with the liquid phase. A design evolved in which, it is claimed that, very high volume fractions solid of up to 80% can be sheared\(^{(83)}\). This was achieved by replacing the stirring mechanism by a system of stationary baffles through which the semi-solid alloy was forced to pass by mechanical pressure. In this way, shear rates far in excess of those associated with previous designs can be obtained. Fulmer Research Institute were also known\(^{(84)}\) to have produced a design which did not use a stirring technique. This was thought to be similar to the Fiat design, although Fulmer were unable to divulge exact details on the grounds of commercial confidentiality.

From the literature, it appeared that work on compocasting had been confined to the design used by Mehrabian et al.\(^{(63)}\) (Fig. 14). This design had two main limitations which were, that air was entrapped in the slurry during shearing and solidification was necessary prior to remelting and casting.

**Industrial liaison:**

The opinions of various industrial research establishments involved with rheocasting and squeeze casting process development were sought about the design of compocasting equipment and the suitability of squeeze casting for component production. A design similar to that described by Mehrabian\(^{(63)}\) was suggested
to be suitable for introducing graphite into semi-solid melts.

Those liaised with were:

- Fulmer Research Institute Ltd. (84).
- Associated Engineering Development (85).
- G.K.N. Group Technological Centre (86).

In addition a fourth source was consulted, the Department of Metallurgy at Sheffield University (87), which, whilst not involved directly in research towards the use of rheocasting in industry was involved with the design of rheocasting units.

Fulmer Research Institute were enthusiastic about the viability of incorporating graphite in aluminium-silicon alloys by compocasting, but suggested that designs of the type put forward by Mehrabian et al. may not be practical. The suggestion was made because Fulmer had found a major problem when stirring a semi-solid slurry with a paddle arrangement, in that severe porosity was encountered as a result of air entrapment. The representative of Fulmer also expressed a belief that high power was required to shear by this method (approx. 1 kw/kg) and stated that they were investigating a means of shearing which did not involve stirring. Squeeze casting was thought to offer an excellent means of producing components from semi-solid slurries because of enhanced mechanical properties but it was suggested that a continuous process may be necessary for large scale production.

Associated Engineering Development were not directly involved with rheocasting but had experience of producing graphitised aluminium alloys by the Vortex technique. They suggested that compocasting may be a superior means of graphite introduction.
because temperatures could be lower and there may not be problems of graphite segregation or agglomeration as with the vortex technique. The view was expressed that compocasting must be combined with primary alloy production in order to avoid the need for extra processes and so reduce energy input to a minimum. One representative had a particular interest in powder metallurgy and suggested that for many components this was the better route. A.E.D. have wide experience of squeeze casting and thought in general, that this offered a viable means of producing components made from graphitised aluminium alloys, because the lack of defects, in the nature of porosity, would ensure as good cast properties as possible.

The representatives of G.K.N. Group Technological Centre expressed a view that processes based on semi-solid casting developed at MIT may find few practical applications in view of the large number of process variables and the need for their fine control. However, they expressed a view that compocasting was a possible technique for including graphite particles in aluminium alloys and that squeeze casting should increase the strength and general mechanical properties of composites.

The Department of Metallurgy at the University of Sheffield were involved in the production of a rheocasting unit for copper base alloys. Their design was similar to that put forward by Ramati et al. (68) for a continuous rheocaster. A computer programme had also been written to estimate parameters such as heat energy required, motor power and material output flow rate. They had concluded that a motor power of 300 W would be adequate.
to shear approximately 8 Kg of copper base alloy which did not agree with the findings of Fulmer using the paddle mixer. However, the continuous rheocaster design sheared a smaller quantity of material at any one time. The design reported by Mehrabian et al. was largely thought to have been superseded by the continuous unit but had not been applied to compocasting due to difficulties in introducing particles to the semi-solid zone.

**Experimentation:**

Initial experiments were carried out at Loughborough using an existing paddle-type rheocasting unit to assess the suitability of this design for rheocasting aluminium alloys. The slurry was bottom poured into a gravity die casting mould. The results confirmed the major problem of porosity caused by air being stirred into the slurry, the high apparent viscosity of which prevented air escaping (Fig. 16).

When graphite was added, it was found that the lower temperature of the graphite particles reduced the temperature of the melt with the result that volume fraction solid increased rapidly and the melt viscosity increased, consequently the melt would not pour. This illustrated the need to ensure that graphite particles were at the same temperature as the semi-solid.

**Design Requirements:**

From the above it was concluded that the design should fulfil the following requirements:

a) Provision should be made to prevent porosity due to air entrapment.
b) The resulting composite slurry should be directly cast after the rheocasting operation eliminating the need to produce and remelt ingots.

c) The addition of particles of graphite should be achieved with minimal variations of the volume fraction solid and shear rate.

d) There should be provision for monitoring volume fraction solid, shear rate and viscosity.

e) The output should be in a suitable form for transferring to a squeeze casting mould.

Certain features of the continuous rheocaster design allowed for all of the above requirements to be met. Therefore, it was decided to adapt the design of the continuous rheocaster for compocasting. This design utilised special two stage heating and a crucible which enabled a continuous flow of cooling liquid from the upper stage to the lower stage where it then became semi-solid, was agitated and ejected continuously. The completely liquid upper zone remained undisturbed and so prevented gas entrapment.

In adapting this design to compocasting, a problem existed in transmitting the liquid zone to place the particulate in the semi-solid zone. A further problem was that the graphite particles needed to be at the same temperature as the semi-solid zone. A proposal was formulated to achieve this by storing graphite particles within the shearing rotor itself. The particles would be injected into the melt by mechanical pressure when the required
volume fraction solid and shear rate has been stabilised.

The general arrangement of the proposed design is shown in Fig. 17. The equipment was designed to operate as a batch rather than a continuous rheocaster. A plug was, therefore, incorporated in the base of the crucible which, when removed, allowed the semi-solid to be ejected through the crucible base. The collection crucible has only enough volume for the slurry, and excess alloy from the liquid zone is allowed to flow into a sand pit beneath the unit. The design details are described in Appendix 1.
6.2.3 **Gravity Die Casting Equipment.**

A copper die, as shown in Fig. 23, was employed. This was mainly as a means of producing gravity die castings from which cast mechanical properties could be determined and compared with similar properties of castings produced by squeeze casting.

The gravity die was used with graphitised alloys produced by the vortex technique and ungraphitised alloys in a completely liquid state.

6.2.4 **Squeeze Casting Equipment.**

Squeeze casting of the semi-solid alloy which contained dispersed graphite particles, was envisaged in order to obtain optimum mechanical properties from the composite. Squeeze casting facilities existed at Loughborough as used by Chattejee and Das (88). The facilities consisted of:

- 50 tonne plastics press (Turner)
- Squeeze casting dies (2 - off)
- Electric die heaters
- Temperature controller (Eurotherm, 0 - 400°C)
- Temperature recorder (Rikadenki DBE-3)
- Thermocouples (Chromel - Alumel)

The die illustrated in Fig. 24 was used for the production of the castings to evaluate the vortex technique.

A simpler die shape was employed to produce castings made from semi-solid slurry. This enabled composite material to be produced in an ingot shape, (Fig. 25). This casting enables all the samples which were required for mechanical and tribological tests to be produced in the sizes and shapes required. In addition, the simple shape with low aspect ratio, was not prone to prior solidification
before pressure was applied and so homogeneous material was likely to be produced. Homogeneity was known to be more difficult to achieve where there were thin sections in a casting shape (85).

Certain modifications were carried out to the squeeze casting ingot die. Fig. 25 shows that the simple punch allowed no means for removal of the casting after solidification. The press also had only a single action and so there was no provision for an ejector pin as shown in Fig. 8. Therefore a new punch was manufactured to incorporate a dovetail as shown in Fig. 26. A shoulder was also incorporated to prevent the punch moving into the die too far, resulting in interference with the die taper. In the existing arrangement, die temperature was controlled manually using resistance heaters, thermocouples and temperature recorders. This system had resulted in difficulties in controlling and maintaining a constant die temperature at the time casting was carried out, especially as it was necessary to remove the heaters before pouring could take place. Therefore, the system was replaced by four compact 500 W cartridge heaters (manufactured by Cole Equipment Ltd.) in conjunction with the Eurotherm temperature controller and chromel-alumel thermocouple. This allowed accurate control of die temperature in the range between ambient temperature and 400°C. Temperature was monitored with a further thermocouple and millivolt recorder.

The squeeze casting punch and die were manufactured from H13 hot working die tool steel, hardened and tempered and ground in accordance with the manufacturers instructions.

During initial experiments, a problem was encountered which
resulted in inconsistent mechanical properties in successive castings. This was due to poor temperature control when material was transferred to the die. To overcome this, a base thermocouple, (Fig. 26), was incorporated to allow the temperature change near the die surface to be monitored. This made it possible to ensure that the temperature rise was consistent each time slurry was poured into the die.

The punch and die fitted to the press are shown in Fig. 35.

6.2.5 Manufacture, Evaluation and Design Modification of Compocasting Unit.

The compocasting unit was manufactured and assembled as shown in Figs. 17-22. The completed unit is shown in Fig. 27.

Initial testing was carried out to evaluate the performance of the unit as a processor of semi-solid alloy without the addition of graphite. (The procedures and results of these trials are reported in sections 6.4 and 8.2.1 respectively). As a semi-solid alloy slurry processor, the unit was found to perform well, enabling a wide range of structures to be obtained. However, upon further testing to determine the performance of the unit in a compocasting mode, (i.e. processing slurry with the addition of dispersed graphite) two problems were encountered. These were:

i) The graphite injection system did not function satisfactorily.

On operation of the graphite injector screw, it was found that it was not possible to force the graphite particles to flow from the centre of the rotor through the 3 mm diameter angled holes (Fig. 19) and into the slurry. The screw locked solid after very few turns.
due to the graphite becoming compacted inside the rotor. This was due to the graphite particles' flow becoming constricted on entry to the small angled holes - the particles were thought to resist a change of direction as they were moved. Therefore, it was concluded that it would be necessary to redesign the rotor so that particles were moved in straight paths, thus preventing constrictions at points of change of direction. This was achieved by extending the 25 mm bore to the base of the rotor as shown in Fig. 28.

A grid was fixed in the base of the rotor in an attempt to encourage the graphite particles to disperse throughout the semi-solid zone and to prevent graphite falling from the rotor prior to injection. However, the grid also tended to act as a restriction on the flow of graphite with compaction again taking place. This problem was solved with the use of a small piece of 0.025 mm aluminium foil placed in the base of the rotor. The foil became part of the semi-solid slurry when the injection screw was operated thus preventing graphite falling from the rotor before injection was required.

ii) Having successfully enabled graphite to leave the rotor as in (i) above, it was found that although the rotor was providing an excellent shearing action, the graphite particles were not becoming stirred into the slurry. This was a result of an agglomeration of graphite forming in the base of the crucible near the exit from the rotor. Therefore, it was concluded that it was necessary to redesign the rotor to include a mixing action
in conjunction with a shearing action. This was to be achieved by encouraging some vertical movement of the semi-solid slurry to enable graphite particles to be transported from the exit point at the base of the rotor into the whole area of the semi-solid slurry. A consideration in encouraging vertical movement of the slurry was that it must not become mixed with, or disturb the liquid zone in the crucible, in order to ensure that volume fraction solid was not affected and that air was not allowed to enter the melt.

The rotor was redesigned as shown in Fig. 29. Four splines were placed along the length of the rotor which was to operate in the semi-solid zone. The section of the rotor which was to operate in the liquid zone was left smooth in order to ensure that the minimum disturbance occurred in this region. The splines were extended beyond the base of the rotor, formed to the angle shown, and joined by welding in the centre to form four spokes. The angles on the spokes were incorporated to impart some vertical movement to the slurry. The graphite became placed on the spokes on operation of the graphite injection screw and so became dispersed throughout the semi-solid by the vertical movement of the slurry. Therefore it was possible to obtain a satisfactory shear rate by the shearing action of the teeth and dispersion of graphite particles by the vertical movement caused by the spokes. The smooth surface on the portion of the rotor in the liquid zone ensured that this area remained relatively undisturbed, this being confirmed by the appearance of the upper surface of the melt during operation of the unit where a surface skin was visible, which remained intact.
When tested, the redesigned rotor gave a good shearing action and dispersed graphite throughout the slurry.

Thermocouples were placed in the liquid zone of the crucible and at top centre and base of the semi-solid zone. The unit was charged with the correct quantity of aluminium - 8% silicon alloy and the temperatures allowed to stabilise. With the rotor running at 1200 rpm, it was found that the temperature in the liquid zone reflected set temperature to within ± 5°C. Temperatures in the semi-solid were found to be within ± 3°C of set temperature. The average difference in temperature between the liquid and semi-solid regions was found to reflect the theoretical temperature difference which was 35°C. (Liquid zone controller set at 630°C and semi-solid zone controller set for 16% solid at 595°C).

The main crucible frequently fractured around the upper flange during trials. After consultation with the manufacturer, the flange thickness was increased to 13 mm which solved the problem.

The compocasting unit together with the squeeze casting press are shown in Fig. 36.

6.3 MATERIALS.

Vortex Method Experiments:

Alloy used: BS 1490 LM30 - composition 16-18% Si,
4-5% Cu, 0.4-0.7 Mg, 1.1 Max Fe, 0.3 Max Mn,
balance Al.
(From L.U.T. stock).

Graphite particles: - 120 → + 180 mesh (80 - 125 μm)

Supplied by Sherrit Gordon Mines, Canada.
Nickel coated by decomposition of nickel carbonyl directly onto the particle surface.

**Refractory coating on impellor:**
- White Firit refractory wash.
  - Supplied by Foseco Foundry Services Ltd., Tamworth, Staffs.

**Compocasting Experiments:**

**Alloy used:**
- Alloys of 4, 8, 12 and 16% silicon (remainder Aluminium) were made up from master alloys.

The master alloys were:
- (i) 50% Si, 50% Al, supplied by Anglo Blackwells Ltd., Widnes, Cheshire. Analysis certificate with the material stated 48.8% Si, 0.4% Fe remainder Al.
- (ii) BS1490 LMO, (99.6% pure aluminium) supplied by British Aluminium Co. Ltd., Inverness. Analysis certificate with the material stated 0.04% Si, 0.16% Fe, 0.001% Cu, 0.002% Mn, 99.8% Al.

**Graphite particles:**
- 100 mesh (150 μm) uncoated synthetic graphite, supplied by S & A Blackwells Ltd., Lytham St. Annes.

**Refractory coating on rotor:**
- Holcote 110, supplied by Foundry Services Ltd., Tamworth, Staffs.

**Cement for sealing plug and fixing thermocouples:**
- Triton Kaowool Cement, supplied by Morgan Ceramics Ltd., Merseyside.
Sodium metal: Sodium metal, stored under oil, supplied by Fisons Ltd., Loughborough.

Magnesium metal: Magnesium turnings, supplied by Fisons Ltd., Loughborough.

Aluminium foil: 0.025 mm pure aluminium foil, supplied by British Aluminium Co. Ltd.

Chlorine degassing: Hexachloroethane degassing tablets, supplied by Foundry Services Ltd., Tamworth, Staffs.

Squeeze casting.

Die lubricant and release agent: Acheson DAG 2582.

Graphite and water base mixture.

6.4 EXPERIMENTAL PROCEDURE.

6.4.1 Vortex Experiments.

The procedure reported by Badia and Merica$^{(58)}$ was followed for the introduction of nickel coated graphite particles into aluminium alloys by the vortex method. This consisted of using the impeller mixer equipment shown in Figs. 11 and 12. The rotational speed of the impeller was first adjusted to form a deep vortex cone in the molten alloy. The nickel coated graphite particle addition was poured directly into the vortex at as rapid a rate as possible without discernible clogging of the vortex. After the desired amount of nickel coated graphite particles had been added, the impeller was held at speed for about one minute.
to ensure proper alloying and dispersion, whilst degassing with nitrogen. The impeller was then removed and the alloy cast.

Graphite amounts dispersed were 0, 2, 4 and 8 wt %, which also resulted in a similar amount of nickel being added to the melt. The base alloy used was LM30.

The composites were cast into the gravity casting die and also the squeeze casting die (Fig. 24). (The die shown in Fig. 25 would have been preferable because both casting processes would have allowed a similar cast shape to be produced, but the ingot die was not available at the time). Squeeze castings were solidified under a pressure of 59 MN/m². Pouring temperature was between 700 and 750°C. Pressure was applied to the squeeze castings when the temperature was below 700°C.

After solidification, the castings were sectioned to enable inspection of graphite distribution. A sample was removed for micro examination and sections were cut for the production of tensile testing specimens so that mechanical properties could be evaluated.

6.4.2 Composite Production by Compocasting.

i) Aluminium-Silicon alloy production: The alloys were produced by melting together the required quantities of pure aluminium alloy and 50% Si - 50% Al alloy. Compositions produced were 4, 8, 12 and 16% silicon. (A specimen calculation is shown in Appendix 8 for determination of relative quantities). The
melt temperature was maintained between 750 and $800^\circ$C until all the 50% Si - 50% Al alloy became fully dissolved. Nitrogen degassing was carried out for five minutes to remove dissolved hydrogen and oxidation was minimised by ensuring that the melt surface did not become disturbed. The alloys were produced in quantities of 10 kg and cast at a temperature below $750^\circ$C into steel ingot moulds which produced ingots of 0.5 kg.

ii) Evaluation of the compocasting unit as a slurry producer:

The unit was evaluated using an 8.25% silicon-aluminium alloy. For control purposes the microstructure of the alloy was examined after production as in (i) above and after sand casting. This was to obtain comparisons between conventionally cast alloy and slurry cast material.

The determination of the processing parameters for the slurry cast alloy are detailed in Appendix 2.

The following rotor RPM settings and temperatures were used to gain data on the slurry processing performance of the compocasting unit:

<table>
<thead>
<tr>
<th>Rotor rpm</th>
<th>Shear rate (sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>750</td>
<td>270</td>
</tr>
<tr>
<td>500</td>
<td>190</td>
</tr>
<tr>
<td>250</td>
<td>90</td>
</tr>
<tr>
<td>Temperature</td>
<td>% Volume solid</td>
</tr>
<tr>
<td>-------------</td>
<td>---------------</td>
</tr>
<tr>
<td>595 °C</td>
<td>16</td>
</tr>
<tr>
<td>590 &quot;</td>
<td>23</td>
</tr>
<tr>
<td>583 &quot;</td>
<td>31</td>
</tr>
</tbody>
</table>

The following operating method was used for each of the above shear rates at each of the above % volume solid settings:

a) Temperature of liquid zone set to 10-20°C above liquidus temperature of 8.25% Silicon alloy on liquid zone temperature controller.

b) Temperature of semi-solid zone set to give % volume solid required on semi-solid zone temperature controller.

c) Liquid alloy poured into the unit and temperatures allowed to stabilise. (Temperatures monitored on temperature readout and recorder.)

d) Rotor activated at the rpm required for the shear rate employed. (Rpm set using tachometer).

e) When temperature in semi-solid zone was monitored to be constant and viscosity was monitored to be stable, (by a constant wattmeter reading) bearing housing was lowered to allow rotor to push out plug.

f) The slurry was then collected in the collection crucible (if viscosity sufficiently low).

g) Collection crucible then released and slurry transferred to ingot die.

h) After solidification, microstructures were observed and
conclusions were made about the performance of the compocasting unit as a semi-solid alloy slurry producer. (A further casting was also produced (shear rate 500 sec\(^{-1}\), 23% vol. solid) which was isothermally held so that time dependent properties of the slurry could be observed.)

iii) **Determination of optimum conditions for addition of uncoated graphite to 8.25% silicon aluminium-alloy, using the compocasting unit and characterisation of the relationship between shear rate, volume solid, graphite content and viscosity:**

The performance of the graphite injection system was first evaluated by using a similar method to that above except that graphite was injected at stage 'e'. This was achieved by operation of the graphite injection screw when temperature and viscosity in the semi-solid zone were observed to be constant. The method of operation was otherwise unchanged.

At this stage it was found that the rotor performance was not adequate in dispersing graphite in the alloy and so the design was changed for the reasons outlined in 6.2.5. The modified design is shown in Fig. 29.

Having proved the new rotor design, the following additions of graphite were made to the 8.25% silicon aluminium alloy at the volume solid and shear rate indicated:

Graphite addition by weight:

2%, 4%, 6% and 8%

for each shear rate of:

90 sec\(^{-1}\), 190 sec\(^{-1}\), 300 sec\(^{-1}\) and 500 sec\(^{-1}\)

and each volume solid of:

5%, 16%, 23%, 31%. 
Observations were then made about the effect of graphite content on the shear rate required to ensure a sufficiently low viscosity for casting. Similarly observations were made on the effect of volume solid in the slurry. The temperatures and rotor rpm used were obtained from Figs. 30 and 32. In total, 32 castings were produced at this stage in order to allow evaluation of combinations of graphite content, shear rate and volume solid.

After solidification, the microstructure of each casting was observed to enable conclusions to be made on the distribution of graphite particles. Samples were removed from selected castings to enable a short programme of tensile testing to be carried out. The samples were from castings produced with a shear rate of 500 sec⁻¹ and graphite contents of 2%, 4% and 6% with volume solid of 16% and 23%. U.T.S., % elongation and % reduction in area were recorded for each of two samples from each casting. Tensile testing was carried out using a Hounsfield tensometer and associated equipment. Specimens were machined to the specification of Hounsfield No.13.

iv) Production of squeeze castings from which optimum squeeze pressure and die temperature could be obtained:

Castings were produced with silicon content of 25% by weight at a volume solid of 16% and shear rate of 500 sec⁻¹. 4% by weight graphite was added to each casting.

Squeeze pressures assessed were:

69 MN/m², 115 MN/m², 162 MN/m² and 208 MN/m².

Die temperatures investigated were:

180°C, 240°C, 300°C and 360°C.
The squeeze pressure was set by adjusting the force of the press. Pressure was calculated by dividing press force by the area of the cast section (50 mm in diameter).

Die temperatures were set on the eurotherm controller and monitored by a chromel-alumel thermocouple and millivolt recorder.

Four castings were produced using a constant squeeze pressure of 208 MN/m$^2$ with die temperatures of 180$^\circ$C, 240$^\circ$C, 300$^\circ$C and 360$^\circ$C. Each casting was then tested for surface finish and hardness using Brinell hardness test (10 mm ball 750 Kg load) and RTH Talysurf 4 ($\mu$M Ra) respectively. The castings were then sectioned and samples were removed from each to produce three Hounsfield No.13 tensile specimens. U.T.S. and elongation were evaluated by tests on a Hounsfield Tensometer tensile testing machine.

A conclusion was then made about optimum die temperature.

Three castings were then produced using the previously determined optimum die temperature at squeeze pressures of 69 MN/m$^2$, 115 MN/m$^2$ and 162 MN/m$^2$. The castings were evaluated in the same manner as the castings produced to assess die temperature. A conclusion was then made about optimum squeeze pressure.

The results of this programme of experiments were inconclusive. This was thought to be due to poor control of the slurry temperature when it was transferred to the squeeze casting die. Therefore, it was necessary to repeat the programme and attempt to ensure consistency of the temperature of the slurry in the die before pressure was applied. This was achieved by the incorporation of a base thermocouple (Fig. 26 and 6.2.4) attached to a millivolt
recorder which allowed the temperature of an area in the die close to the melt interface to be monitored. This allowed the production of consistent castings by ensuring an equal temperature rise (indicated by the base thermocouple voltage) for each casting.

The programme of experiments was repeated using the same method but with the addition of slurry temperature monitoring.

v) Production of squeeze castings with various silicon and graphite contents from which samples could be taken for the investigation of mechanical and tribological properties.

Castings were produced having silicon contents of 4%, 8%, 12% and 16% by weight with graphite additions of 0%, 2%, 4%, 6% and 8% by weight.

The parameters used were:

Shear rate: 500 sec$^{-1}$ (1500 rpm)

Volume solid: (16% Si alloy) 8% (585°C)
" " (12% Si ) 1% (580°C)
" " ( 8% Si ) 16% (595°C)
" " ( 4% Si ) 21% (625°C)

Die temperature = 250°C
Squeeze pressure = 138 MN/m$^2$.

The castings, (20 in all) were produced by the method previously outlined. The microstructure of each casting was examined for the correct structure. The macrostructures of selected castings were examined to check graphite distribution.

Each casting was then cut to produce material for:

1 diamond scratch test specimen,
1 pin on disc test specimen,
3 No.13 Hounsfield tensometer specimens.
(See Fig. 33) Material for fatigue corrosion and machining tests was cut from remaining pieces.

In order to obtain data which could be used as a basis for comparison of the tensile results from castings manufactured as described in this section, four control castings were produced. These were gravity die cast from a temperature of 750 - 800°C (i.e. above the liquids) as follows:

a) 16% Si (no added graphite)
b) 12% Si (" " " )
c) 8% Si (" " " )
d) 4% Si (" " " )

These castings, produced by conventional techniques, were considered to offer a basis for comparison of tensile properties of castings produced by compocasting and squeeze casting with graphite inclusions.

vi) Determination of the relationship between shear rate, graphite content and viscosity:

During the production of cast samples in (iii) above, suitable combinations of shear rate, volume solid and graphite content were investigated to enable conclusions to be made about combinations which allowed a viscosity which was suitable for pouring into a die. However, numerical values were not assigned to the viscosities which were suitable. Therefore this was attempted during the production of castings in (v).

The following method was employed: In order to obtain values
for the viscosity of the slurry as it was stirred, it was necessary to obtain a measurement of torque on the stirring shaft. This presented problems because there was no simple means of measuring the torque produced by the three phase induction motor which was used to power the rotor which sheared the slurry.

However, a technique was used whereby power consumed in shearing by the motor could be measured and from this torque could be calculated for a given stirring shaft rpm. The method used is described in Appendix 3.

The procedure used to obtain results:

a) Power consumed was measured with no slurry in the compocasting unit at various constant rotor speeds (or shear rates). From this the torque on the rotor shaft was calculated, for the various shear rates concerned, to give "off load torque" values.
b) Ditto, but with the compocasting unit on load; (i.e. charged with alloy and with temperatures stable) to give "on load torque" values.

c) The torque consumed in stirring the alloy was calculated by deducting "off load torque" from "on load torque".

d) The viscosity of the slurry was calculated.

Viscosity values were obtained for the following alloys and composites:

4\% Silicon, without included graphite.

2\%, 4\%, 6\% and 8\% graphite addition to the 4\% silicon alloy.

These combinations enabled the effects of different graphite contents to be noted.

A specimen calculation for viscosity is shown in Appendix 8 (iv).

In general, the unit of viscosity used in published literature on semi-solid processing is the "poise",

where \(1 \text{ poise} = 1 \text{ dynsec/cm}^2\)

and \(1 \text{ dyne} = 10^{-5} \text{ newtons}\)

\(\therefore 1 \text{ newton meter} = 10^7 \text{ dyne cm}.\)

(This convention has been used in this work).

6.4.3 Graphite Rejection.

During production of graphite aluminium silicon alloys by compocasting, a problem arose whereby graphite was rejected from the melt within the compocasting unit. The procedure for
The problem occurred for no apparent reason. A series of castings could be produced without rejection of graphite, that is, graphite was consistently accepted. However, a further group of castings could be produced where graphite was consistently rejected. This problem was serious because the occurrence of graphite rejection was totally unpredictable. Therefore, it was decided that investigation was necessary.

The following factors were identified as being possibly critical in whether graphite was accepted or rejected:

i) Temperature - (volume % solid)

ii) Rotor rpm - (shear rate)

iii) Contamination of graphite particles

iv) Contamination of refractories

v) Contamination of base alloy.

(i) Temperature:

Experiments were carried out to assess whether small variations in temperature in the semi-solid zone may affect graphite acceptance. The alloy chosen for investigation was the 8% wt silicon alloy. Volume % solid was varied from 0% (i.e. completely liquid with 25°C superheat) to 30% solid. The completely liquid alloy, as expected, resulted in rejection of graphite particles as did the 30% solid alloy. When using the 30% solid alloy, the viscosity was too high to allow casting. The results of this temperature investigation are reported in detail in Chapter 3. It was concluded that temperature was not the cause of graphite rejection.
ii) Rotor rpm:

Rotor rpm was not varied during the production of castings containing various silicon and graphite contents. The shear rate remained constant at 500 sec$^{-1}$ in both rejection and acceptance of graphite. This was easily checked and maintained with the aid of the tachometer. Therefore changes in rotor rpm were not likely to be the cause of graphite rejection.

iii) Contamination of Graphite particles:

Experiments were conducted using combinations of volume % solid and shear rate which had previously been successful. These were 15% solid and 500 sec$^{-1}$ respectively. Three batches of graphite were compared in an attempt to determine the effects of possible contamination. These were:

a) Original batch (supplier S & A Blackwells Ltd.)

b) New batch ("")

c) Nickel coated graphite (supplier Sherrit Gordon).

Results are reported in Chapter 8.

iv) Contamination of Refractories:

Five items were considered:

a) Gas melting crucible, in which the aluminium silicon alloys were produced (Salamander)

b) Compocasting crucible (Mullite)

c) Rotor refractory coating (Foseco Holcote 110)

d) Refractory cement (Morganite Tritan Kaowool)

e) Launder (Mullite)
a) The gas melting crucible was renewed.

b) The compocasting casting crucible was renewed.

c) The Holcote 110 refractory coating was found to have changed in its consistency after storage. Therefore, a melt was produced without its use together with a further melt using a new batch of the refractory coating. Holcote 110 is based on zirconia which was thought to be a possible contaminant. The manufacturers were consulted.

d) The onset of graphite rejection occurred at a point in the experimental programme which coincided with the use of a new batch of cement. The cement was therefore replaced by material from a previous batch.

e) The launder was recoated with mullite in an attempt to remove contamination which may possibly have caused graphite rejection. Results are reported in Chapter 8.

v) Contamination of base alloys:

The melt was observed to take up a different upper surface form when rejection of graphite occurred. When graphite was accepted the meniscus was concave and the side of the crucible and rotor were wetted. When rejection occurred the meniscus appeared slightly convex and the crucible and rotor were not wetted.

Small amounts of Coverall 11 (a surface active flux) had been found to cause a convex meniscus and non wetting. However, the use of fluxes had been carefully avoided in later work and
so this was not a possible cause of rejected graphite particles.

Therefore, it seemed possible that contamination of the aluminium-silicon alloy melting stock might be the cause of the non wetting of graphite particles. This was investigated by the use of a technique to analyse the elements in the material.

Analysis of Elements in Melting Stock.

Analysis was carried out using a scanning electron microscope analyser (Cambridge Stereoscan, Xray analyser @ 20keV) in an attempt to discover if there was any significant difference between samples where graphite was accepted and samples which rejected graphite.

The samples selected for analysis were:

a) 4% silicon which rejected graphite,
b) LM30 which rejected graphite,
c) 12% silicon which accepted graphite,
d) 16% silicon which accepted graphite.

The samples (a), (c) and (d) were chosen because they represented a wide variety of silicon contents. The LM30 sample (b) was chosen because this alloy came from a different source to the plain aluminium-silicon alloys. Any elements which may have been present in sample (b) and sample (a) but not in (c) and (d) would therefore be possible causes of rejection of graphite.

The full results of analysis are reported in Chapter 8. It was found that sodium was present where acceptance of graphite had occurred. Sodium is known to modify the structure of the eutectic in aluminium-silicon alloys. Therefore, it was decided that
microstructures should be examined in an attempt to establish whether any modification had taken place. The microstructures are shown in Chapter 8. The sodium content in the alloys was considered to be a possible factor in affecting graphite acceptance.

Therefore, it was decided to assess the effects of sodium by deliberately adding small quantities to the melt and noting the effect on acceptance of graphite. This was achieved by plunging 0.5% wt. sodium metal wrapped in aluminium foil beneath the melt surface and holding until the metals became completely dissolved.

At this stage, the possible reasons for sodium having some effect on the wetting properties of the slurry were not clear. Sodium is known to displace the eutectic point to the right and lower solidus temperatures on the aluminium-silicon equilibrium diagram whilst refining the structure of the eutectic. However, this did not explain why there should be any change in the manner of graphite inclusion, other than lowering of the semi-solid temperature range. Lowering of the semi-solid temperature range was subsequently eliminated by ensuring that viscosity remained constant for both modified and unmodified melts. Shear rate was maintained constant, and so volume % solid could be maintained constant by ensuring viscosity was constant. This was achieved by slightly lowering the temperature in the semi-solid zone which maintained the required constant volume % solid. Therefore changes in volume % solid were unlikely to be the cause of graphite rejection. For this reason, the possibility of a chemical reaction within the melt was considered. Research in India (57), into graphitic
aluminium-silicon alloys using completely liquid alloys and coated graphite particles had found that degassing with the aid of chlorine based tablets had resulted in rapid rejection of graphite particles from melts. Traces of chlorine had been noted in the analysis of samples where rejection of graphite had occurred (see results) and so it was decided to investigate whether chlorine degassing at some stage of the production of the primary melting stock had resulted in the presence of traces of chlorine in the aluminium-silicon alloy. (Degassing by the use of chlorine compounds is in common practice in the aluminium industry.) This may have offered an explanation of why the presence of sodium was associated with acceptance of graphite particles in the slurry, sodium and chlorine may react together to form sodium-chloride and so removing chlorine from the melt.

The following treatments were applied to aluminium 8% silicon alloys at 16% volume solid using a shear rate of 500 sec⁻¹.

- e) Chlorine degassing using hexachloroethane tablets,
- f) Sodium addition (0.5% wt),
- g) Sodium addition and chlorine degassing,
- h) Magnesium addition (0.5% wt).

The magnesium addition to (h) was considered because magnesium was known to form a chloride more readily than sodium and so removal of chlorine may have been achieved more easily. The results of analysis are shown in Chapter 8. In an attempt to trace the source of possible chlorine contamination the basic stock used in the production of the aluminium-silicon alloy was also analysed:

- i) 50% Si, 50% Al alloy,
- j) LMO alloy.
During the course of the investigation the wetting properties of the alloys onto the crucibles and stirring rotor were observed. Results are reported in Chapter 8.

A further means of removing chlorine from melts was to heat the melt, when initially produced, to beyond 900°C and hold for fifteen minutes. This treatment was carried out on a further sample (k) before reducing the temperature and attempting graphite inclusion by compocasting. The high temperature was thought to remove possible traces of chlorine from the melt. However, this treatment was carried out as a purely academic exercise because use of very high temperatures in alloy production results in poor mechanical properties and is wasteful of energy.

6.4.4 Castings Produced to Assess the Repeatability of Composite Alloy Production.

The following castings were produced by compocasting using identical equipment, procedures to those described in previous sections.

Repeat casting No.1 8% Silicon + 4% graphite
Repeat casting No.2 8% Silicon + 4% graphite
Repeat casting No.3 16% Silicon + 4% graphite
Repeat casting No.4 16% Silicon + 4% graphite

Therefore a total of three identical composite alloy castings were produced with compositions of both 8% Silicon, 4% graphite and 16% Silicon, 4% graphite.

Repeatability of the production process was assessed by tensile
and hardness tests and examination of structures. Comparisons were made between the three castings of each of the above compositions.
CHAPTER 7

COMPOSITE ALLOY EVALUATION

7.1 PROGRAMME

a) To observe microstructures and macrostructures of castings produced as described in 6.4.

b) To evaluate mechanical properties of castings produced as described in 6.4 in terms of ultimate tensile strength, % elongation and % reduction in area.

c) To determine changes in hardness resulting from different silicon and graphite contents.

d) To design suitable wear testing equipment for single diamond scratch tests and pin on disc wear tests. The equipment was to be similar to that used by Brunel University Tribology Group so that tests could be designed to give data which was comparable with that produced by Brunel University. The data generated being:

   i) Coefficient of friction (Pin on disc)
   ii) Running temperature (" " " )
   iii) Length of pin lost (" " " )
   iv) Weight loss (" " " )
   v) Surface finish (" " " )
   vi) Abrasive wear volume (Diamond Scratch)

e) To use electron optical techniques to observe the effects of wear testing on surfaces and attempt to identify wear mechanisms so that conclusions could be made about the reasons
for variations in tribological properties of composites with different graphite and silicon contents.

f) To determine the effects that silicon and graphite content may have on fatigue properties.

g) To determine the effects of graphite content on the corrosion resistance of the alloy.

h) To investigate machinability of the composites.

7.2 EQUIPMENT.

7.2.1 Microstructures and Macrostructures:

A Vickers Photoplan microscope with photographic attachments was used to examine all microstructures and to produce all micrographs.

Macrostructures were examined with the naked eye or photographed and enlarged using standard photographic equipment.

Grinding and polishing equipment used was:

i) Buehler hand grinder with four grades of SiC paper; P240, P360, P480 and P600.

ii) Metaserv rotary grinder (paper as above)

iii) Metaserv polisher with 'Nylon' cloth and 6 µM diamond paste for rough polishing and 'Metron' cloth with 1 µM diamond paste for finishing.

7.2.2 Tensile Testing:

Tensile testing was carried out on castings as follows:
i) Castings produced by Vortex method (see 6.4.1)

ii) Castings produced to determine optimum conditions for the addition of graphite particles (see 6.4.2 (iii)).

iii) Castings produced to obtain optimum squeeze pressure and die temperature (see 6.4.2 (iv)).

iv) Castings produced with various silicon and graphite contents (see 6.4.2 (v)).

v) Castings produced to assess repeatability of composite alloy production (see 6.4.4).

Tensile tests on samples from castings in groups (i), (ii) and (iii) were carried out using:

Hounsfield Tensometer fitted with collet type chucks suitable for No.13 tensile specimens,*

Hounsfield % reduction in area gauge and
Hounsfield % elongation gauge.

Tensile tests on samples from castings in groups (iv) and (v) were required for generating fundamental data on graphitised aluminium-silicon alloys and for comparison purposes between different specimens. Therefore a higher degree of accuracy and reliability of results was required. For these reasons, it was necessary to control strain rate in tensile tests. This was achieved by using a Mayes ESH 250 tensile testing machine with load cell and strain rate control.

* Hounsfield No.13 tensile specimens have dimensions of:

Gauge length 18.4 mm

Diameter 4.526 – 4.544 mm.
7.2.3 **Hardness Testing:**

Hardness testing was carried out on a Brinell Hardness Testing Machine with a 10 mm diameter ball. The Brinell hardness tester was considered suitable because the ball indentor covered a large area and so was more likely to accurately indicate hardness of the composite than a point indentor. A point indentor is more likely to give inaccurate results when used with composite materials because the point may penetrate very small areas which may not include all the constituents of the composite.

7.2.4 **Wear Testing:**

The design of Wear Testing equipment evolved with reference to the following requirements:

1. The equipment should be suitable for the production of tribological data which is comparable with data produced by other researchers in the field of tribological evaluation of aluminium-silicon alloys.

2. The equipment should be capable of producing wear mechanisms of:
   (i) abrasive wear, delamination and
   (ii) accelerated combinations of adhesive wear, fatigue, fretting, delamination and abrasion.

3. Tests should allow assessments of graphitised aluminium-silicon alloys' tribological properties to be obtained when mated with ferrous components.

4. Data should be produced from standardised and repeatable
tribological conditions in the form of:

- steady coefficient of friction,
- steady running temperature,
- mass of material lost from a specimen in a given time,
- loss of length of wear specimen in a given time, and
- volume of material lost in a given wear test.

5. The equipment should allow tests to be carried out in both dry and lubricated conditions and should allow for future modifications which would enable simulations of wear situations found in industrial applications. (e.g. piston ring against cylinder).

6. The design should include sufficient instrumentation to allow control of test conditions and recording of data produced.

The requirements were fulfilled in the following manner:

In order to produce data which was comparable with that produced by other researchers it was necessary to test material using similar methods to those used by other researchers. The Tribology Group at Brunel University led by Dr. T.S. Eyre, had established an interest in the tribological properties of aluminium-silicon alloys (27,94,95) and so it was decided that published data and consultation available from this source could provide a basis for comparison of wear testing results from graphitised aluminium alloys. Various other sources of data, gained in a similar manner were also available (28,96,97).

Therefore, wear testing equipment was designed with two testing facilities. These were:
i) Pin on disc test (Fig. 4)

ii) Abrasive wear using a diamond scratch test. (Fig. 3).

The pin on disc test fulfilled the requirement for combined accelerated adhesive wear, fatigue, fretting delamination and abrasion whilst an abrasive wear test using a single point diamond scratch fulfilled the requirement for abrasive wear and delamination.

A hardened steel disc was specified in the design for the pin on disc facility so that the requirement for data to be established which related to tribological properties of the composites when mated with ferrous components could be satisfied. This was important because the applications suggested in the literature for graphitised aluminium-silicon alloys usually involved mating with a ferrous component.

The design of the equipment incorporated baths to enable tests to be carried out under lubricated conditions if required. The reciprocating nature of the abrasive wear test also would allow simulation of various wear situations by substituting the diamond for various relevant mating materials as required. The disc material could also be changed if necessary.

Instrumentation and control consisted of:

a) A counting device to count revolutions of the disc or reciprocations of the diamond. The device could be set to the required number of reciprocations or revolutions for a particular test, which when reached, triggered an electrical signal to cut the power from the motor.

b) An inductive position transducer which measured the deflection of the pin under test in a direction tangential to the disc. This
was to allow data suitable for the determination of tangential force to be obtained for calculation of coefficient of friction (see 2.3.).

c) An inductive position transducer placed in the pin holder to measure downward movement relative to the disc and so indicate the change in length of the wear pin during the test.

d) A chromel-alumel thermocouple was attached to the wear pin, at a distance of 3 mm away from the wear interface with the steel disc, to allow changes in temperature to be monitored.

e) A chromel-alumel thermocouple was placed in the wear testing environment to allow the ambient test temperature to be monitored.

f) A hygrometer probe was placed within the wear testing environment to allow the humidity of the test environment to be measured.

The output from items b - e was fed into a four channel Linseis millivolt recorder which allowed coefficient of friction, change of length in wear pin, pin temperature and ambient temperature to be recorded continuously.

The General Arrangement of the design proposed is shown in Fig. 37a and parts list in Fig. 37b. The design allowed both pin on disc and reciprocating diamond scratch tests to be carried out on one unit. The design details are described in Appendix 4.
In addition to the above equipment, a chemical balance accurate to 0.0001 gm was used to weigh test pins before and after pin on disc wear tests and a tool makers microscope was used to measure scratch widths from the reciprocating diamond test.

Figs. 41 and 42 show the dimensions of the wear test specimens used for the reciprocating diamond test and the pin on disc test respectively. The specimens were designed in consultation with Brunel University Tribology group.

Surface texture measurements were made with a Rank Taylor Hobson Talysurf 4 with datum attachment and Talydata computer for computing Roughness Average Ra and Bearing Ratio ($t_p$).
7.2.5 Use of Electron Optical Techniques.

Two techniques were used:

(i) Scanning Electron Microscope,

(ii) X-ray Photoelectron Spectroscopy surface analysis (ESCA).

(i) The scanning electron microscope was a Cambridge Stereoscan 2A with X-ray and photographic facilities.

(ii) The ESCA machine was a VG Escalab with ion sputtering composition depth profiling facility. ESCA is a technique for the chemical analysis of solid surfaces.

7.2.6 Quantitative Analysis of Elements.

In addition to quantitative chemical analysis, quantitative metallography was used to analyse the quantities of graphite in the composites. A Cambridge Quantimet was used with an optical microscope and T.V. facility.

This equipment was able to differentiate between separate phases from the colour of light which was reflected from them. Graphite can be easily identified due to the large colour contrast between it and the surrounding phases. The result is given in terms of the percentage of area which the graphite particles take up in a given cross-section. This enables quantitative metallographic techniques to be used to determine the quantities in volume or weight.

7.2.7 Fatigue Testing.

The fatigue life of the composites was tested using a Wöhler-type machine manufactured by G.T.G. Engineering Ltd., Loughborough. The specimen (Fig. 43) in the form of a cantilever, forms the
extension of a shaft driven by an electric motor at a speed of 2850 rpm. Dead loading is applied to the end of the specimen through a ball race bearing. As the specimen rotates, there is a sinusoidal variation in stress which is greatest at the surface and zero at the centre. The system of loading is also known as reverse bending. The machine is shown in Fig. 44 with specimen.

7.2.8 Corrosion Testing.

The composites were tested in the types of environment they are likely to meet in bearing applications. This consisted of testing composites coupled to cast iron in heated oil baths. The equipment therefore consisted of a hotplate, 50 ml pyrex beakers, Ford SSM-2C9001 - AA 20w 50 Motor oil, acetic acid and water. The corrosion testing specimen is shown in Fig. 45.

7.2.9 Machinability Testing.

The equipment used was:

(i) Dean Smith & Grace 17 x 48 Centre Lathe

(ii) 2 component lathe tool dynamometer with inductive position transducers to measure tool deflections and analogue indicators for centripetal cutting force ($F_t$) and circumferential cutting force ($F_c$).

(iii) Micrometer with pin anvils

(iv) High speed cutting tool

    with 5° top rake angle
    5° side rake angle
    and 5° clearance angle.
The lathe with tool dynamometer fitted is shown in Fig. 46. The tool deflection indicator is shown in Fig. 47.

The equipment enabled tool forces to be evaluated for given sets of cutting conditions. The data generated was used to calculate various measures of machinability (see 7.3).

Rank Taylor Hobson Talysurf 4 surface finish measuring equipment was used to evaluate roughness average ($R_a$) and bearing ratio ($tp$) of the machined surfaces.

The scanning electron microscope was used to examine turned surfaces and chips of material machined from the specimens.

7.3 EXPERIMENTAL PROCEDURES.

7.3.1 Microstructures and Macrostructures.

Microstructures of the following were observed:

(i) Specimens produced by the vortex technique (as in 6.4.1)

(ii) Specimens produced to evaluate the compocasting unit as a slurry producer (as in 6.4.2(ii)).

(iii) Specimens produced to determine optimum conditions for the addition of uncoated graphite to 8.25% silicon aluminium alloy (as in 6.4.2(iii)).

(iv) Specimens produced with various silicon and graphite contents (as in 6.4.2(v)).

(v) Specimens produced to establish the repeatability of composite alloy production (as in 6.4.4).
Microstructures were prepared by grinding with successive
grades of wet silicon carbide paper from P360 down to P600.
The samples were then rough polished with a nylon cloth and 6 μM
diamond paste and fine polished with 1 μM diamond paste and a
metron cloth.

Although high standards of cleanliness and correct metallographic
procedures were observed, difficulties were experienced in the
production of microstructures from graphitised alloys. This was due
to graphite becoming smeared over the surface of the matrix and
accentuating any minor departures from flatness or scratches.
Metaserve Metallurgical Services and Vickers Instruments were consulted
on this matter but were unable to improve on the method above using
the equipment available. Experiments with hard alumina polishing
gave slightly better results but definition and texture were poor.
Therefore microstructures were produced by diamond polishing to give
the highest quality. Etching was found to be unnecessary.

Macrostructures were produced by cutting vertical and horizontal
sections from castings then grinding (and polishing to improve quality
if necessary). The dispersion and distribution of graphite particles
was observed in this way. Structures were photographed and enlarged
where slightly higher magnifications (e.g. x 2) were required.

7.3.2 Tensile Testing.

Tensile testing using the Hounsfield Tensometer: Strain was
applied manually by turning a screw therefore strain rate could not
be accurately controlled. A load vs extension graph was obtained
from which the maximum load could be determined. The beam to give
a maximum load of 0.5 tonnes was employed and the magnification
on the extension axis was 8 times.

Values obtained for ultimate tensile stress, % elongation and
% reduction in area were the average of the values obtained from
three specimens.

Ultimate tensile stress (UTS) was calculated using the formula

\[
\text{U.T.S.} = \frac{\text{Ultimate load}}{\text{Cross-sectional area}}
\]

Units used to express U.T.S. were MN/m². A specimen calculation
is shown in Appendix 9.

Tensile testing using the Mayes ESH 250:
This machine allowed automatic and accurate control of strain rate.
A similar experimental procedure was used to that above.
Strain rate was maintained at 0.6 mm/min for all tests. Averages
were taken from three specimens and the load range was 0 – 5 kN.

7.3.3 Hardness Testing.

Hardness testing was used to measure hardness differences of
castings with various silicon and graphite contents. An average
of three measurements was taken from each specimen. The Brinell
hardness test uses the principle of a ball being pressed into the
specimen by a known load. The diameter of the impression is
proportional to the Brinell hardness number. The load is varied
according to the relationship

\[
\frac{P}{D^2} = \text{constant}
\]

where

\[
P = \text{load}
\]

\[
D = \text{ball diameter.}
\]
For aluminium alloys the constant is between 5 and 10. 
The load used was 750 kg and the ball diameter was 10 mm. 
The formula used to calculate Brinell hardness is

\[ H = \frac{P}{\frac{\pi D}{2} \left[ D - \sqrt{\left( D^2 - d^2 \right)} \right]} = \frac{\text{load}}{\text{area}} \]  

(2)

where \( H \) = Brinell hardness number 
\( D \) = ball diameter 
\( d \) = impression diameter.

A specimen calculation is shown in Appendix 9.

7.3.4 Wear Testing.

(i) Reciprocating diamond scratch test: (abrasive wear).

The following test parameters were used:

- Stroke lengths: 20 mm and 40 mm
- Loads: 1 kg, 5 kg, and 10 kg
- Average linear speed: 3.33 cm/sec
- No. of strokes: 1, 5, 10, 20, 50, 100, 500, 1000

The parameters were arrived at in consultation with Brunel University who had found them to be suitable for aluminium-silicon alloys and so data was available for comparison.

Results were obtained in the form of "wear volume" which was proportional to the width of the scratch.

The formula used was:

\[ \text{wear volume} = (0.144 w^2 - 1.63 \times 10^{-3}) \times L \]  

(3)

where \( w \) = scratch width

and \( L \) = stroke length.
The formula was derived as shown in Appendix 9iii. A specimen calculation is also shown (see also Fig. 48).

Specimens from castings produced in 6.4.2(v) were tested as follows:

No. of passes 1, 5, 20, 50, 100, 500.
Stroke length 40 mm
Load 5 kg and 10 kg
4% wt Si + 4% wt, 6% wt and 8% wt graphite
8% wt Si + 2% wt, 4% wt, 6% wt and 8% wt graphite
12% wt Si + 4% wt, 6% wt and 8% wt graphite
16% wt Si + 2% wt, 4% wt, 6% wt and 8% wt graphite.

In addition, a further programme was carried out by Brunel University:

Stroke length 20 mm
Load 1 kg
4% wt Si + 2% wt and 8% wt graphite
12% wt Si + 2% wt and 8% wt graphite
16% wt Si + 2% wt and 8% wt graphite
4, 8, 12 and 16% Si Silicon specimens without graphite addition were also tested in both programmes.

The specimens were machined as shown in Fig. 41.
Scratch widths \( W \) were measured using a tool-makers microscope at the position shown in Fig. 49 in order to avoid erroneous results due to measurement from the peaks of the piled up edges.

The diamond and specimen were thoroughly cleaned with industrial spirit prior to each test. After each test the specimen was removed for scanning electron microscope studies.
(ii) Pin on disc wear tests.

The following test parameters were used after consultation with Brunel University to ascertain the most suitable conditions for pin-on-disc wear tests on aluminium-silicon alloys:

- Average wear interface linear velocity: 100 cm/sec.
- Axial loads: 3.25 kg, 7.8 kg, 12.6 kg and 17.1 kg
- Pin diameter: 6.35 mm
- Disc material: BS970 En32 (RC 57)
- Test duration: 0.5 hrs - unless transition to high wear rate occurred necessitating termination of test.
- Environment: Unlubricated system, enclosed environment with temperature and relative humidity monitored.

Results were obtained in the form of:

a) Coefficient of friction.

b) Pin temperature rise.

c) Surface textures of pin and disc after test.

d) Change in length of pin.

e) Weight loss from pin.

a) Procedure for obtaining coefficient of friction: Fig. 51 shows the position of the transducer (detail 23) installed to measure the deflection of the pin holder resulting from rotation of the disc.

The output from the transducer was fed into the millivolt recorder where the reading indicated was proportional to pin deflection.

To calibrate the system for coefficient of friction, the axial load was applied to the pin in contact with the stationary disc the force required to cause a similar deflection to that caused by
the rotating disc was then determined by attaching a spring balance to the base of the pin and applying a load to deflect the pin. A graph was then drawn of deflection force vs. the millivolt reading, which enabled the system to be calibrated. When the disc was rotating with the loaded pin in contact, the millivolt reading could therefore be equated directly to the force required to cause a certain deflection of the pin holder. In a friction system between two surfaces this force is known as the friction force ($P$). With reference to Fig. 50; when one body is sliding on another, the tangential force resisting motion is directly proportional to the normal force between the surfaces in contact. Therefore if $P$ is the friction force and $N$ is the normal force,

$$P = \mu N$$ (4)

where $\mu$ is constant for any given pair of surfaces. This constant ($\mu$) is known as the coefficient of friction. The resultant of the friction force $P$ and the normal force $N$ is represented by $R$ and the angle between $R$ and $N$ is known as the friction angle $\phi$ hence from Fig. 50:

$$\tan \phi = \frac{P}{N} = \mu$$ (5)

Therefore in the case of the pin on disc wear test:

$$\text{Coefficient of friction } \mu = \frac{\text{Pin deflection force}}{\text{Axial load on pin}}$$ (6)

A specimen calculation is shown in Appendix 9 iv. The millivolt recorder allowed coefficient of friction to be recorded continuously throughout pin on disc wear tests which allowed a record to be obtained of any changes during the test.
b) Pin temperature rise:

A chromalumel thermocouple was wired to the pin at a distance of 3 mm from the wear interface. The millivolt output voltage was recorded by the Linseis recorder which provided a continuous record. During aluminium-silicon alloy pin on steel disc tests by Razavizadeh and Davies (26) the pin temperature at a distance of 3 mm from the wear interface was shown to be very close to the actual temperature at the interface and so the thermocouple was likely to give a good indication of temperature changes resulting from events at the wear interface. The cold junction was placed outside the perspex cover and the temperature was measured with a mercury thermometer. B.S. 4937 (1973) was then used to convert millivolts to absolute temperature in °C to determine the steady running temperature.

c) Surface textures of pins and disc:

Before all tests, surface texture was prepared on both pins and disc to be better than:

2 µm Ra (pins)

and 0.2 µm Ra (disc)

Measurements were taken perpendicular to the direction of lay in all cases. The surface of the disc was prepared by grinding with various grades of wet silicon carbide paper, finishing with P600 providing a circumferential direction of lay. Pins were finished by face turning which also resulted in a circumferential direction of lay.

The main parameter used was the "Roughness Average" Ra, however
Ra gives little information about the actual shape of a surface profile because it is simply a measure of area above and below a centre line, Therefore two surfaces such as those shown in Fig. 52 may have very similar Ra values whilst their topography is totally different.

For this reason, the "Bearing Ratio" (tp) was used. This gave an indication of the actual proportion of the surface which would be in direct contact with the flat disc surface. The bearing ratio is the length of a bearing surface expressed as a given percentage of the sampling length L at a depth p below the highest peak, (see Fig. 53). The depth p can be taken at any level and so must be constant for all readings. However, for the purposes of this work, the Talydata computer was used to compute the bearing ratio at the mean of the amplitude distribution of the peaks and valleys on the surface.

Bearing ratio, whilst giving more useful information about areas of contact and surface topography, does not provide a detailed description of amplitude variations. Therefore, it was also necessary to study a trace of the surface profile to gain information about the actual shape of the surface profile. However, this had the disadvantage of being completely subjective.

d) Change in length of pin:

This was measured by the position transducer in the load plate. The system was calibrated by placing a feeler gauge of known thickness between the transducer probe and the disc and noting the millivolt reading on the recorder. The change in length of the pin during a
wear test was recorded from a millivolt output from the transducer and converted to a linear distance (in mm) using the calibration data on completion of the test.

e) Weight loss from pin:

Pins were weighed before and after all wear tests so that weight loss could be determined. Monitoring of weight loss was necessary in addition to monitoring of change in pin length because it was possible for a situation to arise where the pin deformed plastically without loss of debris. This condition could not be detected by change in length measurements alone.

In general, pin on disc tests were carried out whilst ambient temperature and relative humidity were monitored to ensure that there were no significant changes in the ambient conditions during the tests.

The tests were applied to the following alloys and composites:

4% wt Si, 8% wt Si, 12% wt Si and 16% wt Si each with graphite additions of:

0% wt, 2% wt, 4% wt, 6% wt and 8% wt.

Repeatability of Tests.

The repeatability of the wear tests was assessed by repeating a random sample of tests and applying statistical significance testing. The method used was "t test applied to paired observations". The problem was that of testing a hypothetical population mean (assuming population was infinite). See Appendix 5 for details.
The "probability" value refers to the chance that the average discrepancy (in a sample of 12 sets of paired data) of a fictitious infinite population of paired tests is zero. In statistical terms a 't' value of less than 1.8 is not significant. This implies that discrepancies which gave a 't' value of less than 1.8 would occur in more than 10% of samples of 12 from an infinite population and therefore it is reasonable to ascribe discrepancies to the chance arising out of experimental error.

However, it must be noted that the result "not significant" from a statistical significance test is not a verdict of "complete acquittal" so much as "not proven". There may be bias between the two sets of results but the evidence is insufficient to create doubt in the mind of an unbiased observer.

This procedure was carried out for samples of 12 for:

- Coefficient of friction
- Pin temperature rise
- Loss of length of pin
- Surface texture of pin
- Weight losses.

(The actual calculation of each is shown in Appendix 9(v)).

7.3.5 Electron Optical Techniques.

(i) Scanning Electron Microscopy:

The scanning electron microscope was used to examine wear surfaces of pins from pin on disc tests and wear grooves from the reciprocating wear test. This was so that mechanisms of wear could be identified which might offer explanations for differing results
from wear tests on different specimens. Surfaces of both graphitised and ungraphitised alloys were examined after each test at various magnifications which gave indications of surface topography. This was also to enable wear damage on microscopic and submicroscopic levels to be investigated. Plain aluminium-silicon and composite specimens from the reciprocating test were examined in an attempt to explain the effects of graphite on abrasive wear and delamination.

In certain cases, wear debris was also examined.

Machined surfaces and chips produced in machinability tests were examined so that the effects of graphite could be investigated with regard to differences in machinability.

(ii) Xray Photoelectric Spectroscopy: (ESCA).

This technique was applied to certain graphitised and ungraphitised pin surfaces to allow chemical analysis of surface layers. Badia and Rohatgi (101) postulated that the superior gall resistance of graphitised aluminium alloys was due to the presence of a graphite rich layer on the bearing surface. Therefore ESCA which allows a comparatively large area (10 mm²) to be chemically analysed, is a suitable technique for locating a graphite layer. However, the system is very sensitive and so likely to detect very thin surface layers which may include contamination from, for example, human handling. To overcome this, the instrument includes a facility for "composition - depth profiling". This uses a process known as "sequential ion beam sputtering" which allows successive atomic layers to be removed from the surface by "sputtering" so that changes in composition can be monitored as a function of depth. However, the process is limited because it is
necessary for the ion beam to approach the surface at an angle which means that the beam is unable to impinge the base of valleys in common (undulating) engineering surfaces. This problem has been described by Keenleyside (100). However, successive layers were removed from the exposed surface with depths ranging from 20 Å to 0.5 μM.

The specimens from pin on disc tests were examined for a graphite rich surface layer.

7.3.6 Quantitative Analysis of Elements.

(i) Chemical Analysis: This was entrusted to outside contractors. Specimens analysed were:

a) 8.25% silicon alloy (2-off) (Foseco Foundry Services Ltd.).

b) Samples with various quantities of silicon and graphite (as produced in 6.4.2) (Charnwood Consultants Ltd.)

a) Analysis of the 8.25% Si alloy was carried out by wet chemical analysis for the following elements: magnesium, zinc, lead, copper, iron, nickel, titanium, tin, and silicon. This was to assess whether significant trace elements had been introduced during unitial processing of the alloy.

b) The samples with various quantities of silicon and graphite were analysed to assess the actual quantities of silicon and graphite within them.

Analysis of silicon was carried out by dissolution in sodium hydroxide followed by gravimetric assay using the perchloric acid
method of dehydration.

Graphite determinations presented problems because standards do not exist for graphitic aluminium silicon alloys, making absolute determinations difficult. Two methods were used: Firstly, the normal method for determination of carbon content in steels was used. Samples obtained by drilling were combusted to carbon dioxide. This was carried out in air rather than oxygen in order to prevent "thermite" ignition of the drillings (finely divided aluminium is more pyrophoric than steel). The quantity of carbon dioxide was then measured by non-aqueous titration using butylammonium hydroxide. The contractors believed that the pattern of evolution of carbon dioxide was similar to that of steels but were not prepared to guarantee results due to the lack of suitable standards for absolute determination of graphite content. The second method used was similar but combustion was carried out in pure oxygen with fluxing by copper-tin wire.

The contractors stated that for the actual specimens tested using either method the results were, in their opinion, reliable. However, whilst they were prepared to guarantee the relative order of graphite contents determined they were not able to guarantee absolute quantities stated.

(ii) Quantitative Metallography:

Results from chemical analysis were found to be in the relative order expected but absolute quantities did not reflect the quantities of graphite added to the alloys. Therefore, it was decided to investigate graphite contents by optical metallography and recently
developed quantitative metallographic techniques.

The Quantimet equipment allowed areal analysis of the darkest phase within the microstructure (which was likely to be graphite). The result was given in terms of the percentage of area taken up in the microstructure. The principles used in quantitative metallographic techniques are described in Appendix 6.

Quantitative metallographic techniques were used to investigate graphite contents of various specimens, including the variation in graphite content in a cross-section.
7.3.7 Fatigue Testing.

Fatigue testing was carried out using a Wöhler-type (rotating bend) machine. The manufacturers of the machine stated that the reverse bending stress applied to the specimen should be approximately $0.5 \times$ the U.T.S.

Therefore the reverse bending stress of $83\,\text{MN/m}^2$ was used.

This was achieved by using a bending moment of $1.02\,\text{Nm}$.

The bending stress was calculated using the formula:

$$\text{Bending stress} = \frac{\text{bending moment}}{\text{section modulus}}$$

See Appendix 9(vi) for specimen calculation.

The motor speed was 2850 rpm which allowed $171 \times 10^3$ stress reversals per hour.

Three specimens were taken of each composite or alloy composition and an average taken of time to failure.

The fatigue life was then expressed in terms of the number of reversals to failure.

Fatigue test specimens were machined as shown in Fig. 43.

7.3.8 Corrosion Testing.

It was considered that the presence of graphite in aluminium-silicon alloys might affect their resistance to corrosion because graphite particles are electrochemically more cathodic. An example of a short circuited cell could be provided by discontinuous graphite particles in an aluminium-silicon matrix immersed in dilute acid.

The current generated could pass from the graphite to the aluminium-silicon alloy by the path of lowest resistance and return to the
graphite through the solution by the passage of ions. The aluminium-silicon alloy which has the greatest negative potential could dissolve and would therefore be the anode, while the graphite would be the cathode. In such acid attack, the hydrogen which is released as the alloy dissolves is deposited on the surface of the cathode and as it increases in amount, two things may occur. The corrosion of the aluminium-silicon could either be brought to a standstill due to the formation of an opposing electrode, (i.e. the cell is polarised) or, the hydrogen may be evolved as bubbles which stream away with the result that corrosion will occur continuously. In the first case, the corrosion could be accelerated by the presence of air which may act as an oxidising agent removing hydrogen from the cathode.

Small cathodes in a large anode usually become quickly polarised and so corrosion is small. On the other hand, a large cathode coupled to a small anode is likely to result in a high amount of corrosion.

In bearing applications, this analysis is likely to be further complicated by contact and close proximity of ferrous components and the presence of lubricants which may be contaminated with acidic formations or water. This results in a high number of variables which makes corrosion performance difficult to predict.

Consultation\(^{(30)}\) (with an authority commissioned by the motor industry to investigate corrosion in engine bearing materials) revealed that standard corrosion tests applied to materials (e.g. salt spray tests) were totally unsuitable and likely to yield erroneous results because this was not a simulation of the type of environment in which bearing materials are likely to operate.
Therefore the following experimental programme was evolved:

Test specimens (Fig. 45) were coupled to cast iron rods 25 mm in diameter and 70 mm in length (Fig. 54). Three sets of experiments were established, each with immersion in a different oil based mixture.

The mixtures were:

Set 1 New Ford SSM-2C9001-AA 20W-50 motor oil.
Set 2 As above + 5% water and 5% acetic acid.
Set 3 A used engine-oil removed from an automobile engine after the period specified by the manufacturers.

Set 1 was unused oil and so no corrosion should have resulted. This set was therefore deemed to be a control.

Set 2 was the main corrosion test. The mixture was designed to simulate a lubricant with extreme contamination.

Set 3 was included to represent a true mixture in which bearing materials were likely to operate.

Tests were conducted in pyrex beakers heated on a hot plate at a temperature of 75 - 85°C for a period of six weeks. The elevated temperature represented a typical engine running temperature.

Compositions tested were:

<table>
<thead>
<tr>
<th>Set 1</th>
<th>% wt Silicon</th>
<th>% wt graphite addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
### 7.3.9 Machinability Testing.

The widely used term "machinability" may be taken to imply that there is a property or quality of a material which can be clearly defined and measured as an indication of the ease or difficulty with which it can be machined. In fact there is no unambiguous meaning to this term.

Many investigators have given a variety of definitions to machinability. A common definition is: "ease of machining materials with various tools". However, this ease of working can be measured in different ways which often give contradictory results, so that a more precise definition becomes impossible.

Material removal is not connected with one parameter alone, but with many variables which have widely different influences. A material may have good machinability by one criterion but poor
The machinability of a material can be assessed in a number of ways, some of which are:

a) Surface finish: The surface finish achieved under specified cutting conditions.

b) Cutting forces: The forces acting on the tool (measured by a dynamometer) under specified conditions, or the power consumption.

c) Chip formation: The type and size of chip and nature of the swarf produced.

d) Tool life: The amount of material removed by a tool under standardised cutting conditions, before the tool performance becomes unacceptable or the tool is worn by a standard amount.

Surface finish can be assessed using standard surface measuring equipment with reference to bearing area, roughness average or profile.

Cutting forces allow a wide investigation into machinability which includes determination of shear angle, angle of friction, a universal machinability index and power consumption.

The type of chip produced gives information about the type of cutting mechanism in operation.

Tool life under optimum cutting conditions is an important economic consideration and can be assessed by measuring the amount of wear on the tool after a given amount of material has been removed.
For the purposes of this investigation, the machinability testing was conducted to investigate surface finish, cutting forces and chip formation by turning tests on the DSG lathe. Tool life was considered to be impractical because of the large amount of material removal required to impose significant wear on a tool.

Surface finishes produced were measured using the Rank Taylor Hobson Talysurf 4 in terms of $R_a$ (roughness average) and $t_p$ (bearing ratio). The surfaces and chips produced were also examined by low magnification scanning electron microscope. Plain aluminium-silicon alloys and those containing graphite particles were compared.

The measurement of cutting forces was carried out using the dynamometer. The forces on a single point turning tool can be considered as three separate components, these are:

$F_C$ - tangential to the turned surface and at right angles to the direction of turning, i.e. in the direction of the cutting velocity.

$F_T$ - parallel to the axis of turning, i.e. in the direction of the feed movement. This is the feed force.

$F_N$ - normal to the turned surface, i.e. radial.

The forces are shown schematically in Fig. 56.

For the purposes of this work $F_N$ was not considered because it is the least significant component and most established machining models do not consider it. Also, the dynamometer available was able to measure $F_C$ and $F_T$ only. The following variables were measured: $F_C$, $F_T$ and chip thickness ($t_2$).
Experiments were initially carried out on a selection of graphitised and plain aluminium-silicon specimens with all machining conditions maintained constant. This enabled the effect of graphite additions in the specimens to be assessed. The machining conditions were then varied by changing the feed rate \( (t_1) \) for four specimens (two graphitised) so that the effects of increased metal removal rate on machinability could be investigated.

Specimen calculations are shown in Appendix 2.
CHAPTER 8 - RESULTS - COMPOSITE ALLOY PRODUCTION.

8.1 Production by Vortex Technique (as 6.4.1).

8.2 Composite Alloy Production by Compocasting (as 6.4.2).

8.2.1 Evaluation of the Compocasting Unit as a slurry Producer.

8.2.2 Determination of the Optimum Conditions for Addition of Graphite to 8.25% Silicon Alloy.

8.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be obtained.

8.2.4 Determination of the Relationship between Shear Rate, Graphite Content and Viscosity.

8.2.5 Investigation of Graphite Rejection.

CHAPTER 9 - RESULTS - COMPOSITE ALLOY EVALUATION.

9.1 Microstructures and Macrostructures of Castings with various Silicon and Graphite Contents.

9.2 Tensile Testing of Castings with various Silicon and Graphite Contents.

9.3 Hardness Testing of Castings with various Silicon and Graphite Contents.

9.4 Wear Testing.

9.4.1 Reciprocating Diamond Scratch Tests.

9.4.2 Pin on Disc Tests.

9.5 Use of Electron Optical Techniques to study of Fracture Surfaces and Worn Surfaces of composites.
9.6 Chemical Analysis.

9.7 Fatigue Testing.

9.8 Corrosion Testing.

9.9 Machinability Testing.

9.10 Castings Produced to Assess Repeatability (as in 6.4.4).

8.1 Production by Vortex Technique.

(Procedure as 6.4.1)

i) Microstructures:

Fig. 58 - LM30 + 4% nickel coated graphite, squeeze cast.

Fig. 59 - LM30 + 4% nickel coated graphite, gravity die cast.

ii) Macrostructure:

Fig. 60 - Graphite distribution - squeeze cast LM30 + 4% graphite.

iii) Tensile Testing:

<table>
<thead>
<tr>
<th>GRAPHTIE ADDITION (% wt)</th>
<th>U.T.S. (MN/m²)</th>
<th>% ELONGATION</th>
<th>% REDUCTION IN AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>224</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>181</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>129</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>71</td>
<td>1.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
TABLE 2: GRAVITY DIE CASTINGS. (LM30, Vortex technique)

<table>
<thead>
<tr>
<th>GRAPHITE ADDITION (% wt)</th>
<th>U.T.S. (MN/m²)</th>
<th>% ELONGATION</th>
<th>% REDUCTION IN AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>182</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>154</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>119</td>
<td>1.0</td>
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</tr>
<tr>
<td>8</td>
<td>44</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Notes:

Tensile results - average of three.

Hounsfield No.13 Tensile specimens.

Tests carried out on Hounsfield Tensometer.

8.2 Composite Alloy Production by Compocasting.
   (Procedure as 6.4.2).

8.2.1 Evaluation of Compocasting Unit as a Slurry Producer.
   (Procedure as 6.4.2ii).

Microstructures:

Fig. 61 - Sand cast control specimen
8.25% Si alloy.

Fig. 62 - Gravity die cast control specimen
8.25% Si alloy.

Fig. 63 - Shear rate 90 sec⁻¹, 31% vol. solid
8.25% Si alloy.

Fig. 64 - Shear rate 190 sec⁻¹, 23% vol solid
8.25% Si alloy.
Fig. 65 - Shear rate 270 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy.

* Fig. 66 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy.

Fig. 67 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy - Isothermally held.

* Slight difference in texture of microstructure because alumina polishing method used (rather than diamond polishing method).

8.2.2 Determination of the Optimum Conditions for Addition of Graphite to 8.25\% Silicon Alloy.

(Procedure as 6.4.2iii)

i) Microstructures:

* Fig. 68 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy - no added graphite.

Fig. 69 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy + 2\% wt graphite.

Fig. 70 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy + 4\% wt graphite.

* Fig. 71 - Shear rate 500 sec$^{-1}$, 23\% vol solid 8.25\% Si alloy + 6\% wt graphite.

Fig. 72 - Shear rate 500 sec$^{-1}$, 16\% vol solid 8.25\% Si + 8\% wt graphite.

* Slight difference in texture of microstructure because alumina polishing method used (rather than diamond polishing method).
ii) Macrostructures:

Fig. 73 - Shear rate 500 sec\(^{-1}\), 16% vol solid
8.25% Si + 8% wt graphite.

iii) Tensile Testing.

TABLE 3: ULTIMATE LOAD (kg), (Shear rate 500 sec\(^{-1}\))

<table>
<thead>
<tr>
<th>% vol solid</th>
<th>% Graphite</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.</td>
<td>187.5</td>
<td>187.5</td>
<td>178.1</td>
</tr>
<tr>
<td></td>
<td>2.</td>
<td>189.9</td>
<td>187.4</td>
<td>181.4</td>
</tr>
<tr>
<td>23</td>
<td>1.</td>
<td>169.2</td>
<td>170.3</td>
<td>158.3</td>
</tr>
<tr>
<td></td>
<td>2.</td>
<td>147.9</td>
<td>132.8</td>
<td>142.1</td>
</tr>
</tbody>
</table>

Control:
(Shear rate 500 sec\(^{-1}\), 23% vol solid)
No added graphite - 231.25
237.5

Hounsfield No.13 Tensile specimens (2-off)
Tests carried out on Hounsfield Tensometer.

\[ \text{U.T.S.} = \frac{\text{Ultimate load}}{\text{Cross-sectional Area}} \]

TABLE 4: U.T.S. (av.) (MN/m\(^2\))

<table>
<thead>
<tr>
<th>% vol solid</th>
<th>% Graphite</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td></td>
<td>114.8</td>
<td>113.1</td>
<td>109.4</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>96.5</td>
<td>92.2</td>
<td>91.4</td>
</tr>
</tbody>
</table>

Control: 142.6 MN/m\(^2\).
TABLE 5: % ELONGATION.

<table>
<thead>
<tr>
<th>% C</th>
<th>% vol solid 2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>4</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>23</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

Control: 15%

TABLE 6: REDUCTION IN AREA.

<table>
<thead>
<tr>
<th>% C</th>
<th>% vol solid 2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>3.5</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Control: 11%

Tables 7 - 10 show the influence of various combinations of shear rate and % volume solid (for a given % weight graphite addition) on the viscosity of the slurry and the tendency to accept or reject graphite.

TABLE 7:

Adding 2% Graphite:

<table>
<thead>
<tr>
<th>SHEAR RATE</th>
<th>% VOL SOLID</th>
<th>31</th>
<th>23</th>
<th>.16</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 sec⁻¹</td>
<td>VISCOSITY TOO HIGH</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>REJECTED</td>
</tr>
<tr>
<td>190 &quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>O.K.</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>300 &quot;</td>
<td>O.K. BUT FAST THIXOTROPY</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>500 &quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
</tbody>
</table>


**TABLE 8:**

Adding 4% Graphite:

<table>
<thead>
<tr>
<th>SHEAR RATE</th>
<th>% VOL SOLID</th>
<th>31</th>
<th>23</th>
<th>16</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 sec⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>190</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>300</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>O.K.</td>
</tr>
<tr>
<td>500</td>
<td>&quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>O.K.</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>O.K. BUT</td>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>FAST THIXOTROPY</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

**TABLE 9:**

Adding 6% Graphite:

<table>
<thead>
<tr>
<th>SHEAR RATE</th>
<th>% VOL SOLID</th>
<th>.31</th>
<th>23</th>
<th>16</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 sec⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>190</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>300</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>&quot;</td>
</tr>
<tr>
<td>500</td>
<td>&quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>O.K.</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>O.K. BUT</td>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>FAST THIXOTROPY</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
TABLE 10:

Adding 8% Graphite:

<table>
<thead>
<tr>
<th>SHEAR RATE</th>
<th>% VOL SOLID</th>
<th>31</th>
<th>23</th>
<th>16</th>
<th>.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 sec⁻¹</td>
<td>VISCOSITY TOO HIGH</td>
<td></td>
<td></td>
<td>REJECTED</td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>300</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>500</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>O.K.</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

KEY: (TABLES 7 - 10)

- O.K.: Viscosity low enough to allow bottom pouring from crucible of sufficient quantity to produce a 0.5 kg casting and time to allow transfer from receiving crucible to a die without the onset of too high a viscosity as a result of thixotropic effects. (about 30 sec.)

- VISCOSITY TOO HIGH: Viscosity too high to allow bottom pouring after all the graphite is added.

- O.K. BUT FAST THIXOTROPY: Viscosity low enough to allow bottom pouring but increasing too rapidly to allow the metal to be transferred to the die from the receiving crucible.

From Tables 7 - 10, the following combinations of graphite content, shear rate and % volume solid were found to offer a viscosity suitable for casting purposes and no tendency to reject graphite: (Table 11).
Table 11: Suitable Combinations for Casting Purposes.

<table>
<thead>
<tr>
<th>Graphite Addition (% wt)</th>
<th>% Volume Solid</th>
<th>Shear Rate (sec(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>23</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>500</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>500</td>
</tr>
</tbody>
</table>

From Table 11 a graph was constructed to show the influence of graphite content on the shear rate required to allow a sufficiently low viscosity for casting purposes. (Fig. 74). The graphs obtained represent lines of approximately constant viscosity which are the maximum for the % volume solid indicated.
8.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be obtained.

(Procedure as 6.4.2 iv).

Constants:

Shear rate \(500\ \text{sec}^{-1}\)

Volume solid 16\%

Silicon content 8.25\% wt

Graphite addition 4\% wt

**TABLE 12 : VARIATION IN DIE TEMPERATURE.**

<table>
<thead>
<tr>
<th>DIE TEMP.</th>
<th>U.T.S.</th>
<th>% ELONGATION</th>
<th>BHNo.</th>
<th>SURFACE TEXTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>180°C</td>
<td>115 MN/m(^2)</td>
<td>5</td>
<td>52.7</td>
<td>4.8 (\mu)M Ra</td>
</tr>
<tr>
<td>240°C</td>
<td>108 &quot;</td>
<td>4</td>
<td>49.4</td>
<td>3.3 &quot; &quot;</td>
</tr>
<tr>
<td>300°C</td>
<td>103 &quot;</td>
<td>7</td>
<td>46.2</td>
<td>1.09 &quot; &quot;</td>
</tr>
<tr>
<td>360°C</td>
<td>104 &quot;</td>
<td>5</td>
<td>39.4</td>
<td>0.4 &quot; &quot;</td>
</tr>
</tbody>
</table>

(Squeeze Press. 208 MN/m\(^2\))

**TABLE 13 : VARIATION IN SQUEEZE PRESSURE.**

<table>
<thead>
<tr>
<th>SQUEEZE PRESSURE</th>
<th>U.T.S.</th>
<th>% ELONGATION</th>
<th>BHNo.</th>
<th>SURFACE TEXTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>208 MN/m(^2)</td>
<td>103 MN/m(^2)</td>
<td>7</td>
<td>45.3</td>
<td>1.1 (\mu)M Ra</td>
</tr>
<tr>
<td>162. &quot;</td>
<td>107 &quot;</td>
<td>6</td>
<td>47.1</td>
<td>1.3 &quot; &quot;</td>
</tr>
<tr>
<td>115 &quot;</td>
<td>100 &quot;</td>
<td>4</td>
<td>45.0</td>
<td>0.95 &quot; &quot;</td>
</tr>
<tr>
<td>69. &quot;</td>
<td>101 &quot;</td>
<td>5</td>
<td>40.7</td>
<td>1.0 &quot; &quot;</td>
</tr>
</tbody>
</table>

(Die temp. 300°C.)

All results - average of three.

Tensile machine - Hounsfield tensometer.

Castings produced with slurry temperature monitoring.

Base thermocouple (Fig. 26) indicated temperature rise of between 150 - 180°C for all castings.
8.2.4 Determination of the Relationship between Shear Rate, Graphite content and Viscosity.

(Procedure as 6.4.2 vi)

Alloy : 4% wt silicon

Vol. Solid : 21%

TABLE 14: OFF-LOAD WATTMETER READINGS (No material in compocasting unit).

<table>
<thead>
<tr>
<th>RPM</th>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
<th>$\omega_1 + \omega_2$</th>
<th>TORQUE (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>242.5</td>
<td>-12.5</td>
<td>230 watts</td>
<td>-</td>
</tr>
<tr>
<td>462</td>
<td>260</td>
<td>-7.5</td>
<td>252.5 &quot;</td>
<td>5.219</td>
</tr>
<tr>
<td>624</td>
<td>270</td>
<td>-5</td>
<td>265 &quot;</td>
<td>4.055</td>
</tr>
<tr>
<td>880</td>
<td>282.5</td>
<td>5</td>
<td>287.5 &quot;</td>
<td>3.120</td>
</tr>
<tr>
<td>1148</td>
<td>297.5</td>
<td>20</td>
<td>317.5 &quot;</td>
<td>2.641</td>
</tr>
<tr>
<td>1382</td>
<td>315</td>
<td>35</td>
<td>350 &quot;</td>
<td>2.418</td>
</tr>
<tr>
<td>1544</td>
<td>327.5</td>
<td>45</td>
<td>372.5 &quot;</td>
<td>2.304</td>
</tr>
</tbody>
</table>

TABLE 15: ON-LOAD WATTMETER READINGS. (Charge in compocasting unit)

<table>
<thead>
<tr>
<th>RPM</th>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
<th>$\omega_1 + \omega_2$</th>
<th>TORQUE (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>242.5</td>
<td>-12.5</td>
<td>230 watts</td>
<td>-</td>
</tr>
<tr>
<td>450</td>
<td>271</td>
<td>10</td>
<td>281 &quot;</td>
<td>5.961</td>
</tr>
<tr>
<td>740</td>
<td>307.5</td>
<td>15</td>
<td>322.5 &quot;</td>
<td>4.163</td>
</tr>
<tr>
<td>1060</td>
<td>351</td>
<td>20.5</td>
<td>371.5 &quot;</td>
<td>3.347</td>
</tr>
<tr>
<td>1166</td>
<td>354</td>
<td>30</td>
<td>384 &quot;</td>
<td>3.145</td>
</tr>
<tr>
<td>1305</td>
<td>349</td>
<td>50</td>
<td>399 &quot;</td>
<td>2.920</td>
</tr>
<tr>
<td>1544</td>
<td>352.5</td>
<td>62.5</td>
<td>415 &quot;</td>
<td>2.566</td>
</tr>
</tbody>
</table>

Torque = \( \frac{\text{Power}}{\text{Angular Velocity}} \)
A graph (Fig. 75) was drawn to obtain the actual torque required to maintain a steady minimum viscosity of the 4% silicon alloy at 21% volume solid. From this the off load torque was subtracted from the on-load torque to give Table 16.

**TABLE 16 : TORQUE REQUIRED ON ROTOR FOR SHEARING AT VARIOUS SHEAR RATES. FROM FIG. 74.**

<table>
<thead>
<tr>
<th>RPM</th>
<th>SHEAR RATE (sec⁻¹)</th>
<th>TORQUE (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>167</td>
<td>0.75</td>
</tr>
<tr>
<td>700</td>
<td>234</td>
<td>0.70</td>
</tr>
<tr>
<td>900</td>
<td>301</td>
<td>0.66</td>
</tr>
<tr>
<td>1100</td>
<td>368</td>
<td>0.52</td>
</tr>
<tr>
<td>1300</td>
<td>435</td>
<td>0.42</td>
</tr>
<tr>
<td>1500</td>
<td>502</td>
<td>0.30</td>
</tr>
<tr>
<td>1544</td>
<td>517</td>
<td>0.262</td>
</tr>
</tbody>
</table>

**TABLE 17 : VISCOSITY OF SLURRY AT VARIOUS SHEAR RATES.**
(Calculated as shown in 6.4.2 vi). Also shown in Fig. 76.

<table>
<thead>
<tr>
<th>SHEAR RATE (sec⁻¹)</th>
<th>VISCOSITY (Poises)</th>
</tr>
</thead>
<tbody>
<tr>
<td>167</td>
<td>55.2</td>
</tr>
<tr>
<td>234</td>
<td>36.8</td>
</tr>
<tr>
<td>301</td>
<td>27.1</td>
</tr>
<tr>
<td>368</td>
<td>17.4</td>
</tr>
<tr>
<td>435</td>
<td>11.9</td>
</tr>
<tr>
<td>502</td>
<td>7.37</td>
</tr>
<tr>
<td>517</td>
<td>6.26</td>
</tr>
</tbody>
</table>

**Effect of Graphite content:**
(Procedure repeated but with 2, 4, 6 and 8% wt graphite addition).
TABLE 18: OFF-LOAD TORQUE ON ROTOR.

<table>
<thead>
<tr>
<th>RPM</th>
<th>TORQUE (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>4.88</td>
</tr>
<tr>
<td>1000</td>
<td>2.90</td>
</tr>
<tr>
<td>1500</td>
<td>2.32</td>
</tr>
</tbody>
</table>

TABLE 19: ON-LOAD TORQUE ON ROTOR WITH 2, 4, 6 AND 8% wt GRAPHITE ADDITION.

<table>
<thead>
<tr>
<th>RPM</th>
<th>TORQUE (Nm) (2% GRAPHITE)</th>
<th>TORQUE (Nm) (4% GRAPHITE)</th>
<th>TORQUE (Nm) (6% GRAPHITE)</th>
<th>TORQUE (Nm) (8% GRAPHITE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>5.70</td>
<td>5.85</td>
<td>6.02</td>
<td>6.23</td>
</tr>
<tr>
<td>1000</td>
<td>3.69</td>
<td>3.87</td>
<td>4.07</td>
<td>4.25</td>
</tr>
<tr>
<td>1500</td>
<td>2.80</td>
<td>3.08</td>
<td>3.21</td>
<td>3.43</td>
</tr>
</tbody>
</table>

From Tables 18 and 19 a graph (Fig. 77) was drawn to obtain torque on rotor required for shearing. (Table 20).

TABLE 20: TORQUE REQUIRED FOR SHEARING WITH VARIOUS GRAPHITE ADDITIONS.

<table>
<thead>
<tr>
<th>RPM</th>
<th>TORQUE (Nm) (2% GRAPHITE)</th>
<th>TORQUE (Nm) (4% GRAPHITE)</th>
<th>TORQUE (Nm) (6% GRAPHITE)</th>
<th>TORQUE (Nm) (8% GRAPHITE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.82</td>
<td>0.97</td>
<td>1.14</td>
<td>1.35</td>
</tr>
<tr>
<td>1000</td>
<td>0.78</td>
<td>0.97</td>
<td>1.17</td>
<td>1.35</td>
</tr>
<tr>
<td>1500</td>
<td>0.49</td>
<td>0.68</td>
<td>0.88</td>
<td>1.12</td>
</tr>
</tbody>
</table>
TABLE 21: VISCOSITY WITH VARIOUS GRAPHITE ADDITIONS.

<table>
<thead>
<tr>
<th>RPM</th>
<th>VISCOSITY (P) (2% GRAPHITE)</th>
<th>VISCOSITY (P) (4% GRAPHITE)</th>
<th>VISCOSITY (P) (6% GRAPHITE)</th>
<th>VISCOSITY (P) (8% GRAPHITE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>60.4</td>
<td>71.4</td>
<td>84.0</td>
<td>99.5</td>
</tr>
<tr>
<td>1000</td>
<td>28.7</td>
<td>35.7</td>
<td>43.1</td>
<td>49.7</td>
</tr>
<tr>
<td>1500</td>
<td>12.03</td>
<td>16.7</td>
<td>21.6</td>
<td>27.5</td>
</tr>
</tbody>
</table>

8.2.5 Investigation of Graphite Rejection.

The results reported below refer to procedures described in 6.4.3.

i) Temperature:
   0% volume solid (630°C) - Graphite rejected.
   15% volume solid (595°C) - Graphite rejected.
   30% volume solid (583°C) - Graphite rejected.
   Alloy used 8% silicon.
   Shear rate 500 sec\(^{-1}\) (1500 rpm).
   Viscosity of 30% volume solid was too high to allow pouring from crucible.

ii) Rotor rpm:
   Maintained constant at 1500 rpm with the aid of a tachometer. (Shear rate 500 sec\(^{-1}\)).

iii) Contamination of Graphite particles:
   a) Original batch - Graphite rejected.
   b) New batch - Graphite rejected.
   c) Nickel coated graphite - Graphite rejected.
   Shear rate : 500 sec\(^{-1}\).
   Volume solid : 15%.
iv) Contamination of Refractories:

a) New gas melting crucible in which the aluminium-silicon alloys were produced - graphite rejected.

b) New compocasting crucible - Graphite rejected.

c) Rotor refractory coating:
   No coating used - Graphite rejected.
   New batch of coating - Graphite rejected.

d) Refractory Cement:
   New batch - Graphite rejected.
   Further batch - Graphite rejected.

v) Contamination of base alloy:

Concave meniscus and sides of rotor and crucible wetted - Graphite accepted.

Convex meniscus - Graphite rejected.

Analysis of Elements in Melting Stock.


Samples:

a) 4% silicon alloy which rejected graphite.

b) LM30 alloy which rejected graphite.

c) 12% silicon alloy which accepted graphite.

d) 16% silicon alloy which accepted graphite.

The results of analysis are shown in Figs. 78 – 81.

The presence of sodium can be seen in samples which accepted graphite (c and d).
The presence of chlorine can be seen in all the samples. Note: The height of the peaks cannot be considered to quantify the amounts of each element in the alloy. This type of analysis is restricted to assessing the elements present but not physical quantities or proportions.

The microstructures of the samples a) to d) are shown in Figs. 82 - 85. There is evidence of a finer structure in the samples which accepted graphite.

Addition of Sodium, Chlorine and Magnesium to melts.

Samples:

e) Chlorine addition.
f) Sodium addition.
g) Sodium and chlorine addition.
h) Magnesium addition.
Shear rate \(- 500 \text{ sec}^{-1}\)
Volume solid \(- 15\%\)
Alloy \(- 8\% \text{ silicon}\).

The results were:

sample e \(- \text{ Graphite rejected}\).
sample f \(- \text{ Graphite accepted}\).
sample g \(- \text{ Graphite rejected}\).
sample h \(- \text{ Graphite accepted}\).

The results of the analysis of samples e \(- g, i \ (50\% \text{ Si, } 50\% \text{ Al basic master alloy stock}), \text{ and } j \ (LMO (pure aluminium) basic master alloy stock)\) are shown in Figs. 86 - 88 and 89 - 90.
Figs. 91 - 95 show the following observations:

Fig. 91  Convex meniscus, crucible wall not wetted by melt from which sample 'e' (chlorine degassed) was taken.

Fig. 92  Concave meniscus, crucible wall wetted by melt from which sample 'f' (sodium added) was taken.

Fig. 93  Compocasting crucible walls not wetted and graphite completely rejected from sample 'e' melt. (chlorine degassed).

Fig. 94  Compocasting crucible walls wetted and complete acceptance of graphite in sample 'f' melt (sodium added).

Fig. 95  Appearance of rotors (i) from sodium treated melt (sample f) and (ii) from chlorine degassed melt (sample e). The sodium treated melt resulted in wetting of the rotor, the chlorine degassed melt did not.

In general, sample 'h' (magnesium addition) gave similar results to sample 'f' (sodium addition). Crucible and rotor were wetted more readily. The result of increasing melt temperature to above 900°C and holding for fifteen minutes was also to produce an alloy which accepted graphite (sample k).

9.1 Microstructures and Macrostructures of Castings with various Silicon and Graphite Contents.

i) The microstructures of composites produced with various silicon and graphite contents, as in 6.4, are illustrated as follows:
Fig. 96 16% wt Si (no graphite addition).
Fig. 97 16% wt Si + 2% wt graphite.
Fig. 98 16% wt Si + 4% wt graphite.
Fig. 99 16% wt Si + 6% wt graphite.
Fig. 100 16% wt Si + 6% wt graphite (showing graphite agglomeration).
Fig. 101 16% wt Si + 8% wt graphite.
Fig. 102 12% wt Si (no graphite addition)
Fig. 103 12% wt Si (no graphite addition)
(same casting as Fig. 102 - showing variation in structure).
Fig. 104 12% wt Si + 2% wt graphite.
Fig. 105 12% wt Si + 8% wt graphite.
Fig. 106 8% wt Si (no graphite addition).
Fig. 107 8% wt Si + 6% wt graphite.
Fig. 108 8% wt Si + 8% wt graphite.
Fig. 109 4% wt Si (no graphite addition)
Fig. 110 4% wt Si + 4% wt graphite.

ii) Macrostructures:
Fig. 111 16% wt Si + 4% wt graphite.
Fig. 112 8% wt Si + 4% graphite.
(longitudinal and transverse sections).

9.2 Tensile Testing.
Tests conducted to assess the effect of variations in Graphite content and Silicon content on U.T.S., % elongation and % reduction in area.
Specimens:  Hounsfield No.13 (3 - off)

Shear rate  500 sec$^{-1}$

v.f.s.  0.15

Die temp.  300°C

Squeeze press  14.1 kg/mm$^2$

Testing Machine:  Mayes ESH 250

Strain rate  0.6 mm/min

Load  0-5 kN.

**TABLE 1 : MAX LOAD (kN)**

<table>
<thead>
<tr>
<th>% Si</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.50</td>
<td>1.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.60</td>
<td>1.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>1.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
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<tr>
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<td>1.80</td>
<td>1.55</td>
</tr>
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<td>8</td>
<td>2.90</td>
<td>2.05</td>
<td>1.75</td>
<td>1.65</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>2.90</td>
<td>2.15</td>
<td>1.80</td>
<td>1.70</td>
<td>1.45</td>
</tr>
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<td>1.70</td>
<td>1.65</td>
<td>1.75</td>
</tr>
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<td>3.30</td>
<td>2.15</td>
<td>1.70</td>
<td>1.40</td>
<td>1.25</td>
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<td>3.40</td>
<td>2.00</td>
<td>1.75</td>
<td>1.20</td>
<td>1.05</td>
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<td>3.30</td>
<td>2.15</td>
<td>1.65</td>
<td>1.35</td>
<td>1.20</td>
</tr>
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<td>3.00</td>
<td>2.60</td>
<td>1.85</td>
<td>1.75</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
<td>2.50</td>
<td>1.75</td>
<td>1.75</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
<td>2.40</td>
<td>1.90</td>
<td>1.70</td>
<td>1.40</td>
</tr>
</tbody>
</table>
TABLE 2: U.T.S. (MN/m²)

<table>
<thead>
<tr>
<th>% Si</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>85</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>145</td>
<td>125</td>
<td>120</td>
<td>102</td>
<td>93</td>
</tr>
<tr>
<td>8</td>
<td>183</td>
<td>130</td>
<td>108</td>
<td>103</td>
<td>97</td>
</tr>
<tr>
<td>12</td>
<td>207</td>
<td>130</td>
<td>105</td>
<td>80</td>
<td>72</td>
</tr>
<tr>
<td>16</td>
<td>186</td>
<td>155</td>
<td>114</td>
<td>108</td>
<td>93</td>
</tr>
</tbody>
</table>

Fig. 113 Graph showing variation in U.T.S. with graphite addition.

Fig. 114 Graph showing variation in U.T.S. with silicon content.

TABLE 3: % ELONGATION

(Determined using Hounsfield Gauge).

<table>
<thead>
<tr>
<th>% Si</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
<td>6</td>
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<td>8</td>
<td>25</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

TABLE 4: % REDUCTION IN AREA.

(Determined using Hounsfield Gauge)

<table>
<thead>
<tr>
<th>% Si</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>5</td>
<td>4</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>5</td>
<td>4.5</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Control specimens produced from 4, 8, 12 & 16% silicon alloys, cast from above the liquidus into a copper die heated to approximately 200°C.

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>2.25</td>
<td>2.25</td>
<td>2.30</td>
<td>2.45</td>
</tr>
</tbody>
</table>

**TABLE 5 : MAX LOAD (kN)**

**TABLE 6 : U.T.S. (MN/m²), % Elongation and % reduction in area.**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.T.S.</td>
<td>140</td>
<td>161</td>
<td>191</td>
<td>160</td>
</tr>
<tr>
<td>% Elongation</td>
<td>25</td>
<td>22</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>% Reduction in Area.</td>
<td>23</td>
<td>20</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>

9.3 Hardness Testing:

The Brinell hardness test was used with 750 kg load and 10 mm dia ball.

Hardness was calculated using the formula:

\[
H = \frac{P}{\frac{\pi D}{2} \left[ D - \sqrt{D^2 - d^2} \right]}
\]

where

- \( H \) = Brinell hardness No.
- \( D \) = Ball diameter (mm)
- \( d \) = Impression diameter (mm).
<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>TEST No.</th>
<th>Av</th>
<th>BRINELL HARDNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Si % C</td>
<td>1 2 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 0</td>
<td>5.0 5.1 5.2</td>
<td>5.1</td>
<td>34.15</td>
</tr>
<tr>
<td>4 2</td>
<td>5.2 5.3 5.0</td>
<td>5.17</td>
<td>33.1</td>
</tr>
<tr>
<td>4 2</td>
<td>5.0 5.2 5.4</td>
<td>5.2</td>
<td>32.7</td>
</tr>
<tr>
<td>4 6</td>
<td>5.2 5.2 5.3</td>
<td>5.23</td>
<td>32.3</td>
</tr>
<tr>
<td>4 8</td>
<td>5.3 5.4 5.2</td>
<td>5.3</td>
<td>31.4</td>
</tr>
<tr>
<td>8 0</td>
<td>3.9 3.9 4.0</td>
<td>3.93</td>
<td>60.2</td>
</tr>
<tr>
<td>8 2</td>
<td>4.4 4.2 4.5</td>
<td>4.36</td>
<td>47.7</td>
</tr>
<tr>
<td>8 4</td>
<td>4.5 4.5 4.4</td>
<td>4.47</td>
<td>45.3</td>
</tr>
<tr>
<td>8 6</td>
<td>4.8 4.7 4.8</td>
<td>4.77</td>
<td>39.4</td>
</tr>
<tr>
<td>8 8</td>
<td>4.9 4.9 4.8</td>
<td>4.87</td>
<td>37.7</td>
</tr>
<tr>
<td>12 0</td>
<td>3.7 3.8 3.6</td>
<td>3.7</td>
<td>67.3</td>
</tr>
<tr>
<td>12 2</td>
<td>4.3 4.5 4.1</td>
<td>4.3</td>
<td>49.1</td>
</tr>
<tr>
<td>12 4</td>
<td>4.4 4.3 4.5</td>
<td>4.4</td>
<td>46.8</td>
</tr>
<tr>
<td>12 6</td>
<td>4.3 4.4 4.5</td>
<td>4.4</td>
<td>46.8</td>
</tr>
<tr>
<td>12 8</td>
<td>4.2 4.4 4.4</td>
<td>4.33</td>
<td>48.4</td>
</tr>
<tr>
<td>16 0</td>
<td>3.8 3.8 3.8</td>
<td>3.8</td>
<td>63.6</td>
</tr>
<tr>
<td>16 2</td>
<td>3.9 3.9 3.8</td>
<td>3.87</td>
<td>61.3</td>
</tr>
<tr>
<td>16 4</td>
<td>4.1 4.0 4.2</td>
<td>4.1</td>
<td>54.3</td>
</tr>
<tr>
<td>16 6</td>
<td>4.1 4.1 4.0</td>
<td>4.07</td>
<td>55.1</td>
</tr>
<tr>
<td>16 8</td>
<td>4.2 4.2 4.2</td>
<td>4.2</td>
<td>51.6</td>
</tr>
</tbody>
</table>
9.4 Wear Testing.

9.4.1 Reciprocating Diamond Scratch Tests.

Type : Single perpendicular diamond scratch test.

Stroke lengths : 20 mm, 40 mm.

 Loads : 1kg 5kg 10kg.

 Speed (av) : 3.33 cm/sec.

No. of Strokes : 1, 5, 10, 20, 50, 100, 500, 1000.

Diamond : Conical form 120° inc angle

.2 mm tip radius.

Wear volume calculated from

\[ W.V. = \left( 0.144 w^2 - 1.63 \times 10^{-3} \right) \times L \]

(Tables 8 - 19).

**TABLE 8 : 4% SILICON ALLOY WEAR VOLUME.**

**Stroke : 40 mm**

**Load : 5 kg.**

<table>
<thead>
<tr>
<th>Passes</th>
<th>4Si</th>
<th>4Si 4C</th>
<th>4Si 6C</th>
<th>4Si 8C *</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.12</td>
<td>.83</td>
<td>.83</td>
<td>.591</td>
</tr>
<tr>
<td>5</td>
<td>1.56</td>
<td>2.83</td>
<td>2.08</td>
<td>.923</td>
</tr>
<tr>
<td>10</td>
<td>3.24</td>
<td>4.17</td>
<td>3.24</td>
<td>1.56</td>
</tr>
<tr>
<td>20</td>
<td>3.69</td>
<td>4.69</td>
<td>4.67</td>
<td>2.44</td>
</tr>
<tr>
<td>50</td>
<td>4.67</td>
<td>5.77</td>
<td>5.77</td>
<td>3.69</td>
</tr>
<tr>
<td>100</td>
<td>10.51</td>
<td>7.63</td>
<td>7.63</td>
<td>5.21</td>
</tr>
<tr>
<td>500</td>
<td>15.71</td>
<td>13.8</td>
<td>11.3</td>
<td>8.31</td>
</tr>
</tbody>
</table>

* Abbreviated designation of composites;

  e.g. 4Si 8C is a 4% wt silicon alloy with a 8% wt graphite addition.
TABLE 9 : 4% SILICON ALLOY WEAR VOLUME.

Stroke : 40 mm

Load : 10 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>4Si</th>
<th>4Si 4C</th>
<th>4Si 6C</th>
<th>4Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.24</td>
<td>2.83</td>
<td>2.43</td>
<td>2.08</td>
</tr>
<tr>
<td>5</td>
<td>5.77</td>
<td>6.98</td>
<td>6.98</td>
<td>6.98</td>
</tr>
<tr>
<td>10</td>
<td>9.01</td>
<td>8.31</td>
<td>8.31</td>
<td>8.31</td>
</tr>
<tr>
<td>20</td>
<td>12.13</td>
<td>16.67</td>
<td>13.86</td>
<td>14.77</td>
</tr>
<tr>
<td>50</td>
<td>25.44</td>
<td>20.18</td>
<td>20.18</td>
<td>19.75</td>
</tr>
<tr>
<td>100</td>
<td>CHATTER</td>
<td>33.23</td>
<td>25.44</td>
<td>20.83</td>
</tr>
<tr>
<td>500</td>
<td>&quot;</td>
<td>CHATTER</td>
<td>33.23</td>
<td>27.93</td>
</tr>
</tbody>
</table>

TABLE 10 : 8% SILICON ALLOY WEAR VOLUME.

Stroke : 40 mm

Load : 5 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>8Si</th>
<th>8Si 2C</th>
<th>8Si 4C</th>
<th>8Si 6C</th>
<th>8Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.833</td>
<td>.92</td>
<td>.79</td>
<td>.71</td>
<td>.59</td>
</tr>
<tr>
<td>5</td>
<td>2.08</td>
<td>2.08</td>
<td>2.08</td>
<td>2.08</td>
<td>1.94</td>
</tr>
<tr>
<td>10</td>
<td>2.44</td>
<td>3.07</td>
<td>3.51</td>
<td>2.44</td>
<td>2.51</td>
</tr>
<tr>
<td>20</td>
<td>3.78</td>
<td>4.88</td>
<td>4.67</td>
<td>2.99</td>
<td>2.83</td>
</tr>
<tr>
<td>50</td>
<td>5.3</td>
<td>5.77</td>
<td>6.36</td>
<td>4.88</td>
<td>5.07</td>
</tr>
<tr>
<td>100</td>
<td>6.98</td>
<td>6.98</td>
<td>8.31</td>
<td>5.88</td>
<td>6.36</td>
</tr>
<tr>
<td>500</td>
<td>12.98</td>
<td>11.31</td>
<td>11.31</td>
<td>9.75</td>
<td>11.31</td>
</tr>
</tbody>
</table>
TABLE 11 : 8% SILICON ALLOY WEAR VOLUME.

Stroke : 40 mm.
Load : 10 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>8Si</th>
<th>8Si 2C</th>
<th>8Si 4C</th>
<th>8Si 6C</th>
<th>8Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.69</td>
<td>2.83</td>
<td>2.08</td>
<td>2.08</td>
<td>2.44</td>
</tr>
<tr>
<td>5</td>
<td>4.78</td>
<td>6.36</td>
<td>5.77</td>
<td>6.00</td>
<td>5.77</td>
</tr>
<tr>
<td>10</td>
<td>6.00</td>
<td>9.01</td>
<td>9.75</td>
<td>9.01</td>
<td>7.63</td>
</tr>
<tr>
<td>20</td>
<td>7.63</td>
<td>9.75</td>
<td>14.77</td>
<td>11.31</td>
<td>13.00</td>
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<tr>
<td>50</td>
<td>16.7</td>
<td>18.7</td>
<td>18.7</td>
<td>18.7</td>
<td>16.7</td>
</tr>
<tr>
<td>100</td>
<td>%CHATTER</td>
<td>27.9</td>
<td>26.7</td>
<td>24.25</td>
<td>20.8</td>
</tr>
<tr>
<td>500</td>
<td>%CHATTER</td>
<td>33.2</td>
<td>30.5</td>
<td>29.2</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Graphed representation of results:

See Figs. 115 and 117 for variation in wear volume with number of strokes showing the effect of 6% wt. graphite addition on the wear volume of 4 and 8% wt silicon alloys. Fig. 119 illustrates the effect of 2, 4 and 8% wt graphite addition on the wear volume of 8% wt silicon alloy.

TABLE 12 : 12% SILICON ALLOY WEAR VOLUME.

Stroke : 40 mm
Load : 5 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>12Si</th>
<th>12Si 4C</th>
<th>12Si 6C</th>
<th>12Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.59</td>
<td>.52</td>
<td>.59</td>
<td>.75</td>
</tr>
<tr>
<td>5</td>
<td>1.33</td>
<td>1.75</td>
<td>3.69</td>
<td>2.83</td>
</tr>
<tr>
<td>10</td>
<td>1.62</td>
<td>2.83</td>
<td>5.77</td>
<td>3.24</td>
</tr>
<tr>
<td>20</td>
<td>2.5</td>
<td>3.7</td>
<td>6.36</td>
<td>3.69</td>
</tr>
<tr>
<td>50</td>
<td>3.7</td>
<td>5.43</td>
<td>6.98</td>
<td>5.21</td>
</tr>
<tr>
<td>100</td>
<td>4.9</td>
<td>6.12</td>
<td>8.31</td>
<td>5.77</td>
</tr>
<tr>
<td>500</td>
<td>7.63</td>
<td>10.5</td>
<td>11.31</td>
<td>11.3</td>
</tr>
</tbody>
</table>
TABLE 13: 12% SILICON ALLOY WEAR VOLUME.

Stroke: 40 mm
Load: 10 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>12Si</th>
<th>12Si 4C</th>
<th>12Si 6C</th>
<th>12Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.17</td>
<td>2.83</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>5</td>
<td>2.83</td>
<td>6.98</td>
<td>6.36</td>
<td>5.77</td>
</tr>
<tr>
<td>10</td>
<td>5.77</td>
<td>13.6</td>
<td>7.63</td>
<td>8.31</td>
</tr>
<tr>
<td>20</td>
<td>9.01</td>
<td>17.7</td>
<td>8.31</td>
<td>11.31</td>
</tr>
<tr>
<td>50</td>
<td>11.31</td>
<td>27.9</td>
<td>16.7</td>
<td>13.0</td>
</tr>
<tr>
<td>100</td>
<td>27.9</td>
<td>30.5</td>
<td>23.08</td>
<td>14.77</td>
</tr>
<tr>
<td>500</td>
<td>CHATTER</td>
<td>33.2</td>
<td>27.9</td>
<td>33.2</td>
</tr>
</tbody>
</table>

TABLE 14: 16% SILICON ALLOY WEAR VOLUME.

Stroke: 40 mm
Load: 5 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>16Si</th>
<th>16Si 2C</th>
<th>16Si 4C</th>
<th>16Si 6C</th>
<th>16Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.79</td>
<td>.71</td>
<td>.92</td>
<td>.92</td>
<td>.67</td>
</tr>
<tr>
<td>5</td>
<td>2.08</td>
<td>1.87</td>
<td>1.75</td>
<td>1.62</td>
<td>1.75</td>
</tr>
<tr>
<td>10</td>
<td>2.2</td>
<td>2.67</td>
<td>2.82</td>
<td>3.69</td>
<td>2.08</td>
</tr>
<tr>
<td>20</td>
<td>3.7</td>
<td>4.16</td>
<td>4.67</td>
<td>4.16</td>
<td>4.61</td>
</tr>
<tr>
<td>50</td>
<td>5.77</td>
<td>4.16</td>
<td>5.77</td>
<td>4.16</td>
<td>6.0</td>
</tr>
<tr>
<td>100</td>
<td>6.98</td>
<td>6.98</td>
<td>6.98</td>
<td>4.16</td>
<td>6.36</td>
</tr>
<tr>
<td>500</td>
<td>11.3</td>
<td>10.5</td>
<td>9.01</td>
<td>9.75</td>
<td>8.31</td>
</tr>
</tbody>
</table>
TABLE 15: 16% SILICON ALLOY WEAR VOLUME.

Stroke: 40 mm
Load: 10 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>16Si</th>
<th>16Si 2C</th>
<th>16Si 4C</th>
<th>16Si 6C</th>
<th>16Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.44</td>
<td>1.44</td>
<td>1.75</td>
<td>1.75</td>
<td>1.87</td>
</tr>
<tr>
<td>5</td>
<td>3.24</td>
<td>3.9</td>
<td>2.83</td>
<td>3.24</td>
<td>5.77</td>
</tr>
<tr>
<td>10</td>
<td>3.7</td>
<td>5.77</td>
<td>9.01</td>
<td>5.77</td>
<td>7.63</td>
</tr>
<tr>
<td>20</td>
<td>3.7</td>
<td>11.3</td>
<td>14.77</td>
<td>6.98</td>
<td>14.7</td>
</tr>
<tr>
<td>50</td>
<td>8.3</td>
<td>16.7</td>
<td>18.7</td>
<td>13.00</td>
<td>20.8</td>
</tr>
<tr>
<td>100</td>
<td>11.3</td>
<td>18.7</td>
<td>23.1</td>
<td>14.77</td>
<td>23.1</td>
</tr>
<tr>
<td>500</td>
<td>18.7</td>
<td>20.8</td>
<td>25.4</td>
<td>18.7</td>
<td>25.4</td>
</tr>
</tbody>
</table>

Graphical representation of results:

See Figs. 116 and 118 for variation in wear volume with number of strokes showing the effect of 6% wt. graphite addition on the wear volume of 12 and 16% wt silicon alloys.

Fig. 120 illustrates the effect of 2, 4 and 8% wt graphite addition on the wear volume of 16% wt silicon alloy.

TABLE 17: 16% SILICON ALLOY WEAR VOLUME.

Stroke: 20 mm
Load: 1 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>16Si</th>
<th>16Si 2C</th>
<th>16Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.07</td>
<td>.02</td>
<td>.04</td>
</tr>
<tr>
<td>100</td>
<td>.94</td>
<td>.936</td>
<td>.81</td>
</tr>
<tr>
<td>500</td>
<td>2.84</td>
<td>2.3</td>
<td>2.84</td>
</tr>
<tr>
<td>1000</td>
<td>3.73</td>
<td>3.2</td>
<td>3.54</td>
</tr>
</tbody>
</table>
TABLE 18: 12% SILICON ALLOY WEAR VOLUME.

Stroke: 20 mm
Load: 1 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>12Si</th>
<th>12Si 2C</th>
<th>12Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.02</td>
<td>.02</td>
<td>.03</td>
</tr>
<tr>
<td>100</td>
<td>.94</td>
<td>1.11</td>
<td>.604</td>
</tr>
<tr>
<td>500</td>
<td>2.3</td>
<td>2.74</td>
<td>2.3</td>
</tr>
<tr>
<td>1000</td>
<td>2.7</td>
<td>3.98</td>
<td>3.32</td>
</tr>
</tbody>
</table>

TABLE 19: 4% SILICON ALLOY WEAR VOLUME.

Stroke: 20 mm
Load: 1 kg.

<table>
<thead>
<tr>
<th>Passes</th>
<th>4Si</th>
<th>4Si 2C</th>
<th>4Si 8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.60</td>
<td>.28</td>
<td>.35</td>
</tr>
<tr>
<td>100</td>
<td>1.51</td>
<td>2.3</td>
<td>2.74</td>
</tr>
<tr>
<td>500</td>
<td>3.02</td>
<td>3.02</td>
<td>3.32</td>
</tr>
<tr>
<td>1000</td>
<td>3.98</td>
<td>3.32</td>
<td>3.98</td>
</tr>
</tbody>
</table>

9.4.2 Pin on Disc Tests.

Parameters used:

Interface velocity: 100 cm/sec
Pin dia: 6.35 mm
Disc material: EN32 RC57

(RC53 on completion of programme)
Test duration: 30 mins.

Loads: 3.25, 7.8, 12.6 & 17.2 kg

Environment: Unlubricated system, enclosed in perspex cover, temperature and humidity monitored constant at 18-22°C and 42-43% relative humidity respectively.

Data Obtained:

i) Length of pin lost (Effective wear volume lost from pin).

ii) Coefficient of friction.

iii) Pin temperature rise.

iv) Surface textures of pin and disc (Ra, tp and profile).

v) Pin weight loss.

i) Length of Pin Lost. (Tables 20 - 23).

**TABLE 20**: LOAD 3.25 kg.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>.140</td>
<td>.076</td>
<td>.023</td>
<td>.047</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>.062</td>
<td>.047</td>
<td>.023</td>
<td>.015</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>.076</td>
<td>.060</td>
<td>.062</td>
<td>.031</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>.062</td>
<td>.094</td>
<td>.059</td>
<td>.048</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>.094</td>
<td>.094</td>
<td>.062</td>
<td>.078</td>
</tr>
</tbody>
</table>
**TABLE 21:** LOAD 7.8 kg.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.187</td>
<td>.078</td>
<td>.125</td>
<td>.078</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.152</td>
<td>.094</td>
<td>.062</td>
<td>.070</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>NOT TESTED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>.109</td>
<td>.103</td>
<td>.078</td>
<td>.094</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 22:** LOAD 12.6 kg.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.265</td>
<td>.140</td>
<td>.156</td>
<td>.172</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>.260</td>
<td>.140</td>
<td>.140</td>
<td>.225</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>* .390</td>
<td>* .187</td>
<td>.156</td>
<td>.187</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>* .405</td>
<td>* .218</td>
<td>* .218</td>
<td>.156</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>* .425</td>
<td>* .187</td>
<td>* .187</td>
<td>* .223</td>
<td></td>
</tr>
</tbody>
</table>

* Exhibited alteration to higher wear rate during test.

**TABLE 23:** LOAD 17.2 kg.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>PINS DESTROYED</td>
<td>(CATASTROPHIC) FAILURE **</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>*** .405</td>
<td>.251</td>
<td>.312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>*** ***</td>
<td>.390</td>
<td>.248</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>*** ***</td>
<td>***</td>
<td>.312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>*** ***</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** Not tested due to alteration to high wear rate during 12.6 kg test.
Note: Four types of wear exhibited:

i) Steady (mild wear)

ii) Rapid ** (severe wear) i.e. Pins destroyed and material deposited on disc (see Figs. 144 and 145 respectively).

iii) Step (see Figs. 146 and 148).

iv) Alteration * (from steady to rapid) (see Figs. 147 and 149).

Also note:

At 3.25 kg & 7.8 kg :- all pins steady wear.
At 12.6 kg:- 4Si, 8Si, 12Si, 16Si - steady
  4Si 2C  12Si 2C, 2Si 4C, - step
  16Si 2C  16Si 4C, 16Si 6C, 8Si 2C - steady
At 17.2 kg:- 4Si, 8Si, 12Si, 16Si, - rapid
  8Si 2C, - alteration
  12Si 2C - step
  16Si 2C  16Si 4C  16Si 6C - steady but steep
  12Si 4C - rapid.

Graphical Representation:

Fig. 121 Shows variation in length of pin lost with load for 4Si, 8Si, 4Si 2C, 4Si 8C, 8Si 2C and 8Si 8C.

Fig. 122 Ditto for 12Si, 16Si, 12Si 2C, 12Si 4C, 16Si 2C and 16Si 8C.
ii) **Coefficient of Friction.** (average)

**TABLE 24 : 3.25 kg LOAD.**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.34</td>
<td>.27</td>
<td>.34</td>
<td>.38</td>
</tr>
<tr>
<td>2</td>
<td>.30</td>
<td>.24</td>
<td>.27</td>
<td>.20</td>
</tr>
<tr>
<td>4</td>
<td>.27</td>
<td>.20</td>
<td>.23</td>
<td>.22</td>
</tr>
<tr>
<td>6</td>
<td>.25</td>
<td>.23</td>
<td>.25</td>
<td>.23</td>
</tr>
<tr>
<td>8</td>
<td>.20</td>
<td>.23</td>
<td>.27</td>
<td>.20</td>
</tr>
</tbody>
</table>

Fig. 123 Graphical representation of Table 24.

**TABLE 25 : 7.8 kg LOAD.**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.32</td>
<td>.25</td>
<td>.32</td>
<td>.35</td>
</tr>
<tr>
<td>2</td>
<td>.29</td>
<td>.25</td>
<td>.19</td>
<td>.19</td>
</tr>
<tr>
<td>4</td>
<td>NOT TESTED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>.19</td>
<td>.24</td>
<td>.25</td>
<td>.19</td>
</tr>
</tbody>
</table>

**TABLE 26 : 12.6 kg LOAD.**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.34</td>
<td>.29</td>
<td>.35</td>
<td>.39</td>
</tr>
<tr>
<td>2</td>
<td>.24</td>
<td>.29</td>
<td>.31</td>
<td>.25</td>
</tr>
<tr>
<td>4</td>
<td>.35</td>
<td>.27</td>
<td>.27</td>
<td>.24</td>
</tr>
<tr>
<td>6</td>
<td>.34</td>
<td>.25</td>
<td>.25</td>
<td>.25</td>
</tr>
<tr>
<td>8</td>
<td>.34</td>
<td>.28</td>
<td>.27</td>
<td>.25</td>
</tr>
</tbody>
</table>

Fig. 124 Graphical representation of Table 26.
TABLE 27: 17.2 kg LOAD.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-</td>
<td>.32</td>
<td>.34</td>
<td>.29</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>-</td>
<td>-</td>
<td>.34</td>
<td>.26</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>.29</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

iii) Temperature Rise. (°C)

TABLE 28: 3.25 kg LOAD.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>20</td>
<td>26</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>12</td>
<td>16</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>14</td>
<td>16</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>16</td>
<td>14</td>
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<td>14</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Fig. 125 Graphical representation of Table 28.

TABLE 29: 7.8 kg LOAD.

<table>
<thead>
<tr>
<th>% C</th>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>56</td>
<td>36</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>38</td>
<td>32</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>NOT TESTED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>36</td>
<td>30</td>
<td>25</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig. 126 Graphical representation of Table 29.
TABLE 30: 12.6 kg LOAD.

<table>
<thead>
<tr>
<th>% C</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>68</td>
<td>67</td>
<td>83</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>65</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>61</td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>6</td>
<td>56</td>
<td>55</td>
<td>44</td>
<td>42</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
<td>42</td>
<td>40</td>
<td>42</td>
</tr>
</tbody>
</table>

Fig. 127 Graphical representation of Table 30.

TABLE 31: 17.1 kg LOAD.

<table>
<thead>
<tr>
<th>% C</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>75</td>
<td>85</td>
<td>73</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>75</td>
<td>72</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

iv) Surface Textures of Pins and Disc after Tests.

(Typical surface texture of the pins before tests are shown in Fig. 129).

TABLE 32: 3.25 kg LOAD. (μM Ra) (Pins)

<table>
<thead>
<tr>
<th>% C</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>3.49</td>
<td>3.26</td>
<td>3.01</td>
<td>3.05</td>
</tr>
<tr>
<td>2</td>
<td>2.89</td>
<td>2.68</td>
<td>2.91</td>
<td>2.71</td>
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<td>3.56</td>
<td>2.82</td>
</tr>
<tr>
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<td>4.12</td>
<td>2.71</td>
<td>2.82</td>
<td>3.28</td>
</tr>
<tr>
<td>8</td>
<td>3.51</td>
<td>2.62</td>
<td>3.05</td>
<td>3.07</td>
</tr>
</tbody>
</table>
TABLE 33: 12.6 kg LOAD. (μM Ra) (Pins)

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>% C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>8.04</td>
<td>4.26</td>
<td>5.47</td>
<td>4.54</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>3.5</td>
<td>4.9</td>
<td>6.18</td>
</tr>
<tr>
<td>4</td>
<td>6.6</td>
<td>2.3</td>
<td>4.2</td>
<td>3.81</td>
</tr>
<tr>
<td>6</td>
<td>3.95</td>
<td>4.94</td>
<td>3.75</td>
<td>4.03</td>
</tr>
<tr>
<td>8</td>
<td>3.85</td>
<td>3.5</td>
<td>6.25</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Figs. 130-137 show the surface profiles of 4Si, 4Si 2C, 8Si, 8Si 4C, 12Si, 12Si 2C, 16Si and 16Si 8C after 12.6 kg load tests.

Bearing Ratio: (tp %)
(- taken at mean of amplitude distribution, depth (μM) in brackets).

TABLE 34: 3.25 kg LOAD. (Pins)

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>% C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>54.7(8.7)</td>
<td>52.3(7.1)</td>
<td>51.2(16.9)</td>
<td>53.4(10.1)</td>
</tr>
<tr>
<td>4</td>
<td>55.1(10.0)</td>
<td>57.7(6.6)</td>
<td>54.1(17.5)</td>
<td>53.6(11.7)</td>
</tr>
</tbody>
</table>

TABLE 35: 12.6 kg LOAD. (Pins)

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>% C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>51.3(29.2)</td>
<td>53.7(14.3)</td>
<td>52.9(18.7)</td>
<td>59.1(9.5)</td>
</tr>
<tr>
<td>2</td>
<td>49.3(13.2)</td>
<td>49.6(9.4)</td>
<td>53.5(14.6)</td>
<td>43.8(32.8)</td>
</tr>
<tr>
<td>4</td>
<td>47.3(17.1)</td>
<td>52.8(6.5)</td>
<td>55.1(13.7)</td>
<td>54.3(17.9)</td>
</tr>
<tr>
<td>6</td>
<td>59.4(12.4)</td>
<td>50.0(16.4)</td>
<td>57.5(18.2)</td>
<td>53.3(18.3)</td>
</tr>
<tr>
<td>8</td>
<td>55.1(16.2)</td>
<td>48.0(15.6)</td>
<td>47.8(25.5)</td>
<td>48.6(19.1)</td>
</tr>
</tbody>
</table>

Figs. 138 and 139 show the bearing area analysis for 16Si and 16Si 8C pins after 12.6 kg load tests.
Surface Texture of Disc.
(Originally ground to better than 0.2 μM Ra.)

**TABLE 36 : 7.8 kg LOAD. (μM Ra).**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.89</td>
<td>.63</td>
<td>.84</td>
<td>.69</td>
</tr>
<tr>
<td>8</td>
<td>.19</td>
<td>.37</td>
<td>.42</td>
<td>.37</td>
</tr>
</tbody>
</table>

**TABLE 37 : 12.6 kg LOAD. (μM Ra)**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.55</td>
<td>1.34</td>
<td>1.52</td>
<td>1.34</td>
</tr>
<tr>
<td>2</td>
<td>1.37</td>
<td>.95</td>
<td>.73</td>
<td>1.02</td>
</tr>
<tr>
<td>6</td>
<td>1.64</td>
<td>.83</td>
<td>.81</td>
<td>.97</td>
</tr>
</tbody>
</table>

**TABLE 38 : 7.8 kg LOAD - Bearing Ratio (tp %)**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>53.3(4.2)</td>
<td>47.1(4.9)</td>
<td>50.9(2.3)</td>
<td>56.5(1.5)</td>
</tr>
<tr>
<td>8</td>
<td>51.9(1.0)</td>
<td>50.5(1.8)</td>
<td>42.0(2.0)</td>
<td>50.8(1.9)</td>
</tr>
</tbody>
</table>

*tp % (depth of mean of amplitude distribution).*

**TABLE 39 : 12.6 kg LOAD - Bearing Ratio.**

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>46.7(4.9)</td>
<td>47.8(3.9)</td>
<td>52.1(5.2)</td>
<td>51.3(4.4)</td>
</tr>
<tr>
<td>2</td>
<td>47.1(2.2)</td>
<td>48.7(2.1)</td>
<td>50.5(2.0)</td>
<td>52.0(2.7)</td>
</tr>
<tr>
<td>6</td>
<td>46.9(3.0)</td>
<td>49.7(2.7)</td>
<td>48.3(3.3)</td>
<td>47.1(2.8)</td>
</tr>
</tbody>
</table>

*tp % (depth of mean of amplitude distribution).*
v) **Weight Losses.** (Pins)

**TABLE 40:** 3.25 kg LOAD (gm)

<table>
<thead>
<tr>
<th>% Si</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.0113</td>
<td>.0222</td>
<td>.0137</td>
<td>.0064</td>
</tr>
<tr>
<td>2</td>
<td>.0151</td>
<td>.0142</td>
<td>.0103</td>
<td>.0090</td>
</tr>
<tr>
<td>4</td>
<td>.0193</td>
<td>.0058</td>
<td>.0080</td>
<td>.0083</td>
</tr>
<tr>
<td>6</td>
<td>.0156</td>
<td>.0061</td>
<td>.0063</td>
<td>.0080</td>
</tr>
<tr>
<td>8</td>
<td>.0185</td>
<td>.0043</td>
<td>.0041</td>
<td>.0045</td>
</tr>
</tbody>
</table>

**TABLE 41:** 7.8 kg LOAD (gm)

<table>
<thead>
<tr>
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<th>8</th>
<th>12</th>
<th>16</th>
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</thead>
<tbody>
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<td>.0087</td>
<td>.0094</td>
</tr>
<tr>
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<td>.0142</td>
<td>.0091</td>
<td>.0051</td>
<td>.0084</td>
</tr>
<tr>
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<td>.0142</td>
<td>.0091</td>
<td>.0051</td>
<td>.0084</td>
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<td></td>
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<td>.0101</td>
<td>.0066</td>
<td>.0115</td>
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</table>

**TABLE 42:** 12.6 kg LOAD (gm)

<table>
<thead>
<tr>
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<th>12</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
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<td>.0104</td>
<td>.0104</td>
<td>.0210</td>
</tr>
<tr>
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<tr>
<td>4</td>
<td>.0191</td>
<td>.0153</td>
<td>.0172</td>
<td>.0098</td>
</tr>
<tr>
<td>6</td>
<td>.0291</td>
<td>.0158</td>
<td>.0158</td>
<td>.0106</td>
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<tr>
<td>8</td>
<td>.0311</td>
<td>.0163</td>
<td>.0143</td>
<td>.0170</td>
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</table>
TABLE 43: 17.2 kg LOAD (gm)

<table>
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<th>12</th>
<th>16</th>
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<td>.0547</td>
<td>.0561</td>
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<td></td>
<td>.0267</td>
<td>.0237</td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>.0264</td>
<td></td>
</tr>
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<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

vi) Tests to establish repeatability of results.

Repeat tests carried out, such that statistical methods could be applied to the data and a significance level for its validity established:
<table>
<thead>
<tr>
<th>SPECIMEN NO.</th>
<th>COMPOSITION % Si</th>
<th>% C</th>
<th>LOAD (kg)</th>
<th>LENGTH OF PIN LOST</th>
<th>COEFFICIENT OF FRICTION</th>
<th>TEMPERATURE RISE (°C)</th>
<th>SURFACE FINISH μM Ra</th>
<th>WEIGHT LOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>RETEST ORIGINAL</td>
<td>RETEST ORIGINAL</td>
<td>RETEST ORIGINAL</td>
<td>RETEST ORIGINAL</td>
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<tr>
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<td>8</td>
<td>3.25</td>
<td>.085 .094</td>
<td>.21 .20</td>
<td>12 10</td>
<td>2.99 3.51</td>
<td>.0081 .0185</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>8</td>
<td>3.25</td>
<td>.054 .062</td>
<td>.27 .26</td>
<td>10 12</td>
<td>3.12 3.05</td>
<td>.0068 .0041</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>7.8</td>
<td>.131 .094</td>
<td>.27 .29</td>
<td>36 38</td>
<td></td>
<td>.106 .0142</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>8</td>
<td>7.8</td>
<td>.109 .094</td>
<td>.24 .24</td>
<td>30 30</td>
<td></td>
<td>.0107 .0066</td>
</tr>
<tr>
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<td>4</td>
<td>-</td>
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<td>.31 .34</td>
<td>66 68</td>
<td>7.93 8.04</td>
<td>.0167 .0165</td>
</tr>
<tr>
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<td>8</td>
<td>-</td>
<td>12.6</td>
<td>.125 .140</td>
<td>.31 .29</td>
<td>66 67</td>
<td>4.57 4.26</td>
<td>.0096 .0104</td>
</tr>
<tr>
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<td>12</td>
<td>-</td>
<td>12.6</td>
<td>.156 .156</td>
<td>.35 .35</td>
<td>79 83</td>
<td>5.50 5.47</td>
<td>.0111 .0104</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>-</td>
<td>12.6</td>
<td>.187 .172</td>
<td>.39 .39</td>
<td>63 68</td>
<td>4.72 4.54</td>
<td>.0180 .0210</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>6</td>
<td>12.6</td>
<td>.390 .390</td>
<td>.33 .34</td>
<td>55 56</td>
<td>4.75 6.6</td>
<td>.0287 .0291</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>6</td>
<td>12.6</td>
<td>.203 .218</td>
<td>.26 .25</td>
<td>55 55</td>
<td>5.85 4.94</td>
<td>.0171 .0158</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>4</td>
<td>12.6</td>
<td>.174 .156</td>
<td>.27 .27</td>
<td>55 46</td>
<td>5.20 4.20</td>
<td>.0168 .0172</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>8</td>
<td>12.6</td>
<td>.218 .223</td>
<td>.31 .25</td>
<td>47 42</td>
<td>2.57 1.62</td>
<td>.0173 .0170</td>
</tr>
</tbody>
</table>

(see also Appendix 5)

Statistical analysis by the "'t' test applied to paired observations" indicated the results were valid and that the discrepancies in the retests of 12 samples were not significant.
9.5 **Use of Electron Optical Techniques to Study Fracture Surfaces and Worn Surfaces.**

i) **Fracture Surfaces.**

All fracture surfaces were examined at a magnification of x 500 after tensile tests. Micrographs are as follows:

- Fig. 150 4Si fracture surface
- Fig. 151 4Si 4C " "
- Fig. 152 4Si 6C " "
- Fig. 153 4Si 8C " "
- Fig. 154 8Si " "
- Fig. 155 8Si 2C " "
- Fig. 156 8Si 4C " "
- Fig. 157 8Si 6C " "
- Fig. 158 12Si " "
- Fig. 159 12Si 2C " "
- Fig. 160 12Si 6C " "
- Fig. 161 12Si 8C " "
- Fig. 162 16Si " "
- Fig. 163 16Si 2C " "
- Fig. 164 16Si 4C " "
- Fig. 165 16Si 8C " "

ii) **Worn Surfaces.**

Reciprocating Diamond Scratch Tests:

- Fig. 166 Specimen 8Si, side of the scratch, 5 kg load, 200 strokes.
- Fig. 167 Specimen 8Si 4C, side of the scratch, 5 kg load, 200 strokes.
Pin on Disc Tests:

Fig. 168 4Si, load 3.25 kg.
Fig. 169 4Si, " "
Fig. 170 4Si 8C, " "
Fig. 171 4Si 8C, " "
Fig. 172 8Si , " "
Fig. 173 8Si , " "
Fig. 174 8Si 6C, " "
Fig. 175 8Si 6C, " "
Fig. 176 12Si , " "
Fig. 177 12Si , " "
Fig. 178 12Si 8C, " "
Fig. 179 12Si 8C, " "
Fig. 180 16Si , " "
Fig. 181 16Si , " "
Fig. 182 16Si 2C, " "
Fig. 183 16Si 2C, " "

Fig. 184 8Si , load 7.8 kg.
Fig. 185 8Si , load 12.6 kg.
Fig. 186 8Si 6C, load 7.8 kg.
Fig. 187 8Si 6C, load 7.8 kg.

Fig. 188 4Si , load 12.6 kg.
Fig. 189 4Si 2C, " " , "Step wear"
  - test terminated when coefficient of friction was at high peak.

Fig. 190. 4Si 6C, load 12.6 kg.
Fig. 191 12Si, load 12.6 kg.

Fig. 192 12Si 2C, " " , "Step wear"
- test terminated when coefficient of friction was at high peak.

Fig. 193 12Si 4C, load 12.6 kg, "Step wear"
- test terminated when coefficient of friction was low.

Fig. 194 12Si 6C, load 12.6 kg.

Fig. 195 16Si " "

Fig. 196 16Si 2C, " " , "Step wear"
- test terminated when coefficient of friction was low.

Fig. 197 16Si 8C, load 12.6 kg.

Fig. 198 Wear Debris, 16Si, load 12.6 kg.

Fig. 199 " " , 16Si 2C, " "

Fig. 200 " " , 16Si 4C, " "

iii) ESCA Studies.

Specimen: 16Si 2C, load 12.6 kg.

TABLE 45: ELEMENTS (%) ON WORN SURFACE.

<table>
<thead>
<tr>
<th>ETCH TIME (MINS)</th>
<th>DEPTH (Å)</th>
<th>Al</th>
<th>Si</th>
<th>C</th>
<th>N₂</th>
<th>Na</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>17.0</td>
<td>1.4</td>
<td>47.5</td>
<td>0.8</td>
<td>0.7</td>
<td>32.6</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>19.7</td>
<td>1.4</td>
<td>58.7</td>
<td>0.0</td>
<td>0.5</td>
<td>19.6</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>19.9</td>
<td>1.5</td>
<td>59.3</td>
<td>0.0</td>
<td>0.3</td>
<td>19.0</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>21.2</td>
<td>1.7</td>
<td>57.5</td>
<td>0.0</td>
<td>0.0</td>
<td>19.6</td>
</tr>
</tbody>
</table>
Specimen: 8Si 4C, load 12.6 kg.

**TABLE 46 : ELEMENTS (%) ON WORN SURFACE.**

<table>
<thead>
<tr>
<th>ETCH TIME (MINS)</th>
<th>DEPTH (Å)</th>
<th>Al</th>
<th>Si</th>
<th>C</th>
<th>N₂</th>
<th>Na</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
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<td>01</td>
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<td>35.6</td>
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<tr>
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<td>22.7</td>
<td>1.5</td>
<td>50.3</td>
<td>0.0</td>
<td>0.0</td>
<td>25.5</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>23.1</td>
<td>1.6</td>
<td>51.7</td>
<td>0.0</td>
<td>0.0</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Specimen: 12Si, load 12.6 kg.

**TABLE 47 : ELEMENTS (%) ON WORN SURFACE.**

<table>
<thead>
<tr>
<th>ETCH TIME (MINS)</th>
<th>DEPTH (Å)</th>
<th>Al</th>
<th>Si</th>
<th>C</th>
<th>N₂</th>
<th>Na</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>19.3</td>
<td>1.3</td>
<td>49.8</td>
<td>0.9</td>
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<td>28.4</td>
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<tr>
<td>1</td>
<td>20</td>
<td>27.9</td>
<td>2.0</td>
<td>41.2</td>
<td>0.0</td>
<td>0.0</td>
<td>28.9</td>
</tr>
</tbody>
</table>

Specimen 8Si, load 12.6 kg.

**TABLE 48 : ELEMENTS (%) ON WORN SURFACE.**

<table>
<thead>
<tr>
<th>ETCH TIME (MINS)</th>
<th>DEPTH (Å)</th>
<th>Al</th>
<th>Si</th>
<th>C</th>
<th>N₂</th>
<th>Na</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>22.6</td>
<td>3.1</td>
<td>45.2</td>
<td>0.5</td>
<td>0.0</td>
<td>28.5</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>31.8</td>
<td>3.2</td>
<td>31.6</td>
<td>0.0</td>
<td>0.0</td>
<td>33.5</td>
</tr>
</tbody>
</table>
9.6 Chemical Analysis.

i) Results of analysis carried out by Foseco Foundry Services Ltd., on two samples of 8.25% silicon alloy used to evaluate the compocasting unit as a slurry producer and for determination of optimum conditions for the addition of graphite.

**TABLE 49: CHEMICAL ANALYSIS (8.25% Si alloys)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Sample 1 (% wt)</th>
<th>Sample 2 (% wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Zn</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Cu</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Fe</td>
<td>0.36</td>
<td>0.25</td>
</tr>
<tr>
<td>Ni</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Ti</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Sn</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Si</td>
<td>8.45</td>
<td>8.24</td>
</tr>
</tbody>
</table>
ii) Results of analysis carried out by Charnwood Consultants Ltd., using technique No.1 (see 2.3.6i).

**TABLE 50 : CHEMICAL ANALYSIS (1).**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Assumed Quantity</th>
<th>Analysed Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% wt Silicon</td>
<td>% wt Graphite</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

iii) Results of analysis carried out by Charnwood Consultants Ltd., using technique No.2 (see 2.3.6i).

**TABLE 51 : CHEMICAL ANALYSIS (2).**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Added % wt Graphite</th>
<th>Analysed % wt Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>3.53</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.54</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2.54</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1.30</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1.10</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>2.62</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>3.72</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1.17</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>3.58</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>4.87</td>
</tr>
</tbody>
</table>
iv) Quantitative Metallography.

Areal analysis by Quantimet (see 2.3.6ii).

TABLE 52:

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Area Graphite</th>
<th>Av</th>
<th>Equivalent % wt Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>8Si 2C</td>
<td>1.76 3.44 2.29</td>
<td>2.497</td>
<td>2.034</td>
</tr>
<tr>
<td>4Si 6C</td>
<td>6.42 5.49 6.73</td>
<td>6.213</td>
<td>5.06</td>
</tr>
<tr>
<td>12Si 8C</td>
<td>8.80 8.69 7.23</td>
<td>8.84</td>
<td>6.71</td>
</tr>
<tr>
<td>12Si 4C</td>
<td>4.77 3.59 4.40</td>
<td>4.25</td>
<td>3.46</td>
</tr>
<tr>
<td>16Si</td>
<td>0.042 0.059 0.017</td>
<td>0.039</td>
<td>0.032</td>
</tr>
</tbody>
</table>
Areal analysis of 16Si 4C casting section.

**TABLE 53 : VARIATION IN GRAPHITE CONTENT IN A CASTING SECTION.**

(see Fig. 201 for positions on section).

<table>
<thead>
<tr>
<th>POSITION ON SECTION</th>
<th>EQUIVALENT % wt GRAPHITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.94</td>
</tr>
<tr>
<td>2</td>
<td>3.30</td>
</tr>
<tr>
<td>3</td>
<td>14.1</td>
</tr>
<tr>
<td>4</td>
<td>2.47</td>
</tr>
<tr>
<td>5</td>
<td>6.03</td>
</tr>
<tr>
<td>6</td>
<td>4.07</td>
</tr>
<tr>
<td>7</td>
<td>4.10</td>
</tr>
<tr>
<td>8</td>
<td>2.81</td>
</tr>
<tr>
<td>9</td>
<td>1.84</td>
</tr>
<tr>
<td>10</td>
<td>4.21</td>
</tr>
<tr>
<td>11</td>
<td>2.81</td>
</tr>
<tr>
<td>12</td>
<td>4.59</td>
</tr>
<tr>
<td>13</td>
<td>4.30</td>
</tr>
<tr>
<td>14</td>
<td>3.95</td>
</tr>
<tr>
<td>15</td>
<td>0.76</td>
</tr>
<tr>
<td>16</td>
<td>4.23</td>
</tr>
<tr>
<td>17</td>
<td>5.73</td>
</tr>
<tr>
<td>18</td>
<td>4.61</td>
</tr>
<tr>
<td>19</td>
<td>3.77</td>
</tr>
<tr>
<td>20</td>
<td>5.27</td>
</tr>
</tbody>
</table>

$\bar{\text{Av}} = 4.3945$

Equivalent % wt graphite: 3.58.
v) Comparison between Areal analysis by Quantiment and Lineal analysis.

**TABLE 54:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>% wt Graphite by Areal Analysis</th>
<th>% wt Graphite by Lineal Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>16Si 2C</td>
<td>1.87</td>
<td>2.05</td>
</tr>
<tr>
<td>16Si</td>
<td>0.031</td>
<td>0.00</td>
</tr>
<tr>
<td>12Si 6C</td>
<td>5.47</td>
<td>5.32</td>
</tr>
<tr>
<td>12Si 2C</td>
<td>1.95</td>
<td>1.65</td>
</tr>
<tr>
<td>8Si 4C</td>
<td>3.71</td>
<td>4.31</td>
</tr>
<tr>
<td>8Si 2C</td>
<td>2.05</td>
<td>2.09</td>
</tr>
<tr>
<td>4Si 8C</td>
<td>7.27</td>
<td>6.93</td>
</tr>
<tr>
<td>4Si 2C</td>
<td>1.84</td>
<td>2.37</td>
</tr>
<tr>
<td>4Si</td>
<td>0.047</td>
<td>0.00</td>
</tr>
</tbody>
</table>
9.7 Fatigue Testing.

Testing carried out using a Wöhler-type (rotating bend) machine.

Reverse bending stress used = $83 \text{ MN/m}^2$ (i.e. $= 0.5 \times \text{U.T.S}$)

**TABLE 55 : FATIGUE LIFE.**

<table>
<thead>
<tr>
<th>COCOMPOSITION</th>
<th>DURATION TO FAILURE (HRS)</th>
<th>Av</th>
<th>FATIGUE LIFE (REVERSALS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>C</td>
<td>TEST NO.</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>.30</td>
<td>.35</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>.35</td>
<td>.55</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>1.5</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>.85</td>
<td>.65</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>.55</td>
<td>.75</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>.50</td>
<td>1.0</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>.15</td>
<td>.25</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>.35</td>
<td>.25</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>.20</td>
<td>.10</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.25</td>
<td>.35</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>.35</td>
<td>.50</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>.15</td>
<td>.35</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>.10</td>
<td>.20</td>
</tr>
</tbody>
</table>
9.8 Corrosion Testing.

Tests carried out for a period of six weeks at a temperature of 80°C:

All specimens coupled with grey cast iron and immersed in motor oil as follows:

Set 1: Ford SSM-2C9001-AA 20w-50 motor oil (control).
Set 2: As above + 5% Acetic acid + 5% water.
Set 3: Used motor oil.

**TABLE 56: SET 1 (Control, Fresh oil)**

<table>
<thead>
<tr>
<th>% Si</th>
<th>% C</th>
<th>Weight change (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-</td>
<td>- .0004</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>+ .0029</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>+ .0085</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>+ .0021</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>+ .0039</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>+ .0002</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>- .0012</td>
</tr>
</tbody>
</table>
TABLE 57: SET 2. (Fresh oil + acetic acid + water).

<table>
<thead>
<tr>
<th>% Si</th>
<th>% C</th>
<th>Weight change (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-</td>
<td>- .0008</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>+ .0122</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>- .0012</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>+ .0124</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>+ .0023</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>+ .0080</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>+ .0103</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>+ .0032</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>+ .0111</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>+ .0020</td>
</tr>
</tbody>
</table>

TABLE 58: SET 3. (Used oil)

<table>
<thead>
<tr>
<th>% Si</th>
<th>% C</th>
<th>Weight change (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-</td>
<td>- .0013</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>+ .0046</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>+ .0045</td>
</tr>
</tbody>
</table>
9.9 Machinability Testing. (see 2.3.9)

TABLE 59: TOOL FORCES, MACHINABILITY INDEX, SURFACE FINISH, FRICTION COEFFICIENT, SPECIFIC CUTTING POWER.

\((t_1 = 0.137 \text{ mm Constant})\)

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>FORCES ON TOOL</th>
<th>MACHINABILITY INDEX 'D'</th>
<th>SURFACE FINISH</th>
<th>FRICTION COEFF.</th>
<th>SPECIFIC CUTTING POWER MW/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Si</td>
<td>% GRAPHITE</td>
<td>( F_C (N) )</td>
<td>( F_T (N) )</td>
<td>Ra((\mu)m) BEARING RATIO(%)</td>
<td>( \mu )</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>400</td>
<td>250</td>
<td>1.12</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>176</td>
<td>83</td>
<td>1.35</td>
<td>7.8</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>176</td>
<td>79</td>
<td>1.32</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>320</td>
<td>175</td>
<td>1.09</td>
<td>9.2</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>168</td>
<td>91</td>
<td>1.21</td>
<td>9.2</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>168</td>
<td>87</td>
<td>1.32</td>
<td>8.0</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>320</td>
<td>250</td>
<td>1.11</td>
<td>6.25</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>176</td>
<td>104</td>
<td>1.53</td>
<td>6.0</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>168</td>
<td>100</td>
<td>1.41</td>
<td>6.6</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>160</td>
<td>92</td>
<td>1.71</td>
<td>5.0</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>256</td>
<td>171</td>
<td>1.25</td>
<td>6.53</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>152</td>
<td>79</td>
<td>1.32</td>
<td>5.0</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>152</td>
<td>83</td>
<td>1.35</td>
<td>5.1</td>
</tr>
<tr>
<td>16</td>
<td>6</td>
<td>152</td>
<td>75</td>
<td>1.47</td>
<td>4.8</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>144</td>
<td>79</td>
<td>1.44</td>
<td>4.46</td>
</tr>
</tbody>
</table>

Observations: Specimens with graphite exhibit:

i) Considerably lower tool forces,

ii) Improved machinability index,

iii) Improved surface roughness,

iv) Slightly inferior bearing ratio,

v) Lower friction coefficient,

vi) Lower specific cutting power.
TABLE 60: (t_1 variable)

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>FEED PER REV.</th>
<th>FORCES ON TOOL (N)</th>
<th>MACHINABILITY INDEX 'D'</th>
<th>FRICTION COEF.</th>
<th>SPECIFIC CUTTING POWER MW/mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Si</td>
<td>% C</td>
<td>t_1 (mm)</td>
<td>F_C</td>
<td>F_T</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.033</td>
<td>120</td>
<td>83</td>
<td>1.05</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.069</td>
<td>160</td>
<td>87</td>
<td>1.09</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.137</td>
<td>256</td>
<td>171</td>
<td>1.25</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.272</td>
<td>424</td>
<td>250</td>
<td>1.51</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>.546</td>
<td>560</td>
<td>383</td>
<td>2.6</td>
</tr>
</tbody>
</table>

4% Silicon No Graphite

| % Si | % C | t_1 (mm) | F_C | F_T | | |
| 4 | 0 | .033 | 160 | 83 | 1.02 | .41 | 3.28 |
| 4 | 0 | .069 | 304 | 171 | 1.05 | .45 | 2.98 |
| 4 | 0 | .137 | 400 | 250 | 1.12 | .51 | 1.97 |
| 4 | 0 | .272 | 560 | 333 | 1.22 | .48 | 1.39 |

16% Silicon 8% Graphite

| % Si | % C | t_1 (mm) | F_C | F_T | | |
| 16 | 8 | .033 | 64 | 33 | 1.15 | .41 | 1.31 |
| 16 | 8 | .069 | 88 | 46 | 1.21 | .42 | 1.65 |
| 16 | 8 | .137 | 144 | 79 | 1.34 | .44 | .71 |
| 16 | 8 | .272 | 208 | 104 | 1.36 | .39 | .52 |

4% Silicon 6% Graphite

| % Si | % C | t_1 (mm) | F_C | F_T | | |
| 4 | 6 | .033 | 48 | 29 | 1.14 | .49 | .98 |
| 4 | 6 | .069 | 88 | 50 | 1.18 | .46 | .86 |
| 4 | 6 | .137 | 176 | 79 | 1.20 | .34 | .87 |
| 4 | 6 | .272 | 224 | 104 | 1.29 | .36 | .56 |
The following show SEM micrographs of machined surfaces and chips:

Fig. 202 12Si, Machined surface.
Fig. 203 12Si, Chip from machining.
Fig. 204 12Si 6C, Machined surface.
Fig. 205 12Si 6C, Chip from machining.
Fig. 206 16Si, Machined surface.
Fig. 207 16Si, Chip from machining.
Fig. 208 16Si 2C, Machined surface.
Fig. 209 16Si 2C, Chip from machining.

9.10 Castings Produced to Assess Reproducibility of Results (as in 6.4.4)

Hardness testing: (Brinell)

TABLE 61: 8Si 4C (Impression dia (mm))

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Av</th>
<th>BHNo.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Casting</td>
<td>4.5</td>
<td>4.5</td>
<td>4.4</td>
<td>4.47</td>
<td>45.3</td>
</tr>
<tr>
<td>Repeat No.1</td>
<td>4.4</td>
<td>4.5</td>
<td>4.6</td>
<td>4.50</td>
<td>44.6</td>
</tr>
<tr>
<td>Repeat No.2</td>
<td>4.3</td>
<td>4.7</td>
<td>4.7</td>
<td>4.56</td>
<td>43.2</td>
</tr>
</tbody>
</table>

TABLE 62: 16Si 4C

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Av</th>
<th>BHNo.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Casting</td>
<td>4.1</td>
<td>4.0</td>
<td>4.2</td>
<td>4.10</td>
<td>54.3</td>
</tr>
<tr>
<td>Repeat No.1</td>
<td>4.1</td>
<td>4.0</td>
<td>3.9</td>
<td>4.00</td>
<td>57.2</td>
</tr>
<tr>
<td>Repeat No.2</td>
<td>4.0</td>
<td>4.1</td>
<td>4.0</td>
<td>4.03</td>
<td>56.2</td>
</tr>
</tbody>
</table>
Tensile testing: (KN)

**TABLE 63 : 8Si 4C**

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Av</th>
<th>U.T.S. MN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Casting</td>
<td>1.75</td>
<td>1.80</td>
<td>1.70</td>
<td>1.75</td>
<td>108</td>
</tr>
<tr>
<td>Repeat No.1</td>
<td>1.70</td>
<td>1.60</td>
<td>1.70</td>
<td>1.66</td>
<td>103(4.6%)</td>
</tr>
<tr>
<td>Repeat No.2</td>
<td>1.75</td>
<td>1.85</td>
<td>1.70</td>
<td>1.77</td>
<td>110(1.8%)</td>
</tr>
</tbody>
</table>

(ERROR)

**TABLE 64 : 16Si 4C**

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Av</th>
<th>U.T.S. MN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Casting</td>
<td>1.85</td>
<td>1.75</td>
<td>1.90</td>
<td>1.83</td>
<td>114</td>
</tr>
<tr>
<td>Repeat No.1</td>
<td>1.90</td>
<td>1.90</td>
<td>1.95</td>
<td>1.92</td>
<td>119(4.2%)</td>
</tr>
<tr>
<td>Repeat No.2</td>
<td>1.70</td>
<td>1.85</td>
<td>1.90</td>
<td>1.82</td>
<td>113(0.9%)</td>
</tr>
</tbody>
</table>

(ERROR)

**TABLE 65 : ELONGATION (%)**

<table>
<thead>
<tr>
<th>ORIGINAL</th>
<th>REPEAT No.1</th>
<th>REPEAT No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>16Si 4C</td>
<td>3</td>
<td>2.7</td>
</tr>
<tr>
<td>8Si 4C</td>
<td>5</td>
<td>4.7</td>
</tr>
</tbody>
</table>
### TABLE 66: REDUCTION IN AREA (\%)

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Repeat No.1</th>
<th>Repeat No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>16Si 4C</td>
<td></td>
<td>3</td>
<td>4.0</td>
</tr>
<tr>
<td>8Si 4C</td>
<td></td>
<td>5</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Three microstructures, (a, b and c) taken at random from each casting are shown as follows:

- Fig. 210  8Si 4C  Original
- Fig. 211  8Si 4C  Repeat No.1
- Fig. 212  8Si 4C  Repeat No.2
- Fig. 213  16Si 4C  Original
- Fig. 214  16Si 4C  Repeat No.1
- Fig. 215  16Si 4C  Repeat No.2
CHAPTER 10 - OBSERVATIONS OF RESULTS - COMPOSITE ALLOY PRODUCTION.

10.1 Production by Vortex Technique.

10.2 Composite Alloy Production by Compocasting.

10.2.1 Evaluation of the Compocasting Unit as a Slurry Producer.

10.2.2 Determination of the Optimum Conditions for the Addition of Graphite to 8.25% silicon alloy.

10.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be Obtained.

10.2.4 Determination of the Relationship between Shear Rate, Graphite Content and Viscosity.

10.2.5 Investigation of Graphite Rejection.

CHAPTER 11 - OBSERVATIONS OF RESULTS - COMPOSITE ALLOY EVALUATION.

11.1 Microstructures and Macrostructures of Castings with Various Silicon and Graphite Contents.

11.2 Tensile Testing of Castings with Various Silicon and Graphite Contents.

11.3 Hardness Testing of Castings with Various Silicon and Graphite Contents.

11.4 Wear Testing.

11.4.1 Reciprocating Diamond Scratch Tests.

11.4.2 Pin on Disc Tests.

11.5 Use of Electron Optical Techniques to Study the Fracture Surfaces and Worn Surfaces of Composites.

11.6 Chemical Analysis.

11.7 Fatigue Testing.

11.8 Corrosion Testing.

11.9 Machinability Testing.

11.10 Castings Produced to Assess Reproducibility of Results.
CHAPTER 10

OBSERVATIONS ON RESULTS - COMPOSITE ALLOY PRODUCTION

10.1 PRODUCTION BY VORTEX TECHNIQUE.

(Results 8.1).

The results obtained indicate uniformity in the distribution and wetting of the nickel coated graphite particles by the LM30 alloy (Fig. 60). The microstructures (Figs. 58 and 59) show particles of graphite in the interdendritic regions of the matrix and large particles of primary silicon throughout the structures. Tensile test results show substantial decreases in strength with increasing graphite content (Tables 1 and 2, 8.1). Specimens produced by squeeze casting, recovered some of the losses in strength and ductility resulting from graphite inclusions. The squeeze cast specimens with 2% wt graphite addition have a similar U.T.S. to the gravity die cast specimens without graphite addition. Reductions in the tensile strength of the composites are accompanied by corresponding reductions in ductility indicated by elongation and reduction in area results.

During production by the vortex technique, the viscosity of the melt can be observed to increase with increasing graphite content. A melt of about 1 kg requires stirring for about 15 minutes to successfully disperse an addition of 8% wt. nickel coated graphite particles. When it is attempted to add particles more quickly, the vortex becomes clogged and the nickel coating on the particles dissolves before the stirring action can disperse them. This results in rejection of the particles.
10.2 COMPOSITE ALLOY PRODUCTION BY COMPOCASTING.

10.2.1 Evaluation of the Compocasting Unit as a Slurry Producer. (Results 8.2.1).

Figures 61 and 62 show the structures of 8.25% wt silicon-aluminium alloy cast from above the liquidus. Figure 61 shows a dendritic, sand cast structure whilst Figure 62 shows the more equiaxed structure of the gravity die casting.

The structure in Figure 63 is that of 8.25% silicon alloy subjected to a modest rate of agitation whilst held at a temperature between solid and liquid with 31% volume solid. The primary particle size is large and the shape is more spherical than that of the primary particles in Figure 62.

Figures 64 and 65 show structures of 8.25% silicon alloys produced by semi-solid processing. Volume solid was 23% and, the rates of agitation (shear rates) were 190 and 270 sec\(^{-1}\) respectively. When compared to Figure 63 the primary particle size can be seen to be smaller. The specimen produced with a shear rate of 190 sec\(^{-1}\) exhibits "rosette" shaped primary particles. The specimen produced with the higher shear rate shows fewer "rosette" formations and a slightly finer primary particle size.

For comparison, Figure 66 shows a specimen produced with a shear rate of 500 sec\(^{-1}\). There is further refinement of primary particle size and coarsening of the eutectic phase.

Figure 67 shows a specimen produced under similar conditions to Figure 66 except that the specimen was isothermally held after agitation. The primary particle size is larger and there are
interlocking rosette formations.

During production of the specimens, differences in the viscosities of the slurries were noted. Viscosity of a 31% solid specimens sheared at 90 sec$^{-1}$ is very high, making flow very difficult. Increasing shear rate results in reduced viscosity. Reducing volume solid reduces viscosity and also slows down the rate of increase in viscosity when stirring is ceased. The viscosity of isothermally held specimens increases with time.

10.2.2 Determination of the Optimum Conditions for the Addition of Graphite to 8.25% Silicon Alloy.

The microstructures in Figures 68-71 show 8.25% wt silicon alloy with 0%, 2%, 4% and 6% wt graphite particle additions respectively. Figure 68 shows similar primary particle size and coarseness of eutectic to that shown in Figure 67 which was produced under similar conditions.

Figure 69 shows a similar microstructure with the addition of 2% wt uncoated graphite particles ranging in size between 10 μM and 120 μM. The microstructures in Figures 70 and 71 have higher graphite contents but differences in graphite content are not detectable from these results.

Figure 72 shows a microstructure produced from 8.25% silicon alloy with a lower (16%) volume solid. There is evidence of a larger proportion of eutectic solid in the structure. The distribution of graphite particles in Figure 73 can be seen to be uniform with no evidence of areas of high or low graphite concentration.
During production of the composites, viscosity was observed to vary according to graphite content, shear rate and volume solid. Increasing graphite content increases viscosity for a given shear rate and volume solid. To maintain a viscosity low enough for casting with higher graphite contents it is necessary to increase shear rate or reduce initial volume solid in the alloy. Tables 7-11 (8.2.2) indicate suitable combinations of graphite content, shear rate and initial volume solid for satisfactory casting. This observation is interpreted graphically in Figure 74.

When attempting to add graphite particles to 8.25% wt silicon alloy slurries with 5% initial volume solid or less, the particles are rejected from the melt.

Table 4 (8.2.2) shows that tensile strength is lower in the alloys with added graphite. A significant decrease in tensile strength is related to increasing initial volume solid in the alloy slurry. In comparison with the non-graphitic control specimen, Tables 5 and 6 show that ductility is impaired in the graphitic alloys.

10.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be Obtained.

(Results 8.2.3)

Table 12 (8.2.3) shows that the lowest die temperature (180°C) allows production of a composite with the highest ultimate strength. However, this is accompanied by a very poor surface texture on the casting. Surface texture is considerably improved by increasing die temperature but this incurs a small reduction in tensile strength and hardness.

The results in Table 13 (8.2.3) indicate that the pressure
applied during the completion of solidification has little effect on the tensile strength, ductility, hardness and surface texture of castings produced, within the range of pressures considered (7-21 kg/mm²) for the casting shape used in this investigation.

10.2.4 Determination of the Relationship between Shear Rate, Graphite Content and Viscosity.

(Results 8.2.4).

The results in 8.2.4 show that the viscosity of the semi-solid slurry is lower at high shear rates. When graphite is added, the viscosity increases by an amount which is directly related to the amount of graphite added, provided that the initial volume solid in the alloy slurry is maintained constant. (Table 21).

From Figure 76 it can be seen that the maximum limiting viscosity which maintains a slurry suitable for casting is 45 Poises. This confirms the observations presented graphically in Figure 74 because the limiting values of viscosity occur at similar shear rates, volume solid and graphite contents.

Comparison with the results on determination of optimum conditions for addition of graphite (8.2.2) reveals that the slurries with low viscosity produce microstructures with the smallest primary particles and the largest proportions of eutectic solid. For example, the microstructure in Figure 66 was produced with a volume solid of 23% and shear rate 500 sec⁻¹ which is a combination that gives a viscosity of approximately 4 Poises (Figure 76). Slurries with higher viscosities have lower shear rates and/or higher volumes solid and produce microstructures with
larger primary particle sizes and lower proportions of eutectic.
There are also more "rosette" formations.

10.2.5 Investigation of Graphite Rejection.

(Results 8.2.5).

The results in 8.2.5 show that when graphite rejection occurs:

i) Graphite is rejected from the melt sheared with any volume fraction solid in the semi-solid range.

ii) Shear rate has no effect on whether graphite is rejected or not.

iii) Contamination of the graphite particles has been eliminated by changing the source from which they originated.

iv) Contamination of the refractories has been eliminated by replacing them.

v) During the production of aluminium-silicon alloys for compocasting, alloys which accept graphite addition exhibit a concave meniscus and the sides of the crucible are wetted. (Figure 92). Alloys which reject graphite additions have a convex meniscus and do not wet the crucible. (Figure 91).

Analysis of elements (Figures 78-81) shows the presence of sodium in samples which accept graphite (Figures 80 and 81). Chlorine is present in all the results. Further evidence of the presence of sodium is shown by the modification of eutectic in microstructures containing graphite. (Figures 84 and 85).

Addition of chlorine to melts by the use of chlorine based
degassing tablets results in instant graphite rejection and no indication of sodium in the melt (Figure 86). Figure 95ii also shows that the rotor is not wetted by a chlorine degassed melt, addition of a small quantity of sodium allows the melt to accept graphite particles and promotes wetting of the stirring rotor (Figure 95i). Use of sodium addition and chlorine degassing results in graphite rejection (Figure 88). The addition of 0.5% wt. magnesium to melts allows graphite acceptance more readily than sodium addition.

There is some indication of chlorine contamination in the LMO melting stock used in the production of the aluminium-silicon alloys.

The results show that heating the alloy to 900°C and holding for 15 minutes produces an alloy which accepts graphite.

To summarise the results, the surface tension properties of the alloys which accept graphite differ to those which reject graphite. Where there is a concave meniscus, graphite is accepted. Where there is a convex meniscus graphite is rejected. There is evidence to suggest that a convex meniscus is accompanied by a chlorine content and an absence of sodium or magnesium in the melt.
CHAPTER 11

OBSERVATIONS ON RESULTS - COMPOSITE ALLOY EVALUATION

11.1 MICROSTRUCTURES AND MACROSTRUCTURES OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.

(Results 9.1).

Figures 96-101 show the 16% silicon alloy with 0%, 2%, 4%, 6% and 8% wt graphite additions respectively. Primary silicon polyhedra and dispersed graphite particles are present in all the microstructures. Figure III shows a vertical section macrostructure through a 16% silicon casting with 4% graphite addition and displays an even distribution of particles. However, on the microscopic level there appears to be some evidence of clustering of graphite particles. Individual areas of graphite do not appear to be larger than the mesh size of 150 μM, and so it would appear that the matrix is in contact with each individual grain and that they are not adhering to each other. Graphite particles within the microstructures of the 16% silicon alloy appear to have migrated to form clusters but the macrostructure (Figure III) shows that these clusters are well dispersed throughout the casting.

Figure 100 shows a graphite particle in the matrix at a higher magnification. Although the particle is of irregular shape, the matrix is in intimate contact with it along the whole of its boundary. Such intimate contact is not so evident in castings which were not squeeze cast (see 8.2.2.)
Figures 102-105 show the 12% silicon alloys and composites. Figure 102 is not typical of the base alloy structure but is an area which illustrates a typical structure of an alloy produced by semi-solid processing. The primary aluminium particles are spheroidal in shape.

Figure 103 shows the fine, slightly dendritic microstructure of a 12% silicon alloy which has been squeeze cast from a temperature above the liquidus. The primary dendrites have become refined which contrasts with structures produced by semi-solid processing in which the primary particle size is considerably coarser.

Figures 104 and 105 show the structures of the 12% silicon alloys with dispersed graphite particles. Primary silicon particles and primary aluminium particles are present.

In general, there are indications of a lack of consistency in the microstructures produced from 12% silicon alloys. There is evidence of wide variations in primary particle sizes and coarseness of eutectic.

The 8% silicon alloys (Figures 106-108) reflect the microstructures of the similar 8.25% silicon alloys observed in 5.2.2. Vertical and horizontal section macrostructures (Figure 112) indicate no evidence of graphite free areas resulting from graphite particle flotation or agglomeration.

The microstructures of the 4% silicon alloys reflect the larger volume solid which was present in the semi-solid processing stage. There is also a tendency to form rosette structures.
11.2 **TENSILE TESTING OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.**

(Results 9.2).

The tensile tests results shown in Tables 1-4 (9.2), and graphically in Figure 113, show reductions in UTS and ductility resulting from the addition of graphite particles to aluminium-silicon alloys. The reductions apply at all silicon contents.

Figure 114 shows the variation in U.T.S. with silicon content. The maximum strength of the ungraphitised alloys occurs at the near eutectic composition of 12% silicon. There is a marked reversal of this when observing the graphitised alloys where the 12% silicon alloys suffer proportionally greater reductions in UTS for given graphite contents. The addition of 8% wt graphite particles to the 12% silicon alloy results in an 80% reduction in tensile strength. The corresponding reductions for 4%, 8% and 16% silicon alloys are 50%, 60% and 64% respectively.

The reductions in the tensile strengths of the 4%, 8% and 16% silicon alloys are proportional to the quantity of graphite particles added.

Substantial reductions in elongation and reduction in area occur in graphitised alloys. This shows that ductility in the alloys is substantially reduced with virtually any of the graphite additions considered.

The gravity die cast control specimens (Tables 5 and 6) show similar trends in tensile properties for given silicon contents to ungraphitised specimens produced by semi-solid processing and squeeze casting. The latter have consistently higher tensile strengths.
11.3 HARDNESS TESTING OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.

(Results 9.3).

The results in Table 7 (9.3) show that hardness is reduced with increasing graphite content.

In general, the hardness values follow a similar trend to the tensile strength values. (See 9.2). The hardest specimen contains 12% silicon without added graphite. Specimens with added graphite show greater losses in hardness with increasing graphite content in the 12% silicon alloys than in 4%, 8% and 16% silicon alloys. However, the effect on the results from hardness tests was less extreme than the effect on the ultimate tensile strength.

11.4 WEAR TESTING.

11.4.1 Reciprocating Diamond Scratch Tests.

The graphs in Figures 115-118 show the effect of a 6% wt addition of graphite particles to 4%, 8%, 12% and 16% silicon alloys on abrasive wear properties under 5 and 10 kg loads. (The 6% graphite content was chosen as being representative of all the graphite contents considered). Silicon content has a significant effect on reducing wear volume, particularly at higher loads. The 16% silicon (hypereutectic) alloy is particularly significant in reducing wear volume under the high load (10 kg). For example, wear volume is reduced by 58% when compared with the 4% silicon alloy under a 10 kg load after 10 strokes. However, when tested under a 5 kg load the 12% silicon alloy offers minimum wear volume.
Figures 115-118 and Tables 15-19 (9.4.1) show that a 6% wt addition of graphite particles in the alloys has no marked effect on wear volume. All results fall into a similar range to the ungraphitised alloys. However, the presence of graphite particles in the alloys allows some tests to be continued for a greater number of strokes. Alloys of 4%, 8% and 12% silicon without graphite addition all suffered severe chatter which resulted in the need to terminate the tests well before 500 strokes.

Figures 119 and 120 show that the relative amounts of graphite present in the alloys has little effect on the wear volume. Additions of 2%, 4% and 8% wt graphite particles to alloys all appear to yield similar wear volumes to the base alloys when tested under similar conditions.

Tables 17-19 show that there is a tendency towards a constant wear volume after a certain number of strokes (under low loads) which prevails for any further number of strokes.

11.4.2 Pin on Disc Tests.

i) Change in Pin Length: Figures 121 and 122 illustrate the change in length of the wear pin during the pin on disc test. This is evidence of transition from a mild rate of wear to a severe rate of wear when load is increased. This is indicated by a steep increase in the gradient of the graph or complete failure of the pin. The loads at which transitions occur for ungraphitised alloys are between 7.8 kg and 12.6 kg for the 4% silicon alloy and between 12.6 kg and 17.2 kg for the 8%, 12% and 16% silicon alloys.
When comparing the transition loads of graphitised specimens, it can be seen that 8% wt graphite addition has no significant effect but 2% wt graphite addition to the 4%, 12% and 16% silicon alloys allowed the mild rate of wear to be continued to higher loads.

Four wear characteristics can be observed from the results of pin-on-disc testing. Steady wear is wear at a mild rate which does not increase during the course of a test. This type of wear is characteristic of all pins at 3.25 kg and 7.8 kg loads.

Rapid wear, which is a severe rate of wear, occurs when the pin fails during a test and in some cases may result in pin material being deposited on the disc. This type of wear is characteristic of ungraphitised pins tested under a 17.2 kg load. Figures 144 and 145 show the effects of an extreme case.

Figures 146 and 148 show step wear. This characteristic can be observed during the test and is illustrated by cyclic changes in the rate of loss of pin length. The frequency of the changes may vary considerably in different tests. This type of wear appears when the transition load is approached.

Alteration wear occurs when the type of wear is altered from mild to severe wear during the course of the test. (Specimens which exhibit such an alteration have been considered to have exhibited severe wear throughout the test.) The rates of severe wear may vary considerably between a sudden steepening of the change in pin length curve and complete instantaneous catastrophic failure of the pin. Schematic and actual examples are shown in Figures 147 and 149 respectively.
ii) **Coefficient of friction:** The results in Tables 24-27 (9.4.2) and Figures 123 and 124 show that the coefficient of friction between the pin and the disc is lower for alloys which contain graphite particles. Figure 124 shows an exception to the trend. The 4% silicon alloys under 12.6 kg loads exhibit an increased coefficient of friction. This is accompanied by a higher rate of loss of pin length. In tests which characterise step wear, the higher rates of loss of pin length are accompanied by a higher coefficient of friction (Figure 148).

iii) **Pin temperature rise:** The pin temperature rise, measured at a distance of 3 mm from the wear interface, shows trends comparable with the coefficient of friction results. The presence of graphite particles results in reduced steady temperatures. In tests which exhibit step wear, high coefficient of friction peaks accompany high temperature peaks.

Pin temperature rises are higher in higher load tests.

iv) **Surface texture:**

a. **Surface texture of the pins after wear tests:** The surface roughness (Ra value) of the pins is lower for specimens which contain graphite particles than for similar pins of the matrix alloy. The effect is emphasised at the higher load of 12.6 kg (see Tables 32 and 33, 9.4.2). The surface profile graphs of the specimens (Figures 130-137) also show smoother surfaces on the pins containing graphite by illustrating considerably smoother surfaces. The depths of the surface valleys can be seen to be lower. However, the
graphitised alloys exhibit more peaks and valleys for a given length of surface. This is accompanied by a slight deterioration in bearing ratios (see Tables 34 and 35, 9.4.2, and Figures 138 and 139).

b. Surface texture of the disc after wear tests: The surface texture of the disc after tests with graphitised pin specimens is superior to that after tests with specimens of matrix alloy (Tables 36 and 37). This applies to both 7.8 kg and 12.6 kg load tests. There is no significant difference in the bearing ratios of the disc, after tests with graphitised and ungraphitised alloys, (Figures 142 and 143).

v) Weight losses: In general, the weight losses in Tables 40-43 (9.4.2) show similar trends to the results for "change in pin length". There is some evidence to suggest that weight loss was reduced with an increase in graphite content.

vi) Tests to establish repeatability of results: The results of the statistical "t" test applied to paired observations show that the discrepancies in the sample of twelve retests were not significant. This indicates that there is no evidence to suggest that any errors within the original tests are not within the bounds of experimental error.

11.5 USE OF ELECTRON OPTICAL TECHNIQUES TO STUDY FRACTURE SURFACES AND WORN SURFACES.

i) Fracture surfaces: In general, the results of the SEM
analysis show largely brittle fractures for all the composites and alloys. The 4% and 8% silicon alloys show some evidence of a more ductile fracture with some cup-like depressions (dimples) (Figures 150 and 154). Cleavage fractures appear to be indicated by cleavage steps and feathers, river markings and cleavage tongues in most of the SEM micrographs of the ungraphitised alloys. Combined intercrystalline fracture and cleavage fracture is indicated in the graphitised specimens by crystal boundary facets in addition to cleavage features.

In the graphitised alloys (e.g. Figure 161) fracture appears to be accompanied by the removal of graphite from the matrix, as holes can be observed in most of the graphitised specimen fracture surfaces. Figure 164 shows an exception where a particle of graphite appears to have sheared. The particle appears to be locked in position by what are probably primary silicon polyhedra.

The graphitised 12% silicon alloys Figures 159-161 appear to exhibit a smoother fracture surface.

ii) Worn surfaces: The SEM micrographs of specimens from the reciprocating diamond scratch tests (Figures 166 and 167) show evidence of delamination in the form of plates on the wear surface produced by the ploughing action. The graphitised specimen (Figure 167) shows that in addition to plate-like formations, there are areas where plates have been torn away indicating a greater degree of abrasion and lower ductility. The ungraphitised specimen (Figure 166) shows a higher amount of deformation, less fracture and the initiation of fewer cracks.
SEM micrographs of pin surfaces after pin-on-disc tests under a 3.25 kg load (Figures 168-183) and at low magnification show that wear takes place by flattening the asperities of the surface and forming regular grooves and lines which are characteristic of abrasion. The area of flattened asperities decreases with increasing silicon content, up to the eutectic composition, (Figure 176). This coincides with the minimum loss of change in pin length (see 9.4.2). At higher magnifications, cracks are apparent in the worn asperities. The cracks are larger in the ungraphitised specimens and it appears that material is beginning to break away in plate-like form, indicating the initiation of delamination. The cracks in the graphitised specimens are less severe and there is less evidence of material becoming broken away from the asperities. Cracks in the worn asperities of the graphitised 12% and 16% silicon alloys are difficult to detect.

Figures 184 and 186 show the effects of a higher load of 7.8 kg. The features are similar to those described above except that plates have apparently become completely detached from the non-graphitised alloys and the cracks in the graphitised alloy are more severe than with similar alloys under 3.25 kg load.

Figures 185 and 187 show the effects of a further increase in load to 12.6 kg. Material has been torn from the wear surfaces with no evidence of wear being confined to asperities. There are voids in the surface of the graphitised specimen which may have been occupied by graphite particles. This type of surface is common to specimens which exhibit a severe rate of wear. Figure 188 shows an extreme case. The profile of this surface (Figure 130) shows
deep grooves but the micrograph indicates that the peaks have fractured and wear has taken place across the whole surface and fracture of material from the base of the valleys has occurred. Figures 190, 191, 194, 195 and 197 and their respective surface profiles indicate a similar effect but there is evidence to suggest less fracture on the surfaces of those specimens with higher silicon contents. The presence of graphite appears to promote fracture in many more areas but at a lower depth. This supports the evidence of smoother surfaces indicated by the profiles of graphitised specimens.

Figures 189, 192, 193 and 196 show the wear surfaces which exhibited step wear resulting in the loss of material in discrete steps. Figures 189 and 192 show the surfaces of specimens which were removed from the wear test when the coefficient of friction was high. When coefficient of friction is at this high part of the cycle, tongue shaped plates appear to form in the direction of sliding. Figures 193 and 196 show specimens which were removed at the other extreme of the cycle, (i.e. coefficient of friction low). Here, the tongue shaped plates appear to have fractured from the surface.

Wear debris shown in Figures 198-200 appears to show that the wear debris from the ungraphitised hypereutectic specimen takes the form of smooth irregular particles (2 - 9 μM) with occasional small laminates. The graphitised alloys appear to indicate a wider range of particle sizes (3 - 25 μM) with larger plate-like formations which may be thinner in section.
ESCA Studies: Tables 45 and 46, (9.5) show the surface elements in the graphitised specimens to consist mainly of carbon, oxygen and aluminium. With increasing depth, oxygen content is reduced and carbon content increased.

Tables 47 and 48 (9.5) show the surface elements in the worn ungraphitised alloys. The above trend is reversed. Oxygen content is increased with depth and carbon content is reduced. There is also a larger proportion of silicon present.

11.6 CHEMICAL ANALYSIS.

(Results 9.6)

i) Table 49 (9.6) indicates that the procedure for the manufacture of the 8.25% silicon alloys yields silicon contents close to the nominal composition. There is no evidence of significant traces of contamination by the elements considered.

ii) Table 50 (9.6) shows the chemical analysis for the experimental alloys (see 7.3.6). The silicon contents are close to the nominal compositions. The graphite contents, although in the correct order, are all lower than expected.

iii) Table 51 (9.6) shows the analysis carried out by the revised technique (see 7.3.6). Graphite contents are, in some cases, higher but in general, the results are similar to those in Table 50.

iv) Quantitative Metallography by Quantimet areal analysis reveals average graphite contents are close to the nominal additions
(Table 52). Analysis of the composition of a casting section (Table 53) reveals that there are variations in graphite content within a casting, but on average the content is close to the nominal addition.

v) Lineal analysis (which is statistically more reliable than areal analysis) indicates results close to areal analysis (Table 54).

11.7 FATIGUE TESTING.

(Results 9.7).

Table 55 (9.7) shows that the fatigue life of the composites subjected to rotating bend type load is impaired by both increasing silicon content and increasing graphite content. The specimens with the highest ductility exhibit the longest fatigue lives.

11.8 CORROSION TESTING.

(Results 9.8).

The results in Tables 56-58 (9.8) show that there is no increase in the tendency of aluminium-silicon alloys to corrode under the conditions considered.

11.9 MACHINABILITY TESTING.

(Results 9.9).

The results in Table 59, (9.9) show that specimens with added graphite particles exhibit considerably lower tool forces than the matrix alloys and improved machinability index. Surface finish as measured by Ra. is also improved. However, the bearing ratio appears
to be slightly inferior. Coefficient of friction between the tool and the work is reduced which results in a lower specific cutting power.

Table 60 shows that improvements in machinability due to graphite inclusions are not dependent on the feed used. However, machinability improves when feed rate is increased. The improvement is greater in ungraphitised alloys. The 16% silicon alloy allows a higher feed rate than any of the graphitised alloys.

Figures 202, 204, 206 and 208 show machined surfaces of graphitised and ungraphitised alloys. The finer surfaces of the graphitised alloys indicate a smooth deformation and detachment of the chip. The chips in Figures 203, 205, 207 and 209 indicate that graphite in the alloy promotes a greater degree of chip fragmentation and ease of shear from the workpiece.

11.10 CASTINGS PRODUCED TO ASSESS REPRODUCIBILITY OF RESULTS.

Tables 61-66 indicate that results of hardness, U.T.S., elongation and reduction in area are reproducible in three independently produced castings of both 8% silicon with 4% added graphite and 16% silicon with 4% added graphite.

The microstructures in Figures 210-215 indicate there are no substantial variations in structure between the repeated and original castings.
CHAPTER 12 - DISCUSSION - COMPOSITE ALLOY PRODUCTION.

12.1 Production by the Vortex Technique.

12.2 Composite Alloy Production by Compocasting.

12.2.1 Evaluation of the Compocasting Unit as a Slurry Producer.
12.2.2 Determination of Optimum Conditions for the Addition of Graphite to 8.25% Silicon Alloy.
12.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be Obtained.
12.2.4 Determination of the Relationship between Shear Rate, Graphite Content and Viscosity.
12.2.5 Investigation of Graphite Rejection.

CHAPTER 13 - DISCUSSION - COMPOSITE ALLOY EVALUATION.

13.1 Microstructures and Macrostructures of Castings with Various Silicon and Graphite Contents.

13.2 Tensile Testing of Castings with Various Silicon and Graphite Contents.

13.3 Hardness Testing of Castings with Various Silicon and Graphite Contents.

13.4 Wear Testing and S.E.M. Studies.

13.4.1 Reciprocating Diamond Scratch Tests.
13.4.2 Pin on Disc Wear Test.

13.5 Chemical Analysis.

13.6 Fatigue Testing.

13.7 Corrosion Testing.

13.8 Machinability Testing.

13.9 Castings Produced to Assess Reproducibility of Results.
CHAPTER 12

DISCUSSION - COMPOSITE ALLOY PRODUCTION

12.1 PRODUCTION BY THE VORTEX TECHNIQUE.

Figures 58 and 59 show graphite particles between the primary polyhedral β particles in the LM30 hypereutectic alloy. This, with the results in 8.1, indicates that wetting and a uniform distribution of nickel coated graphite is possible. Nucleation and growth of primary solid particles appears to be unaffected by the presence of dispersed graphite particles in the completely liquid alloy. The deterioration in strength and ductility (8.1, Tables 1 and 2) results from interruption of the continuous eutectic phase. Graphite is a soft, low strength material and so its inclusion has the effect of casting defects of voids reducing effective cross-sectional area. Therefore, an increase in graphite content results in the decrease in strength observed in 10.1.

Improved mechanical properties in squeeze-cast samples are primarily due to improved casting soundness. Casting defects such as gas porosity and shrinkage cavities do not occur in squeeze cast forms since self feeding is possible during solidification. Also, gases cannot come out of solution either, because of the applied pressure opposing gas nucleation (115). Use of the vortex technique requires a completely liquid alloy. This allows refinement of all microstructural features (Figure 58) because no part of the alloy is solid prior to solidification under pressure in the squeeze casting die. Consequently, structural refinement may also contribute to improved mechanical properties.
The nickel coating was necessary to impart wettability to the graphite particles. However, there is no evidence of a nickel rich area surrounding the particles in the microstructures and so it is possible that nickel went into solution and Ni Al₃ was formed. The formation of brittle Ni Al₃ has been reported by Surappa et al. (59) to contribute to the low ductility of composites produced by the vortex technique. Ni Al₃ takes the form of needle-like particles in microstructures. (No evidence of needle shaped particles has been found in this work but the magnification of the microstructures in Figures 58 and 59 may not be high enough to show this effect.) It is possible that needle-like particles resulting from nickel in the alloy could be confused with needle-like particles resulting from iron in the alloy. During this experimental work it was noted that a quantity of iron was dissolved in the alloy from the stirring impeller. Iron in aluminium alloys also causes embrittlement and so it is considered likely that a small quantity of iron in the alloy contributed to the low ductility results reported in 8.1.

In contemplating the suitability of the vortex technique for the production of aluminium alloy-graphite particle composites the following should be considered:

i) There is a need for expensive nickel-coated particles which adds to production costs. It should be noted that Krishnan et al. (60) claim that metallic coatings (when adding less than 3wt% graphite) can be precluded by subjecting uncoated graphite to a heat-treatment prior to introduction. However, this claim has not been investigated in this work.
ii) Observations (10.1) show that continuous stirring and rapid solidification are necessary to obtain a satisfactory distribution of particles and to avoid segregation. These problems result from a difference in density between the alloy and the particles, which causes the graphite to float resulting in areas of high graphite concentration at the top of castings. Also, a completely liquid alloy is unable to inhibit particle flotation because there are no suspended solid particles present to prevent movement of graphite particles.

iii) The process is extremely slow and requires close control to successfully introduce particles into the melt. If a high rate of dispersion is attempted, the vortex becomes clogged and rejection occurs. This is believed to be due to the nickel coating becoming dissolved before the particles can be dispersed by the stirrer.

iv) Inert gas shielding may be necessary to avoid oxidation due to the continually changing surface of the melt exposed to air. However, the results in this investigation were obtained without such a facility.

12.2 Composite Alloy Production by Compocasting.

12.2.1 Evaluation of the Compocasting Unit as a Slurry Producer.

The microstructures in Figures 61 and 62 were produced by casting fully liquid 8.25 wt % silicon alloy to provide control microstructures which could be compared to microstructures produced from partially solid alloys. Figure 61 represents an alloy solidified by sand casting and Figure 62 represents an alloy solidified by gravity die casting.
Sand casting caused a very slow cooling rate and so a branch-like dendritic structure was produced. The dendrites are large in size and few in quantity because slow solidification encouraged few nucleation sites and so allowed uninhibited dendritic growth of primary α. (Fig. 61). In comparison, the more rapidly cooled gravity die casting encouraged many more nucleation sites resulting in a finer structure with smaller dendrites and little branch-like growth of primary α. (Fig. 62).

The microstructures produced from agitated semi-solid alloys (Figures 63-67) show that the above structures have been changed during their solidification, by the stirring process. The dendrites have been physically broken up to form primary solid particles which are more spherical in shape. The higher the shear rate, the smaller the primary particles. Lower shear rates produce "rosette" formations which result from growth, merging and welding of the spheroidal primary particles during cooling. Rosette formations are not evident with higher shear rates (Figure 67) because high rates of agitation also result in the extraction of entrapped liquid from clusters of the primary particles. This is illustrated by a higher proportion of eutectic phase in the microstructure (Figure 66). This results in smaller primary particles and a greater separation between them and consequently, there is a reduced tendency for primary α particles to meet as they grow during the completion of solidification.

The viscosity of the agitated slurries has been observed to be at a minimum when there is the greatest proportion of liquid phase present in the semi-solid alloy. Therefore, lower viscosities
are obtained in alloys which possess a structure containing small spheroidal primary particles (e.g. Figure 66). The presence of large rosette shaped primary α particles, results in a high viscosity slurry even when high proportions of liquid phase are present. Therefore, high shear rates and low initial-volume fractions solid result in low viscosity slurries. The structures shown in Figures 63-66 illustrate these effects.

Figure 63 was produced with a high initial volume fraction solid and low shear rate and viscosity was observed to be high. Figures 64 and 65 were produced with lower initial volume fractions solid and higher shear rates and so primary particles are smaller and viscosity was lower. (The structure (Figure 64) with more "rosette" formations had a slightly higher viscosity). Figure 66 shows the alloy which had the lowest viscosity because the primary particles are smallest and there were no rosette formation to inhibit flow.

The above discussion assumes that the cooling rate during the completion of solidification was similar in all cases. This is a reasonable assumption because a standardised procedure was adopted for the production of all specimens. However, changes in cooling rate can result in significant changes in microstructures. The structure in Figure 67 was produced under identical conditions to that in Figure 66 (high shear rate), except that the alloy was held isothermally after agitation and before solidification. As a result there was an increase in viscosity with time which can be explained by growth, merging and welding of primary particles and entrapment of the liquid phase between them. This was not
possible in the time allowed for the completion of solidification of the structure in Figure 66, which was immediately gravity die cast. These principles are the basis of "thixocasting" (68). Cooling rate has a major effect on particle size due to an inverse power-law relationship (112).

12.2.2 Determination of Optimum Conditions for the Addition of Graphite to 8.25% Silicon Alloy.

Compocasting allows the inclusion of uncoated and untreated graphite particles in aluminium-silicon alloys without rejection or agglomeration. In comparison with the vortex technique, there is little tendency towards particle flotation and continued stirring is not necessary to avoid segregation. This is because the process makes use of the rheological properties of the partially solidified and vigorously agitated alloy slurry. The presence of solid particles in the alloy and a high effective viscosity prevent graphite particles from floating and agglomerating, because graphite is entrapped between primary particles, regardless of wetting. The stirring action ensures uniformity in the graphite distribution (Figure 73). However, temperature control is more critical. If the temperature is too low, the volume solid in the alloy is high, resulting in a viscosity which is too high for casting. If the temperature is too high, there are insufficient solid particles in the alloy to allow entrapment of graphite particles and rejection results.

The inclusion of graphite particles results in an increase in alloy slurry viscosity. This is due to an effective increase in the volume of solid in the alloy slurry. To maintain a viscosity
suitable for casting, the volume of solid must be reduced or shear rate increased. This is to reduce the effective amount of solid in the alloy slurry and to encourage the formation of small spherical primary particles which least inhibit flow. (See Figure 74).

For the purposes of this work, an in-depth analysis of the events at the graphite-matrix interface is considered to be beyond the scope of this investigation. However, from the information available, the likely nature of the bond between the graphite particles and the matrix is discussed because it may have some influence on the mechanical properties of the composites.

The bond could be one of six types classified by Metcalfe (71). These are:

i) Dissolution and Wetting bond where a contact angle of less than 90° occurs in wetting.

ii) Reaction bond where a new chemical compound is formed at the interface.

iii) Exchange Reaction bond. This is a special case of reaction bond in which two or more reactions may occur.

iv) Oxide bond where an oxide film exists at the interface and constitutes the bond.

v) Mechanical bond where all chemical sources of bonding are absent.

vi) Mixed bond which could be a combination of any of the above types.
In the aluminium-silicon graphite system, a bond based upon mechanical bonding is most likely because of the non reactive and non wetting nature of graphite in aluminium alloys. However, a purely mechanical bond is not feasible in this situation, in addition weak van der Waals forces will be present in all materials so that a condition where all chemical sources of bonding are absent can never be completely satisfied.

A significant dissolution and wetting bond is unlikely because the contact angle between aluminium and graphite is considerably larger than 90° (56). However, Pepper et al. (114) found that molten aluminium-silicon could wet graphite yarn if a pretreatment was used which was considered to remove contaminants from the graphite surface.

Reaction and exchange reaction bonds may be present on a small scale resulting from the transfer of atoms from one or both constituents, to the reaction site. Gorbunov et al. (4) state that this is the type of bond present between aluminium-silicon and graphite particles, but offer no evidence to support this. Reaction and exchange reaction bonds are unlikely to be present on a significant scale because the temperatures involved in the production process are not of the order required to promote the formation of compounds based upon the elements within the system.

Oxide bonds may be generated by wetting but could also include bonds where intermediate compounds form at the interface. Traces of oxygen may form an intermediate zone within a bond between matrix and particle. Metcalfe (71) has shown that bonding can be assumed to be between natural aluminium oxide films and oxide films on the other constituents of the composite by solution or
reaction. However, an oxide does not readily form on graphite, and so this type of bond is also unlikely.

Fracture surfaces examined with the SEM show holes which were probably vacated by graphite particles. (See Figures 155 and 161). There is no evidence of fractured graphite particles or deposits of graphite in the holes. This lends further evidence to the bond being largely based on mechanical entrapment of particles.

Mechanical bonds are considered to be less desirable than bonds involving a significant chemical contribution because their strength is inferior. From the results considered, there is little likelihood of significant bonding other than mechanical bonding, and so it has been assumed that there is no interaction between the graphite and its matrix, and that the bond makes no contribution to the strength of the composites. However, this assumption cannot be verified without a deeper analysis of the interface, perhaps involving T.E.M. and surface analysis to detect the interface conditions.

In common with aluminium-silicon-graphite composites produced by the vortex technique, compocasting leads to a deterioration in mechanical properties (8.2.2, Tables 3-6). This results from an interruption of the continuous eutectic phase. Graphite particles act as discontinuities and so effectively increase the number of voids and defects in the casting. A lack of strong graphite-matrix bonds probably exacerbates this situation.

There is a reduction in tensile strength resulting from larger initial volume solid in the semi-solid slurry during shearing. For example, the results show that an alloy sheared containing 23%
volume solid has a lower U.T.S. than an alloy sheared containing 16% volume solid. This is because alloys with lower volume solid contain a higher proportion of liquid. On solidification the eutectic phase is derived from the proportion of liquid which was present in the semi-solid slurry. The eutectic phase is the continuous phase and is stronger than the other constituents in the microstructure and so the overall strength of the alloy is related to the amount of continuous phase. Consequently, when a semi-solid alloy which contains a certain amount of liquid is solidified, its strength will be greater when the amount of liquid present during semi-solid processing is greater.

12.2.3 Production of Squeeze Castings from which Optimum Squeeze Pressure and Die Temperature could be Obtained. (Results 8.2.3).

From Table 12 (8.2.3), the lowest die temperature allowed the production of the composite with the highest ultimate strength. This is probably due to structural refinement resulting from a high rate of heat extraction from the cool die. There is unlikely to be refinement of the solidified primary particles because they have solidified before pressure can be applied, and so refinement of the structure is confined to the remaining liquid phase. Primary particles have a very short time to grow before the temperature is below the eutectic temperature so the higher strength alloy which results when using a cooler die is probably caused by there being a large proportion of eutectic solid which has a fine structure. However, the cooler sides of the squeeze casting die resulted in
rapid solidification of the skin of the casting with the result
that a certain amount of skin solidification had taken place before
the squeeze pressure could be applied. This produced an extremely
poor surface texture on the casting surface. Therefore, it was
considered that a higher die temperature should be used in future
work so that ultimate strength, hardness and surface texture could
be optimised. The die temperature chosen for future work was 300°C.

From this work, it appears that squeeze pressure within the
range considered, has little effect on the mechanical properties
of the casting for the shape used (Table 13, 8.2.3). However,
Williams and Fisher (77) report minimum consolidation pressures
for liquid metal which range between 30 – 250 MN/m² depending on
casting shape and volume to surface area ratio. In this work all
castings were produced at pressures within this range and there
were no significant variations in properties which implies that
there was little variation in microstructures. Therefore, the
concept of minimum consolidation pressure is reinforced.

12.2.4 Determination of the Relationship between Shear Rate,
Graphite Content and Viscosity.

Combinations of shear rates, volume solid and graphite content
which result in a viscosity of over 45 Poises appear to be unsuitable
for casting. Observations of viscosity (10.2.4) appear to reflect
the findings of Joly and Mehrabian (69) (who investigated partially
solid alloys with viscosities ranging between 3 and 80P). The
results in 8.2.4 serve to reinforce the concepts observed in 10.2.2
and discussed in 12.2.2. That is, that combinations of shear rate
and volume solid (or graphite content) which produce small spheroidal primary particles in the microstructures, produce semi-solid slurries with low viscosity. However, the size of graphite particles cannot be reduced by stirring action, and so for a given graphite content and initial volume solid, there is a minimum shear rate which will produce a viscosity suitable for casting (i.e. below 45P.). This is illustrated in Figures 74 and 76 and Table 21 (8.2.4). For example, a shear rate of 500 sec$^{-1}$ is required to produce a viscosity below 45 Poises with an initial volume solid of 22% and 8wt % added graphite particles.

The investigation into the relationship between shear rate, graphite content and viscosity shows that viscosity measurement allows changes in viscosity resulting from variations in set parameters to be quantified. However, although the results were all obtained under identical experimental conditions, the values obtained for viscosity may not be absolute for the following reasons:

i) The compocasting unit was not constructed with the tolerances necessary to ensure accurate viscosity measurements from a viscometer.

ii) The liquid zone was not considered in viscosity calculations. The effects on the torque required by the liquid and the semi-solid zones could not be separated. However, only the semi-solid zone has been considered in the calculations, and so the values obtained are slightly high because some torque was required to overcome resistance to the rotor turning in the liquid zone.
12.2.5 Investigation of Graphite Rejection.

Wetting of graphite particles by semi-solid aluminium-silicon alloys appears to be affected by the surface properties of the alloy slurries. (See 10.2.5).

Alloys which reject graphite particles exhibit a convex meniscus when liquid, and analysis shows that chlorine is present, with no evidence of sodium or magnesium. Deliberate addition of chlorine appears to result in instant rejection of graphite. (Badia and Rohatgi (57) observed a similar effect while using a chlorine degassing technique when adding graphite by the vortex technique).

Therefore, it is postulated that chlorine has an effect on the surface energy of the liquid phase in aluminium-silicon alloys which results in a considerably reduced tendency to wet graphite. The effect of chlorine may be removed by the addition of sodium or magnesium. This may be due to the formation of sodium chloride or magnesium chloride which is rejected from the melt and removed from the surface in the form of dross. Magnesium appears to be slightly more successful in this respect which could be due to magnesium forming a chloride more readily than sodium. However, this explanation cannot be verified from the results reported in this work.

Heating the melt to 900°C and holding prior to semi-solid processing is also thought to remove traces of chlorine by allowing it to be "burnt" out. However, heating to such high temperatures results in poor metallurgical properties and is not desirable.

Results show that chlorine contamination may have been
introduced into the LMO (99.6% aluminium) melting stock by the manufacturers who use a chlorine degassing technique. This chlorine was probably carried through when the aluminium-silicon alloys were produced.

Although the graphite rejection problem appears to be solved by the addition of 0.5wt % magnesium, the reasons for this are not confirmed by this work.
CHAPTER 13

DISCUSSION - COMPOSITE ALLOY EVALUATION

13.1 MICROSTRUCTURES AND MACROSTRUCTURES OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.

16wt % Silicon Alloys: Clusters of graphite particles can be viewed in the 16wt % silicon (hypereutectic) alloys (e.g. Figure 98). The macrostructure (Figure 111) shows that the clusters are dispersed throughout the alloy and so the tribological properties of the composites are unlikely to be affected by this type of segregation. There is no evidence of particles adhering to each other because individual areas of graphite in the microstructure do not appear to be larger than the mesh size of 150 μM. Therefore, the matrix is in contact with individual particles. Clustering may be due to the comparatively low amount of primary solid (β) present.

During semi-solid processing, more liquid phase was present than in the hypoeutectic alloys previously discussed (Chapter 12) as a result of the close proximity of the eutectic point to 16wt % Si on the phase equilibrium diagram. Therefore, there is an increased probability of graphite segregation because there are fewer primary solid particles to separate the graphite particles during the stirring operation.

Contact of the matrix with individual particles (rather than whole agglomerations) may result from infiltration of graphite particle agglomerations by the alloy as a result of the pressure applied during squeeze casting. The pressure applied may also enhance contact between graphite particles and the matrix because there is evidence (Figure 100) of intimate contact along the whole
of graphite particle boundaries. This should have the effect of improving the mechanical bond.

12wt % Silicon Alloys: Variations in the structures of the 12wt % silicon alloys may be explained by the very close proximity of the eutectic point to 12wt % silicon on the phase equilibrium diagram. A very short freezing range requires a very high degree of temperature control which is unlikely to have been obtained from the equipment used. This is because the semi-solid temperature range of the 12wt % silicon alloy is of a similar order to the accuracy to which the set semi-solid temperature can be achieved. (i.e. The set temperature was accurate to within 3°C, but the freezing range of the alloy was only 5°C.) Therefore, small variations in temperature within the set semi-solid temperature tolerance result in large changes in volume solid.

The presence of both α and β particles in the 12wt % silicon microstructures can be explained by the close proximity of the eutectic composition to 12wt % silicon on the equilibrium diagram (Figure 31). There may have been small composition variations in localised areas of the alloy which would have resulted in areas which could be either hypoeutectic or hypereutectic. Chatterjee and Das (115) have noted a shift in the eutectic composition due to the pressure applied during squeeze casting. This may also cause a transition from hypereutectic to hypoeutectic when casting alloys of near eutectic composition. Small variations in cooling rates between parts of the casting solidified close to the die wall and the centre of the casting can also cause variations in microstructures.
There is evidence of graphite clusters in the 12wt % silicon microstructures which are similar to those in the 16wt % silicon alloys. There were even fewer solid particles present in the 12wt % silicon alloys than in the 16wt % alloys previously discussed. Therefore the reasons for the clusters in the 12wt % silicon alloys are probably similar to those discussed under 16wt % alloys.

The difference in primary particle sizes between Figures 102 and 103 is caused because the structure in Figure 102 was produced by semi-solid processing and squeeze casting whilst the structure in Figure 103 was produced by squeeze casting a completely liquid alloy. Figure 102 shows that refinement of primary particle size is not possible if a sheared semi-solid alloy is squeeze cast. This is because the alloy is partially solid (containing primary β particles) before squeeze casting and so refinement is confined to the liquid phase, which is indicated by a fine eutectic structure. The accelerated cooling rate resulting from squeeze casting the completely liquid alloy results in a greater number of nucleation sites and so both phases in the structure become refined.

8wt % Silicon Alloys: The 8wt % silicon alloys (Figures 106-108) exhibit structures similar to those for the 8.25% silicon alloys discussed in 12.2.2, and so reflect reproducibility in the process. The longitudinal and transverse macrostructures (Figure 112) show an 8% silicon alloy with 4% graphite particles added. There is less evidence of segregation resulting from a poor distribution of graphite particles. There is a greater proportion of primary solid particles in the 8wt % silicon microstructures which results
from the composition being proportionally further from the eutectic composition than the 16wt % and 12wt % silicon alloys. This appears to aid the graphite particle distribution by reducing the areas of eutectic in the microstructure where graphite particles can be included, and hence encouraging the separation of graphite particles by primary particles.

4wt % Silicon Alloys: The microstructures of the 4wt % silicon alloys (Figures 109 and 110) reflect a further increase in the amount of primary solid to the extent where the primary particle phase has almost become the continuous phase. This appears to encourage graphite agglomeration by inhibiting movement of graphite particles around the primary solid particles within the liquid phase, which results in confinement to large, highly localised areas of eutectic. Agglomerations are confirmed by the size of the individual areas of graphite in the microstructures which are in excess of the maximum mesh size, indicating that particles are adhering to each other. The microstructure with graphite, (Figure 110) appears to indicate that the liquid phase has been forced into one small area, which causes the primary particles to move closer together.

13.2 TENSILE TESTING OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.

Graphite inclusions in aluminium-silicon alloys result in reduced tensile strength and ductility, (Tables 1-4, 9.2). This is due to the introduction of soft, low strength particles into
the continuous phase of the microstructures. (Strength is mainly derived from the continuous phase of the structure). In this case, the continuous phase, being eutectic is the strongest phase and so any interruption of this phase will result in significant deteriorations in overall U.T.S. Therefore, graphite particles may be considered to be voids or discontinuities in the cast structure which will inevitably result in a deterioration in mechanical properties by reducing average cross-sectional area, and providing cavities of irregular shape with small corner radii which become highly stressed areas that encourage crack formation.

SEM studies of fracture surfaces (9.5) confirm higher ductility in the hypoeutectic alloys which do not contain graphite by indicating fractures of a more ductile nature. This may be explained by primary α phase deformation which inhibits crack initiation and fracture in the continuous eutectic phase. Characteristic ductile fracture "dimples" (cup-like depressions) are visible on the ductile primary α phase in the hypoeutectic alloys without graphite shown in Figures 150 and 154. The fracture surfaces of all of the hypoeutectic alloys which contain graphite show fewer dimpled areas in comparison.

Hypereutectic alloys which do not contain graphite exhibit a less ductile fracture because they contain coarse primary β which is considerably less ductile than primary α. For example, Figure 162 shows the characteristic features of a brittle cleavage fracture.

In both hypoeutectic and hypereutectic graphite alloys,
There are voids in the eutectic phase (which were probably vacated by graphite particles during fracture) that are likely to have provided small internal radii from which cleavage cracks have initiated. For cleavage fractures it is known that crack growth along certain crystallographic planes leads to a brittle cleavage fracture. This is indicated by smooth areas separated by cleavage steps and feathers, river markings and cleavage tongues which are a result of crack path disturbances by phase boundaries and inclusions. Observations indicate evidence of this type of fracture (e.g. Figure 161). However, in general, the fracture surfaces indicate "mixed" fractures with a tendency towards much more brittle cleavage fractures in the continuous phases of alloys which contain graphite particles.

The greatest proportion of loss in U.T.S. due to graphite particle inclusions occurs in the 12wt % silicon alloys. (See Figure 113). The microstructures of these alloys show a very low amount of primary solid, (Figures 102-105), which is to be expected because the alloy is of near eutectic composition and so should consist largely of eutectic phase. This results in an alloy with low ductility because no discontinuous phases are present in significant amounts to stop crack propagation and fracture. Therefore, when strain is applied to a 12wt % silicon alloy containing graphite the voids containing graphite particles are not able to deform without fracturing the matrix, and so cracks tend to be initiated from small (highly stressed) radii within the void. The crack grows in the eutectic phase and is unlikely to be terminated unless a primary particle or inclusion is encountered. There are few primary particles of α or β and few inclusions which
form strong bonds with the eutectic phase. Therefore, cracks are easily propagated and likely to result in premature failure of the composite at a value of stress which may be considerably lower than the stress required to fracture a sound alloy of eutectic composition.

13.3 HARDNESS TESTING OF CASTINGS WITH VARIOUS SILICON AND GRAPHITE CONTENTS.

The reduction in hardness with increasing graphite content (see 4.3) is due to the inclusion of soft, low strength particles in the alloys which reduce the overall hardness of the composites. The reduction in hardness with increasing graphite content is confirmed by Gorbunov et al. (4) and Krishnan et al. (60) who independently report similar findings. Losses in hardness are accompanied by losses in tensile strength and can be explained by there being proportions of a comparatively soft, low strength material (graphite) in the alloy.

13.4 WEAR TESTING AND S.E.M. STUDIES.

The wear testing discussed in this section is considered with reference to the wear mechanisms described in 1.5 (Section A).

13.4.1 Reciprocating Diamond Scratch Tests.

Abrasive wear of the non-graphitised alloys appears to be slightly lower with the 12wt % silicon alloy than the 16wt % silicon alloy at low loads. However, the 16wt % silicon alloy is able to offer a higher load carrying capacity (Figures 115-120). (Sarkar (117) has reported a similar effect). This is likely to be due to the presence of primary silicon polyhedra in the hypereutectic microstructures. These particles are hard and resistant to abrasion and delamination, enabling the alloys to withstand higher loads without allowing the diamond to displace material in the form of chips, slivers or plates.
The inclusion of graphite particles in the alloys has no marked effect on abrasive wear volume but does allow a greater sliding distance without chatter.

Chatter is essentially a problem of dynamic stability. Instability is caused by an alteration of the surface conditions produced by a disturbance of the wear process. (e.g. a hard spot in the material). The relative motion between the diamond and the specimen following a disturbance would be extremely complex because such a disturbance would probably excite several modes of vibration in the wear testing unit. Any one of these modes may become unstable and result in chatter.

SEM studies (Figures 166 and 167) indicate that there is a greater amount of wear by fracture and delamination in the alloys which contain graphite. Alloys which do not contain graphite appear to deform without fracture which appears to result in a "build up" of the side of the wear groove that cannot be fractured by the ploughing action of the diamond. This build up probably causes a disturbance in the wear process and hence chatter. The presence of graphite particles appears to allow the material to wear by the detachment of chips and plate like debris (abrasion and delamination) (see Figure 167). Delamination results from cracks initiated below the wear surface. In the case of alloys containing graphite these cracks are probably initiated from voids or discontinuities where graphite particles are accommodated. Such voids do not exist in alloys which do not contain graphite particles and so wear takes place with a greater amount of plastic deformation. This is caused by the ploughing action of the diamond
on a more ductile material which is less prone to the formation of cracks that may initiate abrasion or delamination.

13.4.2 Pin on Disc Wear Testing.

In studying the wear behaviour of aluminium-silicon alloys during pin on disc testing, T.S. Eyre and co-workers at Brunel University have noted two distinct rates of wear which are dependent on the load applied. These two wear rates have become known as "mild" and "severe". The transition from a mild rate of wear to a severe rate of wear occurs at a well defined point as the load on the pin is increased.

Mild wear is associated with oxidative wear where an oxide layer forms on the wear pin asperities followed by fracture and compaction into valleys on the alloy surface. As the oxide layer increases in thickness it also becomes smoother and the wear rate remains relatively low. In bearing applications oxidative wear can be considered to be the most desirable condition because the oxide layer helps to prevent contact between mating components and inhibits failure of the material by common wear mechanisms, such as abrasion and adhesion.

Severe wear is associated with metallic wear which results in deformation and fracture from the pin surface on a fairly massive scale because the oxide layer breaks down and the material begins to yield by common material failure mechanisms (see 1.5). In extreme cases, material may become deposited on the disc. This type of wear occurs when the load on the pin is increased beyond a certain load which has become known as the
"transition load". For a given material, under a given set of conditions the transition load is a constant.

In this work, test conditions were identical to those used by Eyre (119). Transition loads for alloys which do not contain graphite are found to confirm the findings reported in that publication. (See Figures 121 and 122). However, the addition of 2% wt graphite particles to the alloys allows the transition loads to be increased.

This extension of mild wear is probably the result of an extension of oxidative wear which is aided by lubrication from simultaneous compaction and smearing of graphite particles. Evidence of this comes from E.S.C.A studies which show the presence of both oxygen and carbon on the wear surfaces of the alloys containing graphite.

The alloys which contain 8% wt graphite do not permit an extension of mild wear to higher loads. This is probably due to the considerably reduced strength resulting from high graphite contents which causes the material to yield at lower levels of stress.

These observations suggest that there is an optimum graphite addition to maximise load carrying capacity whilst maintaining a mild wear characteristic. In common with Shivanath et al. (27), this investigation shows that a hypereutectic silicon content of 16% wt offers the highest load carrying capacity. Additions of graphite particles ranging between 2 and 8% wt allow the material to exhibit a reduced coefficient of friction when mated with a hardened steel disc. (See Figures 123 and 124). This is due to
the lubrication effect provided by solid graphite particles at the wear interface. However, with graphite contents in excess of 4% wt, although the coefficient of friction remains low, the composites exhibit a transition to a "severe" rate of wear at a lower transition load. This is because there is a considerable loss in strength with graphite contents in excess of 4% wt which causes the material to yield, and hence transfer to a more severe wear rate, at a lower load. Therefore, results indicate that the best combination of silicon and graphite contents which will allow reduced coefficient of friction and increased load carrying capacity whilst maintaining a mild wear rate is a 16% wt silicon alloy with 2 - 4% wt graphite particle addition.

S.E.M. micrographs (Figures 168-183) of worn pin surfaces show that the mild wear rate is characterised by wear taking place on flattened asperities, which adds further evidence to the oxidative wear hypothesis. There are no indications of large fragments of material having been torn by abrasive or adhesive wear mechanisms. At higher magnifications, there is evidence of crack formations on the worn surfaces. The cracks in the alloys with graphite are less severe than in the alloys without graphite. (e.g. Figures 169 and 171). This is probably due to reduced adhesive wear in the composites. Figure 169, which shows an alloy without graphite, shows that the cracks have grown to the extent where a flake is becoming detached from the wear surface due to the flake tending to adhere to the disc. The presence of graphite particles in a similar alloy (Figure 171) has resulted in considerably reduced crack development which is probably due to
graphite inhibiting direct contact, and hence adhesion, between the pin and the disc. The reduction in coefficient of friction resulting from graphite lubrication at the wear interface adds further evidence to this hypothesis. Therefore, it would appear that the extension of mild oxidative wear in alloys which contain graphite is assisted by solid lubrication from graphite particles.

In contrast, severe wear is characterised by the removal of large fragments of material by abrasion, adhesion and particularly delamination. For example, Figure 190 shows an example of delamination where plate-like debris has been torn from the worn surface. This is caused by localised areas of the surface adhering to the disc surface such that localised seizure of the disc and thin plates of test material occurs with the result that plate-like debris remain adhered to the disc. S.E.M. micrographs indicate that there is little difference between worn surfaces of alloys which contain graphite and those that do not under severe wear conditions. This indicates that there is also little difference between wear mechanisms and that wear essentially takes place by a process of comparatively large scale fracture. However, the presence of graphite reduces the coefficient of friction under both mild and severe wear conditions. Under severe wear conditions, this probably results from a more easily fractured material in which cracks can be developed under lower stress conditions from the voids in the material which accommodate graphite particles. The higher ductility of the materials without graphite tends to inhibit fracture and so a higher stress is required to fracture plates of material which have become adhered to the disc. Therefore, the friction
force will tend to be higher resulting in a higher coefficient of friction value.

During this pin on disc wear testing programme, two further wear characteristics were noted. These are; alteration wear and step wear. Both occur at or near the transition loads for the material.

Alteration wear (see 11.4.2) represents a sudden yielding of the test material during the course of a wear test. (See Figures 147 and 149). (For the purposes of this work, materials which exhibited this type of wear were considered to exhibit severe wear through the test in question).

Step wear (see 11.4.2) is a special case which occurs in alloys which contain graphite, when the load applied is approaching the transition load. The overall rate of wear may be considered to be severe or mild depending on the overall rate of loss of material. In step wear, the severe rate of wear is accompanied by a steep increase in coefficient of friction and temperature. Figures 189 and 192 show wear surfaces which were removed from the test when the coefficient of friction and temperature were near the maximum in the cycle. Tongue shaped delamination plates (similar to those discussed above) were forming in the direction of sliding. It is likely that these plates tend to adhere to the disc, and so there is an increase in coefficient of friction. As the plates grow, the area adhering the pin to the disc increases. Therefore the overall force adhering the pin to the disc increases. Consequently, coefficient of friction rises because a higher force is required to overcome the adhesion force. At some point, the
tongue shaped plates become detached from the pin because the force adhering them to the disc has become large enough to cause fracture. Therefore, there is suddenly less adhesion and so coefficient of friction is reduced and the cycle begins again. Figures 193 and 196 show examples where tongue shaped plates have become fractured and consequently the coefficient of friction and rate of wear were low because there was no adhesion to the disc. Step wear appears to represent alternating changes between mild (oxidative) wear and severe (metallic) wear which result from breakdown and replenishment of the oxide layer.

In general, in pin on disc wear testing, the reduced coefficient of friction exhibited by the alloys with graphite is accompanied by a reduced steady running temperature. This is a direct result of a reduced energy input being required to overcome the friction force and so less energy is dissipated in the form of heat.

Surface texture studies indicate that graphite inclusions result in reduced surface damage to both pins and disc. This could be a useful property in reducing scuffing problems on mating components run with aluminium-silicon bearing materials. Under mild wear conditions, this is probably due to an increase in the flattening of asperities resulting from smearing of graphite particles. Under severe wear conditions this is due to more favourable shear and fracture conditions (discussed above) which results in a reduced depth of fracture. (Further evidence is added to this hypothesis by published literature (96, 116, 121) which states that the improved tribological properties of aluminium-silicon alloys containing graphite are partly due to
reduced subsurface damage). In the case of hypereutectic alloys (with hard primary silicon particles) graphite may also act as solid lubrication preventing contact between hard particles and mating components, thus reducing abrasive damage.

Observations of pin weight losses (11.4.2) usually follow the results of "change in pin length". However, in the case of low silicon alloys there is some evidence of loss of pin length without loss of weight. This is due to plastic deformation rather than fracture and is characterised by alloys with high ductility (e.g. 4% silicon).

To summarise, the presence of included graphite particles appears to enhance the tribological properties of aluminium-silicon alloys by reducing coefficient of friction and increasing the load at which a transition to severe wear occurs. This may result from lubricated oxidative wear and a reduction in subsurface damage. This hypothesis is not in complete agreement with published theories on the formation of a continuous graphite layer which separates the wear surfaces (22), but is compatible with modern wear theory (35, 94, 95, 119).

13.5 CHEMICAL ANALYSIS.

The results of graphite contents from wet chemical analysis are all lower than expected. This discrepancy could have arisen because the samples analysed were taken from drillings. Machining tends to remove graphite from chips because chips break at the graphite inclusions and particles are lost in the form of a black dust. There is also no evidence to suggest that the pattern of
evolution of carbon dioxide is similar to that of steels and so the calibration used cannot be verified.

The quantitative metallographic technique of Areal Analysis is statistically unreliable due to the low number of particles considered in each microstructure and also the assumption that the particles are uniform spheroids. However, results from Lineal Analysis do not appear to be significantly different and are statistically more reliable which, in this case, implies that the results from Areal Analysis are likely to be reliable.

13.6 FATIGUE TESTING.

The greatly impaired fatigue life of aluminium-silicon alloys with dispersed graphite probably results from the "notch" effect. Discontinuities in the matrix at the points of graphite inclusion may act as stress raisers and promote the propagation of cracks. However, this is not evidence to suggest that fatigue life will be impaired in bearing applications because a rotating bend fatigue test does not simulate the types of fatigue loadings which occur in bearing applications.

13.7 CORROSION TESTING.

In common with Chandrashekar and Rohatgi (31), no impairment of the corrosion resistance of aluminium-silicon was found when graphite particles were included in the alloys. This is believed to be due to the formation of a passive layer of SiO_2 which is claimed to be responsible for the excellent corrosion resistance of aluminium-silicon alloy (122). The formation of this layer
may be uninhibited by the presence of graphite particles in the alloys because there is no chemical bond between graphite particles and the alloys. This passivation effect prevents contact between the graphite and the alloy and consequently an electrolytic corrosion cell cannot be formed. If there was not a passivation mechanism, severe corrosion would result because graphite is highly cathodic to aluminium-silicon alloys.

13.8 MACHINABILITY TESTING.

The improved machinability of the composites is largely due to a change in the shear angle (Figure 57) and hence an improvement in machinability index. These results indicate a requirement for a lower shear stress to shear the chip from the workpiece in alloys containing graphite. Surface finish is similarly improved by a cleaner cut which results from a reduced tendency for the tool to be pushed away from the workpiece. Graphite particles acting as chip breakers are reported to result in improved machinability\(^{(46)}\). This may be the cause of improved shear conditions. S.E.M. micrographs also indicate smaller, thinner chips, adding further evidence to the verification of this hypothesis.

There is some evidence of improved machinability of both graphitised and ungraphitised specimens with increasing feed rate. This indicates that the conditions chosen for the machining tests may not be ideal and that improvements in surface finish and specific cutting power are obtainable for all the specimens. However, there is strong evidence of improved machinability in alloys which contain graphite.
13.9 **CASTINGS PRODUCED TO ASSESS REPRODUCIBILITY OF RESULTS.**

There are no significant variations in mechanical properties or structures in any of the castings produced to assess reproducibility when compared to their corresponding original castings. This implies that the production process allows reproducibility of the results.
CHAPTER 14

CONCLUSIONS

i) The vortex technique allows dispersion of graphite particles but continuous stirring and rapid solidification are necessary to avoid segregation.

ii) Agitation of semi-solid aluminium-silicon alloys produces a low viscosity slurry which is suitable for casting.

iii) Graphite particles can be dispersed in, and retained by, semi-solid aluminium-silicon alloys but careful control of parameters is required to maintain a viscosity suitable for casting purposes.

iv) Squeeze casting of aluminium-silicon-graphite composites produces superior mechanical properties to those obtained by gravity die casting. The U.T.S. of an alloy containing 2% wt graphite particles may be increased by 18% by squeeze casting.

v) Graphite retention in semi-solid aluminium-silicon alloys is dependent on certain trace elements within the melt. The presence of chlorine results in the rejection of graphite particles but additions of small quantities of sodium or magnesium may prevent such rejection.

vi) Mechanical properties of aluminium-silicon-graphite composites deteriorate with increasing graphite content. Alloys of near eutectic composition suffer a greater deterioration for a given graphite content.
vii) There is no significant effect on the specific abrasive wear volumes of aluminium-silicon alloys resulting from included graphite particles, but there is evidence of a change in the wear mechanism with reduced deformation and increased fragmentation.

viii) Pin on disc wear tests show that certain quantities of graphite particles added to aluminium-silicon alloys increase load carrying capacity with reduced coefficient of friction, reduced steady running temperature and reduced damage to mating components. A 16% wt silicon alloy with 2-4% wt graphite particle addition offers optimum tribological properties with the highest load carrying capacity accompanied by low coefficient of friction and steady running temperature.

ix) Rotating bend fatigue tests show considerable deteriorations in the fatigue life of aluminium-silicon alloys containing graphite particles.

x) There is no evidence of a deterioration in the corrosion resistance of aluminium-silicon alloys resulting from graphite particle additions.

xi) The machinability of aluminium-silicon alloys is greatly improved by the addition of graphite particles.

xii) The experimental procedures allow the experimental results to be reproduced.
CHAPTER 15

SUGGESTIONS FOR FURTHER WORK

15.1 COMPOSITE ALLOY PRODUCTION.

The combination of compocasting to disperse graphite and squeeze casting to produce components offers a number of areas for further development.

A compocasting unit could be developed which is designed to operate on a continuous basis to provide a continuous supply of partially solid composite alloy. A design similar to the continuous rheocasting unit\(^{(68)}\) offers a continuous supply of agitated semi-solid alloy, this would require modifications to provide a continuous supply of graphite particles. The output from a device of this type could be used to form continuous bar for thixocasting at a later date. Alternatively, a valve could be incorporated to allow the output to be controlled in a manner which would allow discontinuous material to be produced for immediate squeeze casting or pressure die casting. The variables of slurry viscosity alloy input rate, graphite input rate, volume solid and shear rate will require very careful control in order to obtain a reproducible output. Automatic control with the use of a microprocessor could offer a solution to this problem by monitoring viscosity and output flow rate. With the use of a feedback loop, input variables could be automatically altered to give the required viscosity and output flow rate.

Scope also exists for automation of slurry handling after exit from the production unit. This might be achieved with mechanical handling devices to transfer composite slurry to a squeeze casting
die or the shot chamber of a high pressure die-casting machine.

An investigation could be carried out into the inclusion of graphite which is not in particulate form. Previous work\(^{(43)}\) has shown that graphite particles of different sizes and shapes have no effect on tribological properties. However, the inclusion of chopped graphite fibres might offer good tribological properties and improved mechanical properties.

Commercial aluminium-silicon alloys have better mechanical and tribological properties than binary aluminium-silicon alloys. It would be beneficial to investigate the semi-solid processing of graphitic commercial alloys and establish their mechanical and tribological properties.

15.2 **COMPOSITE ALLOY EVALUATION.**

Inclusions of further alloying elements to binary aluminium-silicon alloys have been reported to improve load carrying characteristics\(^{(119)}\). Research could be conducted to find an alloy composition which offered optimum tribological properties. The effects of graphite additions on the properties of such an alloy should then be evaluated. Having obtained a composite with ultimate mechanical and tribological properties, comparisons could be made with the properties of established bearing materials so that the most appropriate applications could be identified. At this stage it would become necessary to conduct an investigation into the economics of the production of components by this production route. A need may arise for compromise between the advantages and disadvantages of cost versus performance. Alternatively, there
may be applications where the properties of composites offer a unique solution to a problem, (e.g. the all aluminium engine).

If suitable commercial applications can be identified, prototypes of components made from the composite alloy could be produced and their performance evaluated in their working environments.
CHAPTER 16

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CHAPTER 17

APPENDICES

Appendix No.
1. Composite Alloy Production - Equipment Design
2. Formulae used in Semi-Solid Processing
3. Viscosity Measurement
4. Composite Alloy Evaluation - Equipment Design
5. Statistical Testing of Wear Test Results
6. Quantitative Metallographic Techniques
7. Machinability Tests
8. Specimen Calculations - Composite Alloy Production
9. Specimen Calculations - Composite Alloy Evaluation
Appendix 1

Composite Alloy Production—Equipment Design

Design Features (See Parts List—Fig. 17b).

Detail No.

1. Framework: This was designed as a welded structure made mainly from 38 mm × 38 mm × 6 mm angle iron.

2. Variable speed drive: A means was required to vary rotor speed in order to vary shear rate. There was a choice of three types of speed variation:
   a) D.C. motor with encoder and tachogenerator.
   b) Induction motor with electronic phase variation.
   c) Induction motor with hydraulic variable speed drive.

A d.c. motor with encoder and tachogenerator offered accurate speed variation from zero to 2500 rpm and the advantage that torque was proportional to armature current, which could be easily measured, and so allowed the viscosity of the slurry to be determined. However, the cost of a 1 kW unit with all accessories was quoted as over £2000 which precluded its consideration.
An induction motor with electronic phase variation offered speed variation with 10:1 ratio which was not considered to offer sufficient speed range. Determination of torque taken from the motor presented difficulties and so viscosity could not be easily determined. Cost for a 1 KW unit was quoted at £600.

A variable speed hydraulic drive coupled to an induction motor allowed speed variation from zero to 1500 rpm in both clockwise and anti-clockwise directions and had the advantage of an almost instantaneous response to changes in speed. Torque on the stirring shaft could be determined, but with some difficulty, by noting power consumed by the motor when in the on and off load conditions and computing torque from power consumed in shearing the slurry. The cost was quoted as £350 complete with .75 KW induction motor. A further advantage was that the motor could be easily and inexpensively changed if power did not prove adequate. The speed of the hydraulic drive output also did not vary appreciably with changes in load.

Therefore it was decided that the hydraulic variable speed drive offered all the required features.

Variable Speed drive type: Stone Platt Var-Spe
Type 11 - 12/000.

3. Motor: GEC, 3 phase, 415 v, 0.75 KW Induction Motor.

4. Bearing housing assembly: This was designed to incorporate a hollow rotor drive shaft which allowed the push rod detail [8]
to pass through for operation of the graphite injector piston. Bearings were angular contact type installed in back-to-back mode. The assembly is illustrated in Fig. 18. The housing was mounted on a dovetail slide to allow height adjustment and to facilitate removal of the plug [12] by allowing the rotor [6] to move downwards, thus pushing out the plug. The housing was manufactured from cast iron and the slide En8.

5. Rotor Drive Shaft: Manufactured from En8 steel (See Fig. 18).

6. Rotor: The original rotor was designed to incorporate a slow spiral. (1 rev in 1.0 m). This was an attempt to increase shear rate by introducing a 'screw' action. The rotor was manufactured from mild steel and the centre was bored out for graphite storage and to accommodate the graphite injector screw detail [9].

Mild steel was chosen on the advice of Fulmer Research Institute who stated that although rotor wear did take place due to some solubility of steel in aluminium, the rotor could be easily and cheaply replaced and increases of iron content in the melt were negligible, (Fig. 19).

7. Graphite injector piston: This was manufactured in mild steel and was designed to force graphite from within the rotor into the melt when force was applied to it via the graphite injector screw [9] and the push-rod detail [8] (Fig. 19).

8. Push-rod: See Figs. 18 and 19.
9. Graphite injector screw: This was operated to apply force to the push-rod and graphite injector piston. A phosphor-bronze thrust bearing was incorporated where contact took place with the push-rod (Fig. 18).

10. Main Crucible: This was designed in consultation with Refractory Mouldings and Castings Ltd., Kegworth, Derby who suggested Grade J/A Mullite as the material. This did not allow significant wetting by aluminium, was fairly strong and allowed economic production of the crucible. The working drawing is shown in Fig. 20. Maximum capacity was 2 Kg of aluminium. The crucible was designed to be similar to that reported in the literature (i.e. two distinct zones).

11. Collection crucible: Standard salamander crucible, parallel sides, 60 mm I.D. x 125 mm deep.

12. Plug: Manufactured in mild steel and incorporating a $3^\circ$ included angle to provide a locking taper when fitted into the main crucible, thus preventing unscheduled departure. A wire framework was also included in the design to prevent the plug dropping into the collection crucible after removal from the main crucible, (Fig. 21).

13. Zone heater: Heating was by electrical resistance wire windings wound on a sillimanite tube. The resistance wire was Kanthal Nikrothal of diameter 1.15 mm giving a resistance of 1.27 ohms/meter. The manufacturers suggested a simple calculation to estimate the total length of wire required:
Ohms law: \( V = I \cdot R \)

where

\( V \) = voltage

\( I \) = current

\( R \) = resistance.

A 240v a.c. single phase mains supply was to be used with a maximum steady current of 10 amps to give a power of approximately 2.0 kW which was estimated to be sufficient to melt the quantity of alloy in the semi-solid zone.

\[
R = \frac{V}{I} = \frac{240}{10} = 24\Omega
\]

1.27 \( \Omega \)/m wire

therefore needed \( \frac{24}{1.27} = 18.90 \) m of wire

tube diameter = 120 mm

tube length = 250 mm

tube circumference = \( \pi \times 120 = 377 \) mm

therefore number of turns of wire = \( \frac{18.9}{377} = 50 \)
pitch of turns = \( \frac{250}{50} = 5 \) mm.

See Fig. 22.

14. Liquid zone heater: Design was similar to the semi-solid zone heater [13] (Fig. 22) except tube diameter = 200 mm

tube length = 180 mm.

15. Insulation: Kaowool needle blanket manufactured by Morgan Ceramic Fibres Ltd., was specified. The thickness required was determined from literature published by the company. A thickness of 51 mm of 96/Kg/m\(^3\) density material from a hot face temperature of 1100\(^\circ\)C allowed a cold face temperature
of 81°C. Therefore the furnace was designed with a minimum insulation thickness of 51 mm to ensure the outer casing temperature was not excessive.

16. Timing belt and pulleys: A toothed belt drive was specified to ensure that there was no slip between the motor and the rotor drive shaft, thus maintaining constant shear rate.

17. Collection crucible release lever: This was designed to allow the collection crucible to be lowered when the lever was operated.

18. Liquid zone temperature controller: Temperature control of the liquid zone was achieved with a Newtronic analogue thyristor operated controller, 0 - 800°C temperature range accurate to ± 3°C with automatic cold junction compensation.

19. Semi-solid zone temperature controller: Temperature control of the semi-solid zone was achieved with a Newtronic digital thyristor operated controller, 0 - 999°C temperature range accurate to ± 1°C with automatic cold junction compensation.

20. Thermocouples: Temperatures were in the range for nickel-chrome-nickel alumel thermocouples, which were manufactured from 30 s.w.g. wire. One thermocouple was required for each temperature controller and one was fixed to the main crucible within the semi-solid zone in order to monitor the temperature in that region. This was to ensure that the required volume fraction solid was achieved.
21. Temperature readout: A digital voltmeter accurate to 0.01 mV was used to measure voltage from the main crucible thermocouple. The voltage was then converted to temperature in °C using B.S. 1827. Cold junction compensation was calculated using the reading from a mercury thermometer positioned at the cold junction.

22. Temperature recorder: This recorded the output from the main crucible thermocouple and was used to monitor temperature so that the temperature stability of the semi-solid alloy could be guaranteed. The recorder type was a Rikadenki DBE-3 accurate to 0.1 mV.

23. Tachometer: A digital tachometer, manufactured by Graham and White Instruments, which functioned using a photoelectric counter to count reflected light pulses from a reflector attached to the rotor drive shaft was used to set shear rate. This was achieved by measuring the speed of the shaft in rpm and adjusting drive shaft speed as required.

24. Wattmeter: This was used to determine power consumed by the three phase induction motor in shearing the slurry. From power consumed figures and shaft speed measurements torque on the rotor was calculated. This enabled the viscosity of the semi-solid alloy to be determined.
Appendix 2

Formulæ Used in Semi-Solid Alloy Processing

The average shear rate \( \dot{\gamma}_{ave} \) was calculated using the definition:

\[
\dot{\gamma}_{ave} = \frac{d\theta}{dr} \times r
\]

where \( \theta \) was the angular velocity at a distance \( r \) from the centre of the rotor calculated from the equations of motion\(^{(89)} \) and equal to, in the case of a Newtonian fluid,

\[
\frac{d\theta}{dr} \times r = \left( \frac{2\Omega_o}{1 - K^2} \right) K = \dot{\gamma}_{ave} \quad (1)\(^{(68)} \)
\]

where \( \Omega_o = \) angular velocity of the rotor

\( K = \frac{\text{Perimeter of rotor}}{\text{Perimeter of shearing chamber}} \)

The perimeter of the rotor was calculated assuming that it was square in section with sides of 31.75 mm. However, in practice it is likely that the rotor gave a slightly higher shear rate than that calculated as a result of the toothed form. The perimeter of the shearing chamber was calculated from the diameter of 5 mm.

The variation in shear rate with rotor rpm is shown in Fig. 30.

Volume fraction Solid was calculated as a function of temperature from the "Scheil Equation"\(^{(91)} \) and the Lever rule. The former
assumes no solid diffusion, equilibrium at the liquid-solid interface, complete diffusion in the liquid and constant partition constant coefficient $k^{(91)}$). The latter assumes complete diffusion in the solid. In the Al-Si system the difference between these calculations is significant (see Appendix 8(iii)). For the reasons outlined above, the Scheil equation is likely to be most accurate. Both equations were deduced from a mass balance and give fraction solid in weight. Differences between calculated weight fractions and volume fractions are claimed to be very small due to small differences in the density of the solid and the liquid phases\(^{(90)}\). In published work, the Scheil equation has been used almost universally and fractions solid have been referred to as "volume". Strictly speaking, this is not correct without the use of density corrections. However, this practice has been widely adopted in published literature on semi-solid processing and so has been used here in the interests of standardisation.

The equation used was:

\[
g_s = 1 - \left( \frac{T_M - T}{T_M - T_L} \right)^{1/1-k}
\]

where

$g_s$ = volume fraction solid,

$T_M$ = melting point of pure aluminium,

$T_L$ = Liquidus temperature of alloy in question,

$T$ = actual temperature in liquid-solid range.

$k$ is defined as the "equilibrium partition constant"\(^{(91)}\), and was obtained from the equation:
$k = \frac{C_s^*}{C_L^*}$  

(3)

where $C_s^*$ = composition of the solid and $C_L^*$ = composition of the liquid.

$C_s^*$ and $C_L^*$ were obtained from the Al-Si equilibrium diagram as shown in Fig. 31. The equilibrium diagram was taken from Ref. (92).

The variation in volume fraction solid with temperature is shown in Fig. 32.
APPENDIX 3

VISCOITY MEASUREMENT

The formula used to calculate torque on the rotor was:

\[ \text{Torque} = \frac{\text{Power consumed}}{\text{Angular velocity of shaft}}. \]  

(4)

Unfortunately, this led to a complicated procedure to obtain each torque figure because it was necessary to take two wattmeter readings to obtain each value of power. The two wattmeter method used for measurement of power in the three phase circuit was that described by Hughes (93) and illustrated in Fig. 34. From this

Total power in the circuit = Wattmeter 1 reading + Wattmeter 2 reading.  

(5)

In order to obtain the torque required to shear the alloy, it was necessary to obtain a figure for the torque required to operate the stirring rotor when no load was applied, and then deduct this from the torque required when the machine was on load at the required shear rate, volume solid and graphite content.

Having obtained figures for the torque required to shear the alloy in the compocasting unit, it was then necessary to calculate a value for viscosity. This was achieved as follows:

Shear stresses were those acting on the rotor and so were equal to the torque on the rotor divided by its radius and surface area, i.e.

\[ \tau = \frac{T}{A \times R_i}. \]  

(6) (80)
"Apparent viscosity" of a non-Newtonian fluid is the viscosity a Newtonian fluid would have if it produced an equivalent torque in a viscometer operating at the same rotational speed\(^{(89)}\). It is calculated by:

\[
\eta = \frac{T(1-K^2)}{4\pi L\Omega_0 R_0^2 K^2}
\]

where
- \(\eta\) = apparent viscosity
- \(K\) = ratio of rotor radius to crucible radius
- \(\Omega_0\) = rotational speed
- \(R_0\) = crucible radius
- \(L\) = crucible length.

This can be reduced to:

\[
\eta = \text{constant} \times \frac{T}{\Omega_0}
\]
APPENDIX 4

COMPOSITE ALLOY EVALUATION - EQUIPMENT DESIGN

Design Features. (See Parts List - Fig. 37b)

Detail No.

1. Framework: This was a welded structure made from 38 mm x 38 mm x 6 mm angle iron.

2. Variable speed drive: A means was required to vary the speed of the disc and the carriage. A hydraulic variable speed drive identical to that used on the compocasting unit was chosen. This allowed accurate speed control and a speed range from zero to 150 rpm. A wide-speed range was required because the reciprocating test was run fairly slowly whilst the pin on disc test required a high speed

Variable speed drive type: Stone Platt Var-Spe

Type 11 - 12/000.

3. Motor: GEC 3 phase, 415v, 0.75 KW Induction Motor.

4. Bearing Housing for Disc: The housing, manufactured from cast iron, contained two angular contact bearings, two seals, and a shaft made from En8. The bearings were mounted "back to back" and loaded by a nut on the shaft.

5. Load plate: The plate was made from 12.7 mm aluminium-alloy plate and contained four ball-bushes, detail [20] which were allowed to move freely along finely ground vertical pillars. Weights [17] were placed on the plate to apply load to the diamond. The plate was drilled to form a matrix of holes to allow a minimum load of 1.5 Kg.

6. Base plate: Constructed from 12.7 mm steel boiler plate.
7. **Runners:** Two runners, one vee section and one flat, were made from cast iron to allow the carriage, detail [8] to be guided and supported during the reciprocating test.

8. **Carriage:** Constructed from mild steel with two clamps to hold the specimen in position and a phosphor bronze spigot for the connecting rod, detail [10].

9. **Crank wheel:** Constructed from mild steel to apply reciprocating motion to connecting rod 10. A phosphor bronze spigot was incorporated for the connecting rod. The connecting rod could be attached in several positions to allow various stroke lengths to be used. (40 mm, 60 mm, 80 mm and 120 mm).

10. **Connecting rod:** Mild steel.

11. **Diamond:** A conical diamond with $120^\circ$ included angle and tip radius 0.2 mm was specified. This allowed use of the standard diamond and mounting used in Rockwell 'C' hardness tests.

12. **Base plate:** Constructed from 12.7 mm steel boiler plate.

13. **Load plate:** The pin-on disc load plate was designed to be similar to that used on the reciprocating test except that there were only two bushes running on finely ground pillars.

14. **Disc:** The disc was manufactured from B.S.970 En32 case-hardened and tempered to Rockwell 'C' 57 then ground to a surface finish of 0.2 μM Ra by surface grinding. (Prior to all tests the disc was finished using SiC paper to give a circumferential direction of lay.)
Detail No.

15. Timing belt and toothed pulley drive: This was specified for the disc to ensure that there was no belt-slip when load was applied to the pin. A tensioning device was also found to be necessary.

16. Oil bath: Oil baths were fitted to both pin and disc test and reciprocating test to enable lubricated wear tests to be carried out if required.

17. Weights: Weights were used to apply the load through the load plates fitted with ball bushes running on finely ground pillars, detail [20]. Loads applied to the reciprocating diamond scratch test were 5 Kg and 10 Kg and to the pin on disc test were 3.25 Kg, 7.8 Kg, 12.6 Kg and 17.1 Kg.

18. Perspex cover: This was necessary to isolate the wear tests from the surrounding environment and to allow the temperature and humidity in the vicinity of the wear test to be monitored.

19. Resilient mountings: Both wear test units were mounted on resilient metalastick mountings so that the vibrations from motor and drive mechanisms could be damped out so that they would not affect the test conditions.

20. Ball bushes and Ground pillars: These were specified to ensure that the load plates remained horizontal throughout
the wear tests, by ensuring that the plates were constrained to move vertically. This ensured that the loads applied to both the pin and the diamond were maintained in a vertical direction and hence, axially along the pin or diamond because the system allowed no significant lateral movement of the plates relative to the pillars. Friction in the system was minimal and so the full load was applied at all times whilst allowing the plate small vertical movements due to small flatness errors on the reciprocating wear specimen or the disc.

21. Position Transducer: The transducer specified was an RDP D/100 AG, which was mounted in the pin on disc load plate, detail [13] to measure the change in distance between the load plate and the disc due to pin wear. The d.c. millivolt output from the transducer was fed into a sensitive millivolt recorder, detail [25] to record the change in distance with time. An additional, RDP D11 unit was required to supply an oscillating current to the transducer and provide a d.c. output. The transducer allowed a maximum range of 2.5 mm and best resolution of 0.0001 mm.

22. Counter and automatic test-stop device: This consisted of a magnet mounted to the crank-wheel, detail [9], a reed switch to provide a pulse each time the magnet passed and a counter to count the pulses, with a facility to provide a further pulse which was used to cut the power to the motor
when a preset number of counted pulses had been reached. The pulse from the counter activated a relay which activated a contact breaker in the 3 phase supply to the motor. This facility ensured that tests were stopped automatically when a preset number of reciprocations or revolutions had been reached.

23. **Position Transducer**: (Coefficient of friction). This measured the deflection of the pin holder which resulted from the turning disc. The amount of deflection was proportional to the coefficient of friction and so allowed it to be evaluated. (The method used is described in 2.3). The deflection of the pin holder was very small and so it was necessary to use the transducer near its maximum resolution which resulted in the transducer range being very small. The transducer specified was identical to detail [21]. The output was fed into the millivolt recorder, detail [25].

24. **Thermocouples**: Two chrome-alumel thermocouples were used during the wear tests, one measured ambient temperature inside the perspex cover, the other was attached to the wear pin at a distance of 3 mm from the wear interface with the disc. Both outputs were fed into the millivolt recorder to provide a record of temperature changes during the wear tests.
25. Recorder (millivolt): A sensitive recorder was required to indicate the small voltage changes from the coefficient of friction transducer, detail [23]. A 4-channel Linseis with capability to record voltages down to 1 mV was used (Fig. 39).

26. Transducer power supply: The transducers required a smooth 15v d.c. supply. (Fig. 39).

27. Hygrometer and Probe: This measured humidity inside the perspex cover during wear tests and displayed a reading in % relative humidity on a meter. (Fig. 40). The probe was fitted to protrude inside the perspex cover.
APPENDIX 5

STATISTICAL TESTING OF WEAR TEST RESULTS

Two hypotheses were used:

(i) Null Hypothesis: That there was no difference between true means of original tests and repeat tests, i.e. \( \mu_d = 0 \).

(ii) Alternative Hypothesis: \( \mu_d \neq 0 \).

The variance of the discrepancies (d) between individual original tests and repeat tests was not known for an infinite population and so was estimated from the sample by estimating the average discrepancy (\( \bar{d} \)) from the original tests and repeat tests.

Hence variance
\[
\sigma^2 = \frac{1}{\text{n}-1} \sum (x - \bar{x})^2
\]

where \( x \) = the discrepancy between original and repeat and \( \bar{x} \) = the average discrepancy between original and repeat.

Bessel's correction was applied to obtain a best estimate of the population standard deviation (\( \hat{\sigma} \)) of the discrepancies.

\[
\hat{\sigma} = s \sqrt{\frac{n}{n-1}}
\]

where \( n \) = number of sample.

Assuming that the value of an infinite population mean discrepancy = 0

\[
't' = \frac{\bar{x} - \hat{x}}{\hat{\sigma}}
\]

where referring to 't' tables.

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>20%</th>
<th>10%</th>
<th>5%</th>
<th>2%</th>
<th>1%</th>
<th>0.2%</th>
<th>0.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>'t' value</td>
<td>1.36</td>
<td>1.80</td>
<td>2.20</td>
<td>2.72</td>
<td>3.11</td>
<td>4.02</td>
<td>4.44</td>
</tr>
</tbody>
</table>

\[\downarrow\text{INSIGNIFICANT} \quad \downarrow\text{PROBABLY NOT SIGNIFICANT} \quad \rightarrow\text{SIGNIFICANT} \quad \rightarrow\text{HIGHLY SIGNIFICANT} \]

PARTICULARLY SIGNIFICANT
Two hypotheses were used:

(i) Null Hypothesis: That there was no difference between true means of original tests and repeat tests, i.e. \( \mu_d = 0 \).

(ii) Alternative Hypothesis: \( \mu_d \neq 0 \).

The variance of the discrepancies (d) between individual original tests and repeat tests was not known for an infinite population and so was estimated from the sample by estimating the average discrepancy (\( \bar{d} \)) from the original tests and repeat tests.

Hence variance \( s^2 = \frac{\sum x^2}{n} - \bar{x}^2 \)  

where \( x \) = the discrepancy between original and repeat and \( \bar{x} \) = the average discrepancy between original and repeat.

Bessel's correction was applied to obtain a best estimate of the population standard deviation (\( \hat{\sigma} \)) of the discrepancies.

\[ \hat{\sigma} = s \sqrt{\frac{n}{n-1}} \]  

where \( n \) = number of sample.

Assuming that the value of an infinite population mean discrepancy = 0

\[ 't' = \frac{[\bar{x} - \bar{x}]\sqrt{n}}{\hat{\sigma}} \]  

where referring to 't' tables (99).

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>20%</th>
<th>10%</th>
<th>5%</th>
<th>2%</th>
<th>1%</th>
<th>0.2%</th>
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<tr>
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<td>1.36</td>
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<td>4.02</td>
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</tbody>
</table>

Downwards arrows indicate:

- **INSIGNIFICANT**
- **PROBABLY NOT SIGNIFICANT**
- **SIGNIFICANT**
- **HIGHLY SIGNIFICANT**

Particularly Significant
APPENDIX 6

QUANTITATIVE METALLOGRAPHIC TECHNIQUES

Pickering (102) has summarised the principle employed, that volume fraction of a phase is equal to the area fraction in a random planar section which is also equal to the linear fraction in a random linear line through the three dimensional microstructure which is also equal to the fraction of randomly distributed points which lie with the particular phase. Pickering states that the mathematical proof of these relationships has been reported (103,104) and that this can be summarised by:

\[
V_f = \frac{V_\alpha}{V} = A_f = \frac{A_\alpha}{A} = L_f = \frac{L_\alpha}{L} = P_f = \frac{P_\alpha}{P}
\]  

(10)

where

- \(V_f\) = Volume fraction of \(\alpha\)-phase
- \(V_\alpha\) = Volume of \(\alpha\)-phase in the specimen
- \(V\) = Total volume of the specimen
- \(A_f\) = Area fraction of \(\alpha\)-phase
- \(A_\alpha\) = Area of \(\alpha\)-phase in random planar section
- \(A\) = Total area of random planar section
- \(L_f\) = Linear fraction of \(\alpha\)-phase
- \(L_\alpha\) = Line fraction of \(\alpha\)-phase in a random linear line
- \(L\) = Total length of random linear line
- \(P_f\) = Point fraction of \(\alpha\)-phase
- \(P_\alpha\) = Number of random points falling in the \(\alpha\)-phase
- \(P\) = Total number of random points.
From this, the volume fraction was determined from a random plane of polish through the specimen. To achieve this, it was necessary to measure the area of all of the graphite particles falling in a total area. Traditionally, various techniques involving the use of superimposed grids, planimeters and charts have been used to assess area fractions of a particular phase in a microstructure.

The Quantimet was able to yield a result of the area of a particular phase within a total area of about 5 mm diameter and update the result after each successive examination of different areas of the microstructure.

The following shows that it is necessary to update the result as many times as possible in order to minimise errors associated with areal analysis.

Pickering (102) has used a statistical technique to assess errors:

The relative error or coefficient of variance of the result is given by $\sigma_V/V_f$ where $\sigma_V$ is the standard deviation of the determination and $V_f$ is the volume fraction or areal fraction of the $\alpha$-phase.

The square of the relative error is termed the proportional variance, i.e. $\left(\frac{\sigma_V}{V_f}\right)^2$ and can be related to the number of $\alpha$ particles which are measured. The proportional variance depends on the number of $\alpha$-phase particles with respect to the size of areas examined, and the variation in the size of the $\alpha$-phase particles within the areas examined. Total proportional variance is given by:

$$\left(\frac{dV_f}{V_f}\right)^2 = \frac{1}{N\alpha} \left[ 1 + \left(\frac{\sigma_\alpha}{\bar{a}_\alpha}\right)^2 \right]$$ (11)
where \( N_\alpha \) = number of \( \alpha \)-phase particles measured

\( \sigma_\alpha \) = standard deviation of the area of individual
\( \alpha \)-phase particles

\( \bar{a}_\alpha \) = mean area of the individual \( \alpha \)-phase particles,

it can be shown that:

\[
\left( \frac{\sigma_\alpha}{\bar{a}_\alpha} \right) \approx 0.2 \quad \text{(if \( \alpha \) particles are assumed uniform spheres)}
\]

therefore,

\[
\frac{\sigma_f}{V_f} = \frac{1.1}{\sqrt{N_\alpha}}
\]

(12)

From this, the number of \( \alpha \)-phase areas which have to be measured to achieve a given relative error can be determined as in Table 1:

<table>
<thead>
<tr>
<th>Relative Error</th>
<th>No. of particles required to be counted for:</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>67% confidence</td>
</tr>
<tr>
<td>± 1.0</td>
<td>12000</td>
</tr>
<tr>
<td>± 2.0</td>
<td>3000</td>
</tr>
<tr>
<td>± 4.0</td>
<td>750</td>
</tr>
<tr>
<td>± 5.0</td>
<td>480</td>
</tr>
<tr>
<td>±10.0</td>
<td>120</td>
</tr>
</tbody>
</table>

TABLE 1: ACCURACY OF AREAL ANALYSIS. (102)

Using this method it was necessary to approximate the graphite particles to a spherical uniform shape. This inevitably resulted
in the above confidence limits being overoptimistic. (However, consistency in results indicated that the analysis was probably valid.) Therefore, it was attempted to add further evidence of the validity of results using "Lineal Analysis"\textsuperscript{(102)} where the method does not rely on the phase examined, consisting of uniform spheres.

The volume fraction of the graphite phase was obtained by measuring the length of a random line intercepted by graphite particles \( L_c \) in the total line length \( L \).

The errors involved in linear analysis have been reported by Hilliard and Cahn\textsuperscript{(106)}. From this, Pickering\textsuperscript{(102)} has described a method whereby the number of intercepts can be determined in a particular phase which must be measured, for various volume fractions of that phase in order to achieve the relative error with 95% confidence. For the purposes of the investigation, a minimum of 3 intercepts are required for a volume of 5% graphite to give a relative error of ± 9% with a confidence level of 95%. Lineal analysis was therefore used to give a more accurate indication of the quantities of graphite within a microstructure so that the validity of results obtained from the samples by areal analysis could be postulated. Quantitative metallography is based on statistics and so accuracy will increase with the number of samples. Therefore, an average from three lines was taken. (An example of a typical lineal analysis calculation is shown in Appendix 2 (vi) with reference to Fig. 55).
The analysis used was that due to Ernst and Merchant \cite{107}, who used the shear plane model (Fig. 57). They postulated that the shear zone or primary deformation zone could be reasonably represented by a plane called a shear plane. The angle of the plane was the shear angle ($\phi$).

Using this model, the following were calculated:

- cutting ratio ($r_c$)
- shear angle ($\phi$)
- angle of friction ($\tau$)
- coefficient of friction ($\mu$)
- linear cutting speed ($V_c$)
- Universal machinability index ($D$)
- Specific cutting power ($P_s$)
Referring to Fig. 57:

\( R = \) resultant tool force

\( F_C = \) cutting force

\( F_T = \) feed force

\( F_S = \) shear force on shear plane

\( F_{NS} = \) normal force on shear plane

\( F = \) friction force on rake face

\( N = \) normal force on rake face

\( \phi = \) shear angle

\( \alpha = \) tool rake angle

\( \tau = \) mean angle of friction

\( t_1 = \) undeformed chip thickness

\( t_2 = \) cut chip thickness.

The cutting ratio \( r_c \) was a measure of the deformation in cutting and was expressed as

\[
\frac{\text{undeformed chip thickness}}{\text{deformed chip thickness}} = \frac{\text{feed per revolution}}{\text{cut chip thickness}}
\]

hence

\[
r_c = \frac{t_1}{t_2}
\] (14)

\( t_1 \) was the feed set on the lathe.

\( t_2 \) was measured using a micrometer.

From Fig. 57:

\[
r_c = \frac{t_1}{t_2} = \frac{AB \sin \phi}{AB \cos(\phi - \alpha)}
\] (15)

hence

\[
\phi = \tan^{-1} \left( \frac{r_c \cos \alpha}{1 - r_c \sin \alpha} \right)
\] (16)
Das and Tobias\textsuperscript{(108)} defined a universal machinability index (D) as $F_C/F_S$

\begin{equation}
\text{therefore } D = \frac{F_C}{F_S} = \frac{\cos(\phi + \tau - \alpha)}{\cos(\tau - \alpha)} \tag{17}
\end{equation}

where $\tau - \alpha = \tan^{-1} \frac{F_T}{F_C} \tag{18}$
Power consumption was calculated as follows:

Energy consumption in cutting \( P_m \)

\[
= \text{cutting speed} \times \text{largest force component} \\
= V_C \times F_C \\
\]

or in watts

\[
P_m = \frac{V_C}{60} \times F_C \\
\]  

(19)

(20)

Specific cutting power \( (P_S) \) is the power consumed per unit volume of metal removed

\[
i.e. \quad P_S = \frac{P_{mn}}{\text{Metal removedal rate}} \\
\]

(21)

where metal removal rate

\[
= \frac{\pi}{4} \times \text{average cut diameter} \times \text{feed per rev.} \times \text{rpm.} \\
\]

(22)
The parameters used were:
cutting speed: 350 rpm,
specimen: 9.35 mm diameter turned down to 6.35 mm diameter,
feed per revolution: 0.137 mm/revolution initially.

Experiments were initially carried out on a selection of
graphitised and plain aluminium-silicon specimens with all machining
conditions maintained constant. This enabled the effect of graphite
additions in the specimens to be assessed. The machining conditions
were then varied by changing the feed rate \( t_1 \) for four specimens
(two graphitised) so that the effects of increased metal removal
rate on machinability could be investigated.

Specimen calculations are shown in Appendix 9.
APPENDIX 8

SPECIMEN CALCULATIONS - COMPOSITE ALLOY PRODUCTION

(i) Relative amounts of pure aluminium alloy and 50% Al - 50% Si alloy.

Amount of Si in 50% Al - 50% Si = 48.8%
Weight of 50% Al - 50% Si Ingot = 3.371 kg.
Alloy of 16% Silicon required:

\[ 3.371 \times 0.488 = 1.645 \text{ kg. Si} \]

\[ \frac{100}{16} \times 1.645 = 10.28 \text{ kg. total alloy weight.} \]

Weight of pure Al to add

\[ = 10.28 - 3.371 = 6.909 \text{ kg} \]

check:

\[ \frac{1.645 \times 100}{10.28} = 16.002\% \text{ Si.} \]

(ii) Av shear rate:

\[ K = \frac{\text{Perimeter of rotor}}{\text{Perimeter of shearing chamber}} \]

Rotor assumed square section with sides 31.75 mm
Shearing chamber diameter 55 mm.

Av. shear rate,

\[ = \frac{4 \times 31.75}{\pi \times 55} = 0.74 \]

\[ \dot{\gamma}_{\text{ave}} = \frac{2\Omega}{(1 - K^2)} K \quad (1) \]

At (say) 1000 rpm

\[ \dot{\gamma}_{\text{ave}} = \frac{2 \times 1000 \times 2\pi/60}{(1 - 0.74^2)} \times 0.74 \]

\[ = 343 \text{ sec}^{-1}. \]
(iii) Volume fraction solid:

Scheil equation:

\[ g_s = 1 - \left( \frac{T_M - T_L}{T_M - T} \right)^{\frac{1}{1-K}} \]

\[ = 1 - \frac{1}{\frac{660 - 604}{660 - 590}} \]

\[ K = \frac{C_S^*}{C_L^*} = \frac{1.4}{9.8} = .143 \]

therefore \( g_s = 0.23 \)

\[ = 23\% \text{ solid at } 590^\circ C \]

Lever rule:

\[ \frac{b}{a+b} = \frac{1.55}{6.85 + 1.55} = .184 \]

\[ = 18.4\% \text{ solid at } 590^\circ C. \]

(iv) Viscosity:

\[ \text{Torque (off load)} = \frac{\text{Power consumed}}{\text{Angular velocity of rotor shaft}} \quad (4) \]

\[ = \frac{372 - 5}{1544 \times \frac{2\pi}{60}} \]

\[ = 2.304 \text{ Nm.} \]
Torque \( (on \ load) \)
\[
\frac{415}{1544 \times 2\pi/60}
\]
\[
= 2.566 \text{ Mn.}
\]

Torque required for shearing
\[
= 2.566 - 2.304 = 0.262 \text{ Nm.}
\]

Apparent viscosity \( \eta \)
\[
\eta = \frac{T(1 - K^2)}{4\pi L \Omega_o R^2 K^2}
\]

where
- \( T = 0.262 \times 10^7 \text{ dyne cm} \)
- \( K^2 = 0.669 \)
- \( \Omega_o = 1544 \times 2\pi/60 \text{ rads/sec.} \)
- \( L = 13.5 \text{ cm} \)
- \( R^2 = 7.56 \text{ cm}^2 \)
- \( \eta = \text{constant} \times \frac{T}{\Omega_o} \)

constant
\[
= \frac{(1 - 0.669) \times 10^7}{4\pi \times 13.5 \times 2\pi/60 \times 7.56 \times 0.669}
\]

therefore \( \eta = 36839 \times \frac{T}{\Omega_o} \)

where \( T \) is in Nm
and \( \Omega_o \) is in rpm.

hence \( \eta = 36839 \times \frac{0.262}{1544} \)

\[
= 6.261 \text{ Poises.}
\]
SPECIMEN CALCULATIONS - COMPOSITE ALLOY EVALUATION

(i)  U.T.S. = \frac{\text{Ultimate load}}{\text{Cross sectional Area}} \tag{1}

Ultimate loads from 3 specimens: 187.5 kg
189.9 kg
186.3 kg

Average = \frac{187.5 + 189.9 + 186.3}{3}
= 187.9 kg

Diameter of specimen = 4.53 mm

Therefore cross-sectional area = \pi \times \left( \frac{4.53}{2} \right)^2
= 16.117 \text{ mm}^2

U.T.S. = \frac{187.9}{16.117} = 11.66 \text{ kg/mm}^2
= 114 \text{ MN/m}^2

(ii)  Brinell hardness number H = \frac{P}{\pi D}{2} \left[ D - \sqrt{D^2 - d^2} \right] \tag{2}

D = ball diameter = 10 mm

\( d \) = impression diameter = 5.1 mm

H = \frac{750}{\pi D \left[ 10 - \sqrt{10^2 - 5.1^2} \right]}

H = 34.15
(iii) Wear volume for reciprocating diamond test:

Derivation: (ref. Fig. 48).

The wear tract was assumed to be a similar form to the diamond, i.e. 120° inc. angle

0.2 mm tip radius.

\[
\tan 60 = \frac{1}{2} \frac{w}{h} = \frac{w}{2h}
\]

\[
2h = \frac{w}{\tan 60}
\]

hence \( h = \frac{w}{2\sqrt{3}} \)

Area \( \Delta ABC = \frac{1}{2} w \times \frac{w}{2\sqrt{3}} \)

\( = 0.144 w^2 \text{ mm}^2 \)

Area \( \Delta EFC = 0.069 \times DC \) (26)

\[
\tan 60 = \frac{0.069}{DC}
\]

hence \( DC = \frac{0.069}{\sqrt{3}} = 3.98 \times 10^{-2} \)

Area \( \Delta EFC = 0.069 \times 3.98 \times 10^{-2} \)

\[ = 2.75 \times 10^{-3} \text{ mm}^2 \]

\[
\sin \frac{\theta}{2} = \frac{0.069}{0.2}
\]

\( \theta = 20.18^\circ \)

\( \theta = 40.36^\circ \)

Area segment \( GEHF = \frac{40.36}{360} \times \pi \times 0.2^2 \)

\[ = 1.41 \text{ mm}^2 \times 10^{-2} \]

\[ \times \sqrt{(0.2^2 - 0.069^2)} \]

\[ = 0.188 \text{ mm}^2 \]
\[
\text{Area } \Delta \text{ GEF} = 0.069 \times 0.188 \\
= 1.297 \times 10^{-2} \text{ mm}^2
\]

\[
\text{Area EDHF} = 1.41 \times 10^{-2} - 1.297 \times 10^{-2} \\
= 1.12 \times 10^{-3} \text{ mm}^2
\]

Volume of Scratch
\[
= (\text{Area } \Delta \text{ ABC} - \text{Area } \Delta \text{EFC} + \text{Area EDHF}) \times \text{Stroke Length}.
\]
\[
= (0.144w^2 - 2.75 \times 10^{-3} + 1.12 \times 10^{-3}) \times \text{Stroke Length}
\]
\[
= (0.144w^2 - 1.63 \times 10^{-3}) \times L
\]  (3)

Specimen calculation:

\[
w = 0.45 \text{ mm}
\]

\[
\text{wear volume} = (0.144 \times (0.45)^2 - 1.63 \times 10^{-3}) \times 40
\]
\[
= 1.12 \text{ mm}^3.
\]

(iv) Coefficient of friction:

\[
\mu = \frac{P}{N} = \frac{\text{Pin deflection force}}{\text{Axial load on pin}}
\]  \hspace{1cm}  \text{(6)}

\[
= \frac{1.10}{3.25}
\]

\[
\mu = 0.34
\]

(v) Statistical Significance Testing.

Method used: "t test applied to paired observationsP.  
The problem was that of testing a hypothetical population mean (assuming population is infinite. 

Two hypotheses used:

1) Null Hypothesis: That there is no difference between the true means of original and retests, i.e. $\mu_d = 0$.

2) Alternative Hypothesis: $\mu_d \neq 0$.

Wear Distance:

The variance of the discrepancy (d) between individual original and retests was not known and so estimated from the sample.

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>9</th>
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<th>12</th>
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<tbody>
<tr>
<td>ORIGINAL</td>
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<td>.062</td>
<td>.094</td>
<td>.094</td>
<td>.265</td>
<td>.140</td>
<td>.156</td>
<td>.172</td>
<td>.390</td>
<td>.218</td>
<td>.156</td>
<td>.223</td>
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<tr>
<td>RETEST</td>
<td>.085</td>
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<td>.131</td>
<td>.109</td>
<td>.468</td>
<td>.125</td>
<td>.156</td>
<td>.187</td>
<td>.390</td>
<td>.203</td>
<td>.174</td>
<td>.218</td>
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<tr>
<td>DISCREPANCY</td>
<td>-.009</td>
<td>-.008</td>
<td>+.037</td>
<td>+.015</td>
<td>+.203</td>
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<td>0</td>
<td>+.015</td>
<td>0</td>
<td>-.015</td>
<td>+.018</td>
<td>-.005</td>
</tr>
</tbody>
</table>

$\bar{d} =$ $+.019667$

$\text{variance } s^2 = \sum \frac{x^2}{n} - \bar{x}^2$

$= \frac{1}{12} \left[ .009^2 + .008^2 + .037^2 + .015^2 + .203^2 + .015^2 + .015^2 + .015^2 + .018^2 + .005^2 \right] - (0.019667)^2$

hence $s^2 = 3.2775 \times 10^{-3}$

$s = 5.72498 \times 10^{-2}$

Applying Bessel's correction to obtain a best estimate of the population standard deviation of the discrepancies:

$\hat{\sigma} = s \sqrt{\frac{n}{n-1}}$ (8) = $5.72498 \times 10^{-2} \sqrt{\frac{12}{12-1}}$

$= 5.97955 \times 10^{-2}$
Assuming value of an infinite population mean discrepancy = 0

\[ 't' = \frac{\bar{x} - \bar{\bar{x}}}{\frac{\sigma}{\sqrt{n}}} \]  

\[ = \frac{0.019667 \times \sqrt{12}}{5.97955 \times 10^{-2}} \]

\[ 't' = 1.14. \]

Referring to 't' tables for 11 degrees of freedom:

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>20%</th>
<th>10%</th>
<th>5%</th>
<th>2%</th>
<th>1%</th>
<th>.2%</th>
<th>.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>'t'</td>
<td>1.36</td>
<td>1.80</td>
<td>2.20</td>
<td>2.72</td>
<td>3.11</td>
<td>4.02</td>
<td>4.44</td>
</tr>
</tbody>
</table>

HIGHLY PROBABLY INSIGNIFICANT NOT SIGNIFICANT SIGNIFICANT HIGHLY SIGNIFICANT

The "probability" refers to the chance that the average discrepancy (in a sample of 12 sets of paired data) of a fictitious infinite population of paired tests is zero.

The null hypothesis was therefore accepted in the case of wear distance.

Coefficient of Friction:

<table>
<thead>
<tr>
<th>SPECIMEN PAIR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORIGINAL</td>
<td>.21</td>
<td>.27</td>
<td>.27</td>
<td>.24</td>
<td>.31</td>
<td>.31</td>
<td>.35</td>
<td>.39</td>
<td>.33</td>
<td>.25</td>
<td>.27</td>
<td>.31</td>
</tr>
<tr>
<td>RETEST</td>
<td>.20</td>
<td>.26</td>
<td>.29</td>
<td>.24</td>
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<td>.29</td>
<td>.35</td>
<td>.39</td>
<td>.34</td>
<td>.25</td>
<td>.27</td>
<td>.25</td>
</tr>
<tr>
<td>DISCREPANCY</td>
<td>.01</td>
<td>.01</td>
<td>-.02</td>
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<td>-.03</td>
<td>.02</td>
<td>0</td>
<td>0</td>
<td>-.01</td>
<td>.01</td>
<td>0</td>
<td>.06</td>
</tr>
</tbody>
</table>
Null Hypothesis: There is no difference between the true means of original and retests, i.e. $\mu_d = 0$

Alternative Hypothesis: $\mu_d \neq 0$

Average discrepancy $d = 4.16667 \times 10^{-3}$

Variance $s^2 = \frac{\sum x^2}{n} - \bar{x}^2$

\[
= \frac{1}{12} \left[ .01^2 + .01^2 + .02^2 + .03^2 + .02^2 + .01^2 + .01^2 + .06^2 \right]
- \left( 4.1667 \times 10^{-3} \right)^2
\]

$s^2 = 4.65972 \times 10^{-4}$

$s = 2.15864 \times 10^{-2}$

Bessel's correction:

$\bar{\sigma} = s \sqrt{\frac{n}{n-1}}$

$= 2.25462 \times 10^{-2}$

\[
't' = \frac{4.16667 \times 10^{-3} \times \sqrt{12}}{2.25462 \times 10^{-2}}
\]

\[
't' = 0.64
\]

Referring to 't' tables, $'t' = 0.64 \Rightarrow$ highly insignificant, therefore null hypothesis accepted and original rests were highly likely to be valid.
Temperature Rise.

<table>
<thead>
<tr>
<th>SPECIMEN PAIR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>11</th>
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</thead>
<tbody>
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<tr>
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<td>55</td>
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<tr>
<td>DISCREPANCY</td>
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<td>-2</td>
<td>-2</td>
<td>0</td>
<td>-2</td>
<td>-1</td>
<td>-4</td>
<td>5</td>
<td>-1</td>
<td>0</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>

av. discrepancy $\bar{d} = 0.75$

Null hypothesis $H_0: \mu_d = 0$

Alternative hypothesis $H_1: \mu_d \neq 0$

Variance $s^2 = \frac{\sum x^2}{n} - \overline{x}^2$

$$s^2 = \frac{1}{12} \left[ 2^2 + 2^2 + 2^2 + 2^2 + 1^2 + 4^2 + 5^2 + 1^2 + 9^2 + 5^2 \right] - (0.75)^2$$

$$s^2 = 2.1875$$

$$s = 1.47902$$

$$\hat{\sigma} = \frac{1.47902}{\sqrt{12}} = 1.54497$$

$$t' = \frac{0.75 \times \sqrt{12}}{1.54497} = 1.68$$

Referring to $t$ tables $t' = 1.68 \Rightarrow$ not significant therefore

null hypothesis is accepted and original tests are likely to be

valid. (However, evidence is not as strong as in previous cases.)
Surface Texture.

<table>
<thead>
<tr>
<th>SPECIMEN PAIR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</tr>
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<tbody>
<tr>
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<td>3.05</td>
<td>8.04</td>
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<td>4.54</td>
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<td>4.94</td>
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</tr>
<tr>
<td>RETEST</td>
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<td>5.50</td>
<td>4.72</td>
<td>4.75</td>
<td>5.85</td>
<td>5.20</td>
<td>2.57</td>
</tr>
<tr>
<td>DISCREPANCY</td>
<td>0.52</td>
<td>-0.07</td>
<td>0.11</td>
<td>-0.31</td>
<td>-0.03</td>
<td>1.85</td>
<td>-0.91</td>
<td>-1.0</td>
<td>-0.95</td>
<td></td>
</tr>
</tbody>
</table>

av. discrepancy $\bar{d} = .097$

Null hypothesis $\mu_d = 0$

Alternative hypothesis $\mu_d \neq 0$

Variance $s^2 = \frac{\sum x^2}{n} - \frac{x^2}{n}$

$$s^2 = \frac{1}{10} \left[ 0.52^2 + .07^2 + -11^2 + -31^2 + .03^2 + .18^2 + 1.85^2 + .91^2 \
+ 1^2 + -95^2 \right] - (.097)^2$$

$s^2 = .647581$

$s = .804724$

$\hat{\sigma} = .804724 \sqrt{\frac{12}{11}} = .840507$

$t' = \frac{.097 \sqrt{12}}{.840507} = 0.4$

$t' = 0.4 \Rightarrow$ highly insignificant (10 df.)

Null hypothesis accepted.
Weight Losses.

<table>
<thead>
<tr>
<th>CIMEN PAIR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
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<td>.0041</td>
<td>.0142</td>
<td>.0066</td>
<td>.0165</td>
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<td>EST</td>
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<td>-.0041</td>
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<td>-.0007</td>
<td>+.003</td>
<td>.0004</td>
<td>-.0013</td>
<td>.0004</td>
<td>-.0000</td>
</tr>
</tbody>
</table>

av. discrepancy $\bar{d} = -7.23333 \times 10^{-3}$

Null hypothesis $: \mu_d = 0$

Alternative hypothesis $: \mu_d \neq 0$

Variance $s^2 = \frac{\sum x^2}{n} - \overline{x}^2$

$$s^2 = \frac{1}{12} \left[ .0097^2 + .0027^2 + .0918^2 + .0041^2 + .0002^2 + .0008^2 + .0007^2 + .003^2 \\ + .0004^2 + .0013^2 + .0004^2 + .0003^2 \right] - (7.23333 \times 10^{-3})^2$$

$s^2 = 6.65070 \times 10^{-4}$

$s = .0257890$

$\hat{\sigma} = s \sqrt{\frac{n}{n-1}} = 2.69357 \times 10^{-2}$

$t' = \frac{7.23333 \times 10^{-3} \sqrt{12}}{2.69357 \times 10^{-2}}$

$t' = 0.93$

$t' = 0.93 \Rightarrow$ highly insignificant discrepancies.

Null hypothesis accepted.
(vi) Lineal analysis: (Ref. Fig. 55)

(Minimum of three intercepts required)

Total length of line $L_1 = 82 \text{ mm}$

length of Intercepts $= l_1 + l_2 + l_3 + l_4 + l_5$

$= 8 + 7 + 8 + 3 + 2$

$= 28 \text{ mm}$

$$L_f = \frac{\text{length of Intercepts}}{\text{Total length}} = \frac{28}{82}$$

$= 0.34$

Total length of line $L_2 = 83 \text{ mm}$

length of Intercepts $= 10 + 2 + 3 + 5 + 3$

$= 23$

$$L_f = \frac{23}{83}$$

$= 0.28$

Total length of line $L_3 = 82 \text{ mm}$

length of Intercepts $= 1 + 9 + 8 + 7 + 4$

$= 29$

$$L_f = \frac{29}{82}$$

$= 0.35$

Average $= (0.34 + 0.28 + 0.35)/3$

$= 0.32$

Therefore the lineal fraction ($L_f$) of graphite in Fig. 55 (assuming a random distribution) is 0.32 from (10) lineal fraction = volume fraction therefore specimen contains a volume of 32% graphite by volume.
Density ratio between graphite and aluminium = 2.2 : 2.7
therefore wt fraction = $32 \times \frac{2.2}{2.7} = 26\%$.

(vii) Fatigue Testing:

Bending stress = \( \frac{\text{bending moment}}{\text{section modulus}} \) \hspace{1cm} (13)

\[
= \frac{1.02}{\pi \times 0.053}\frac{32}{32}
\]

Bending stress = 83.11 MN/m\(^2\).

(viii) Machinability Calculations:

\[
r_c = \frac{t_1}{t_2} = \frac{.137}{.89} = .154
\] \hspace{1cm} (14)

\[
\phi = \tan^{-1}\left[\frac{r_c \cos\alpha}{1 - r_c \sin\alpha}\right]
\] \hspace{1cm} (16)

\[
= \tan^{-1}\left[\frac{.154 \cos 5}{1 - .154 \sin 5}\right] = 8.84^\circ.
\]

\[
\tau - \alpha = \tan^{-1}\left[\frac{F_T}{F_C}\right]
\] \hspace{1cm} (18) = \tan^{-1}\left[\frac{250}{400}\right] = 32^\circ.

\[
D = \frac{\cos(\tau - \alpha)}{\cos(\phi + \tau - \alpha)} \hspace{1cm} (17) = \frac{\cos 32}{\cos(8.84 + 32)}
\]

\[
= 1.12
\]
\[ \mu = \tan \alpha = \tan(\alpha + 5) \]
\[ = \tan 37 = 0.51 \]

\[ P_s = \frac{P_c \times V_c / 60}{\pi / 4 \times \left( D_W^2 - D_M^2 \right) f.N.} \quad (21) \]

\[ V_c = \text{rpm} \times \text{circumference} = 350 \times \pi \times 0.0785 \]
\[ = 8.63 \text{ m/min} \]

\[ P_s = \frac{400 \times 8.63 / 60}{\pi / 4 \times \left( 9.35^2 - 6.35^2 \right) \times 0.136 \times \frac{350}{60} \times 10^{-6}} = 1.97 \text{ MW/m}^3 \]
FIGURES
Fig. 1  Hohman Wear Tester

Fig. 2  Typical Result - Hohman Wear Test
Fig 3. - Diamond Scratch Test

Fig 4. - Pin on Disc Test
Fig. 5 Rheocast Process

Fig. 6 Thixocast Process
Fig 7  Thixotropic Hysteresis Loops

Fig 8  Squeeze Casting
Fig 10  Production of Bi-metallic Strip
Fig 11 Vortex Equipment

Fig 12 Vortex Impeller

Schematic diagram of impeller (R, = 15 mm, R, = 10 mm, 6-3 mm, R, = 18 mm, R, = 22 mm)
Fig. 13 - VISCOMETER (Spencer)

Fig. 14 - COMPOCASTING EQUIPMENT (Mehrabian)
Fig. 15 CONTINUOUS RHEOCASTING UNIT
Fig. 16—AIR ENTRAPMENT
<table>
<thead>
<tr>
<th>DETAIL NO.</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>1.</td>
<td>Framework</td>
</tr>
<tr>
<td>2.</td>
<td>Variable speed drive</td>
</tr>
<tr>
<td>3.</td>
<td>Motor</td>
</tr>
<tr>
<td>4.</td>
<td>Bearing housing assembly</td>
</tr>
<tr>
<td>5.</td>
<td>Rotor drive shaft</td>
</tr>
<tr>
<td>6.</td>
<td>Rotor</td>
</tr>
<tr>
<td>7.</td>
<td>Graphite injector piston</td>
</tr>
<tr>
<td>8.</td>
<td>Pushrod</td>
</tr>
<tr>
<td>9.</td>
<td>Graphite injector screw</td>
</tr>
<tr>
<td>10.</td>
<td>Main crucible</td>
</tr>
<tr>
<td>11.</td>
<td>Collection crucible</td>
</tr>
<tr>
<td>12.</td>
<td>Plug</td>
</tr>
<tr>
<td>13.</td>
<td>Semi-solid zone heater</td>
</tr>
<tr>
<td>14.</td>
<td>Liquid zone heater</td>
</tr>
<tr>
<td>15.</td>
<td>Insulation</td>
</tr>
<tr>
<td>16.</td>
<td>Timing belt and pullies</td>
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<tr>
<td>17.</td>
<td>Collection crucible release lever</td>
</tr>
<tr>
<td>18.</td>
<td>Liquid zone temperature controller</td>
</tr>
<tr>
<td>19.</td>
<td>Semi-solid zone temperature controller</td>
</tr>
<tr>
<td>20.</td>
<td>Thermocouples</td>
</tr>
<tr>
<td>21.</td>
<td>Temperature readout</td>
</tr>
<tr>
<td>22.</td>
<td>Temperature recorder</td>
</tr>
<tr>
<td>23.</td>
<td>Tachometer</td>
</tr>
<tr>
<td>24.</td>
<td>Wattmeter</td>
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</tbody>
</table>

Items not shown:

18. Liquid zone temperature controller
19. Semi-solid zone temperature controller
20. Thermocouples
21. Temperature readout
22. Temperature recorder
23. Tachometer
24. Wattmeter

Fig. 17b. GENERAL ARRANGEMENT-PARTS LIST.
Fig 18  BEARING HOUSING ASSEMBLY
Fig. 19. Rotor Assembly

- 32.0 mm
- Milled Spiral Form
- 38 mm Square Section Spiral
- Push-Rod (8)
- Graphite Injector Piston (7)
- Rotor (6)
- ø25 mm Bore
- Graphite Storage Area
- Mat: Mild Steel (Refractory Coated)
- 4 Holes: ø3 mm
Fig. 20 - MAIN CRUCIBLE
Fig. 21 - PLUG

Fig. 22 - HEATER DESIGN
Fig. 23 - COPPER DIE

Fig. 24 - SQUEEZE CASTING DIE & PUNCH
Fig. 26 - MODIFICATIONS TO PUNCH & DIE
Fig. 25 - SQUEEZE CASTING DIE (INGOT CASTING)
Fig 27. COMPOCASTING UNIT

Fig 28. Rotor Modifications (i)

- GRID
- Φ 25.4 mm bore extended to base of rotor
Fig. 29 - ROTOR MODIFICATIONS (ii)
Fig. 30 - Variation in Shear Rate

Fig. 32 - Variation in % Solid (8% Si)
Fig. 31. - Al-Si EQUILIBRIUM DIAGRAM

TEMP. (°C)

% SILICON
1-OFF
Ø10 MM
(FOR P.O.D.
WEAR TESTS)

1-OFF
(FOR ABRASIVE
WEAR TESTING)

8 MM

3-OFF
Ø12.5 MM
(FOR TENSILE
TESTS)

Fig. 33- CUTTING OF INGOT CASTING
Fig. 34 - POWER MEASUREMENT

\[ \text{POWER} = I \times V \]
\[ \text{TOTAL POWER} = W_1 + W_2 \]
Fig. 36 - COMPOCASTING UNIT & SQUEEZE CASTING PRESS
<table>
<thead>
<tr>
<th>DETAIL NO.</th>
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<tbody>
<tr>
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<tr>
<td>3.</td>
<td>Motor</td>
</tr>
<tr>
<td>4.</td>
<td>Bearing housing and shaft assembly</td>
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<tr>
<td>5.</td>
<td>Load plate</td>
</tr>
<tr>
<td>6.</td>
<td>Base plate</td>
</tr>
<tr>
<td>7.</td>
<td>Runner and guide</td>
</tr>
<tr>
<td>8.</td>
<td>Carriage</td>
</tr>
<tr>
<td>9.</td>
<td>Crantiwheel</td>
</tr>
<tr>
<td>10.</td>
<td>Connecting rod</td>
</tr>
<tr>
<td>11.</td>
<td>Diamond and mounting</td>
</tr>
<tr>
<td>12.</td>
<td>Base plate</td>
</tr>
<tr>
<td>13.</td>
<td>Load plate</td>
</tr>
<tr>
<td>14.</td>
<td>Disc</td>
</tr>
<tr>
<td>15.</td>
<td>Timing belt and toothed pullies</td>
</tr>
<tr>
<td>16.</td>
<td>Oil bath</td>
</tr>
<tr>
<td>17.</td>
<td>Weights (load)</td>
</tr>
<tr>
<td>18.</td>
<td>Perspex cover</td>
</tr>
<tr>
<td>19.</td>
<td>Resilient mounting</td>
</tr>
<tr>
<td>20.</td>
<td>Ball bushes and ground pillars</td>
</tr>
<tr>
<td>21.</td>
<td>Position transducer (to record change in pin length)</td>
</tr>
<tr>
<td>22.</td>
<td>Counter and automatic test-stop device</td>
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</tbody>
</table>

Items not shown:

<table>
<thead>
<tr>
<th>DETAIL NO.</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>23.</td>
<td>Position transducer (to record coefficient of friction)</td>
</tr>
<tr>
<td>24.</td>
<td>Thermocouples</td>
</tr>
<tr>
<td>25.</td>
<td>Recorder (millvolt)</td>
</tr>
<tr>
<td>26.</td>
<td>Transducer power supply</td>
</tr>
<tr>
<td>27.</td>
<td>Hygrometer and probe</td>
</tr>
</tbody>
</table>

Fig. 37b. PARTS LIST FOR WEAR TEST UNIT.
Fig. 38 - COMPLETED WEAR TEST UNIT.

Fig. 39 - TRANSDUCER POWER UNIT (ABOVE) & LINSEIS 4-CHANNEL RECORDER (BELOW)
Fig. 40 - HYGROMETER & PROBE

DIRECTION OF MACHINING LAY

SURFACE FLYCUT MILLED TO SURFACE TEXTURE 0.5 µmRq

40 MM

55 MM

4 - 8 MM

Fig. 41 - WEAR TEST SPECIMEN FOR RECIPROCATING TEST
**Fig. 42 - Wear Test Specimen for Pin on Disc Test**

**Fig. 43 - Fatigue Test Specimen**
Fig. 44 - FATIGUE TESTING MACHINE

Fig. 45 - CORROSION TESTING SPECIMEN
Fig. 46 - CENTER LATHE & DYNAMOMETER

Fig. 47 - LATHE TOOL DYNAMOMETER (a) & TOOL DEFLECTION INDICATOR (b)
Fig. 48 - DERIVATION OF WEAR VOLUME

Fig. 49 - MEASUREMENT OF SCRATCH WIDTH.
Fig. 50 - Calculation of Coefficient of Friction

Fig. 51 - Position of Transducer
Fig. 52 - SURFACES WITH SIMILAR RA VALUES.

Fig. 53 - BEARING RATIO (tp)

tp = \frac{l_1 + l_2 + l_3 + l_4 + l_5 + l_6}{L} \times 100 (\%) 

P = DEPTH OF MEAN OF AMPLITUDE DISTRIBUTION
Fig. 54 - Corrosion Sample Coupled to Cast Iron Rod.

Fig. 55 - Lineal Analysis
Fig. 56 - Tool Forces
Fig. 57 - SHEAR PLANE MODEL IN CUTTING
Fig 58 - LM30 + 4% WT. GRAPHITE (x100)  
(SQUEEZE CAST)

Fig 59 - LM30 + 4% WT. GRAPHITE (x100)  
(GRAVITY DIE CAST)
Fig. 60 - GRAPHITE DISTRIBUTION

Fig. 61 - SAND CAST CONTROL (8.25% WTSi) X100
Fig. 68 - S.R. 500 sec⁻¹
23% Vol. Solid
(8.25% WT Si)

Fig. 69 - S.R. 500 sec⁻¹
23% Vol. Solid
(8.25% WT Si)
+ 2% WT GRAPHITE

Fig. 70 - S.R. 500 sec⁻¹
23% Vol. Solid
(8.25% WT Si)
+ 4% WT GRAPHITE

Fig. 71 - S.R. 500 sec⁻¹
23% Vol. Solid
(8.25% WT Si)
+ 6% WT GRAPHITE
Fig. 72 - S.R. 500 sec\(^{-1}\)  
16% VOL. SOLID  
(8.25 % WT Si)  
+ 8% WT GRAPHITE

Fig. 73 - GRAPHITE DISTRIBUTION
Fig. 74 - Influence of shear rate & graphite content on viscosity of 8.25% Si alloy.
Fig. 75 - TORQUE REQUIRED FOR SHEARING

BAND OF TORQUE REQUIRED TO SHEAR 4% WT Si ALLOY
Fig. 77 TORQUE REQUIRED FOR SHEARING WITH VARIOUS GRAPHITE ADDITIONS
Fig. 78 - SAMPLE (a) ANALYSIS

(4% Si-Al-GRA Phite RES)
Fig. 70 - SAMPLE (b) ANALYSIS

(LM 30 GRAPHITE RES.

K alpha lines
Fig. B1 - Sample (d) analysis

(16% Si - Al: Graphite Accept)

K alpha lines
Fig. 82 - Microstructure: Sample (a)  
X 100  
(4% Si-Al. Graphite REJ)

Fig. 83 - Microstructure: Sample (b)  
X 100  
(LM 30. Graphite REJ)
Fig. 84 - Microstructure: Sample (c)  
X 100  (12% Si-Al-Graphite Accept)

Fig. 85 - Microstructure: Sample (d)  
X 100  (16% Si-Al Graphite Accept)
(CHLORINE DEGASSED)
Fig. 87: SAMPLE (f) ANALYSIS
FIG. 8B - SAMPLE (8) ANALYSIS

(SODIUM ADDITION & CHLORINE DEGASED)
Fig. 93: REJECTION

Fig. 94: ACCEPTANCE

Fig. 95:
A. ROTOR FROM GRAPHITE ACCEPT MELT
B. ROTOR FROM GRAPHITE REJECT MELT
Fig. 96 -
16% WT Si
X100

Fig. 97 -
16% WT Si + 2% WT GRAPHITE
X100

Fig. 98 -
16% WT Si + 4% WT GRAPHITE
X100
Fig. 99 -
16% WT Si
+ 6% WT
GRAPHITE
X 100

Fig. 100 -
16% WT
+ 6% WT
GRAPHITE
X 400

Fig. 101
16% WT Si
+ 8% WT
GRAPHITE
X 100
Fig. 102 - 12% WT Si
x 100

Fig. 103 - 12% WT Si
x 100

Fig. 104 - 12% WT Si + 2% WT GRAPHITE
x 100
Fig. 105 - 12% WT Si + 8% WT GRAPHITE

Fig. 106 - 8% WT Si

Fig. 107 - 8% WT Si + 6% WT GRAPHITE
Fig. 108 - 8% WT Si + 8% WT GRAPHITE

Fig. 109 - 4% WT Si

Fig. 110 - 4% WT Si + 4% WT GRAPHITE
Fig. III - 16% WT Si + 4% WT GRAPHITE
x 2
Fig. 112 - 8% WT Si + 4% WT GRAPHITE
A - LONGITUDINAL SECTION x1
B - TRANSVERSE SECTION x1
Fig. 113 - Variation in U.T.S. with graphite content
Fig. 114 - Variation in UTS with silicon content
Fig. 114 - VARIATION IN UTS WITH SILICON CONTENT
LOAD: 5 kg

- 4% Si
- 8% Si
- 4% Si + 6% C
- 8% Si + 6% C

Fig. 115 - VARIATION IN WEAR VOLUME WITH Nº STROKES
(4 & 8% Si @ 5 kg)
Fig. 116 - VARIATION IN WEAR VOLUME WITH Nº OF STROKES
(12 & 16% Si @ 5kg)

LOAD: 5kg

- 0 12% Si
- △ 16% Si
- × 12% Si + GC
- □ 16% Si + GC

WEAR VOLUME (mm³)

Nº OF STROKES
Fig. 11.7 - VARIATION IN WEAR VOLUME
WITH Nº OF STROKES
(4 & 8% Si @ 10 kg)

LOAD: 10kg

○ 4% Si
× 8% Si
□ 4% Si + 6% C
△ 8% Si + 6% C

T - TERMINATED DUE TO CHATTER
Fig. 118 - Variation in Wear Volume with No. of Strokes (12 & 16% Si @ 10 kg)

LOAD: 10 kg
- 12% Si
- 16% Si
- 12% Si + GC
- 16% Si + GC

T - TERMINATED DUE TO CHATTER
Fig. 119 - Variation in Wear Volume with No. of Strokes.
(8Si @ 5, 10 kg Loads with 2, 4 & 8 C.)
Fig. 120 - Variation in Wear Volume with No. of Strokes
(16Si @ 5 & 10kg with 2, 4 & 8 C)
Fig. 121 - Variation in length of pin lost with load (4Si & 8Si + 2 & 8C)
Fig. 122 - VARIATION IN LENGTH OF PIN LOST WITH LOAD IN 0.5 HR TEST
(12Si & 16Si + 2 & 8C)
Fig. 123- VARIATION IN COEFFICIENT OF FRICTION WITH GRAPHITE ADDITION (3.25 KG LOAD)
Fig. 124 - Variation in Coefficient of Friction with Graphite Addition (12.6 kg load)
Fig. 125 - Variation in Temperature Rise with Graphite Addition (3.25 kg load)

Temperature Rise (°C)

% Graphite (wt)

0 1 2 3 4 5

0 5 10 15 20 25

8 10 12 14 16

X 16% Si

8% Si

4% Si

2% Si

0% Si

VARIATION IN TEMPERATURE RISE WITH GRAPHITE ADDITION (3.25 KG LOAD)
Fig. 126 - Variation in temperature rise with graphite addition (7.8 kg load)
Fig. 127 - Variation in temperature rise with graphite addition (12.6 kg load)
Fig. 128 - Disc surface texture before tests. (Typical)

(a) Profile (b) Bearing area analysis
Fig. 129 - Typical profiles of pins' surfaces before tests

(a) 12Si 2C
(b) 4Si
Fig. 130 - 4-Si PIN SURFACE PROFILE AFTER 12.6 Kg TEST

Ra - 8.04 μM

Fig. 131 - 4-Si 2C PIN SURFACE PROFILE AFTER 12.6 Kg TEST

Ra 2.1 μM
Fig. 132 - 8 Si PIN Surface Profile After 12.6 kg Test

Ra 4.26 µm

Fig. 133 - 8 Si 4C PIN Surface Profile After 12.6 kg Test

Ra 2.3 µm
Fig. 134 - 12Si PIN SURFACE PROFILE AFTER 12.6 Kg TEST

Ra 5.47 \mu M

Fig. 135 - 12Si.2C PIN SURFACE AFTER 12.6 Kg TEST

Ra 4.9 \mu M
Fig. 136 - 1G Si PIN SURFACE PROFILE  
AFTER 12.6 Kg TEST

Ra 4.54 μM

Fig. 137 - 1G Si 8C PIN SURFACE PROFILE  
AFTER 12.6 Kg TEST

Ra 2.62 μM
### Roughness Assessment

**ISO Filter C/O 0.8 mm**

2 Cut-offs Assessed

**Run # 5**

<table>
<thead>
<tr>
<th>Slice Level</th>
<th>Height (μm)</th>
<th>Depth (μm)</th>
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<tr>
<td></td>
<td>-0.7</td>
<td>9.5</td>
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</tbody>
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**Amplitude Distribution**

**Zone Width**

- 6.0 μm
- 13 cm²

**ID: AL-GR**

20-1-83 Gibson

**Bearing Ratio**

- HSC 9

---

**Roughness Assessment**

**ISO Filter C/O 0.8 mm**

4 Cut-offs Assessed

**Run # 5**

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<th>Slice Level</th>
<th>Height (μm)</th>
<th>Depth (μm)</th>
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</thead>
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<tr>
<td></td>
<td>-0.4</td>
<td>19.1</td>
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</tbody>
</table>

**Amplitude Distribution**

**Zone Width**

- 12.8 μm
- 3 cm²

**ID: 16S 8G PIN 25LB 20-1-83 P R Gibson**

**Bearing Ratio**

- HSC 22

---

**Fig. 138 - Bearing Area Analysis for 16S1 pin**

**Fig. 139 - Bearing Area Analysis for 16S1 8C pin**
Ra 1.52 μM

Fig. 140 - DISC PROFILE AFTER 12.6 Kg LOAD TEST WITH 12Si PIN

Ra 0.73 μM

Fig. 141 - DISC PROFILE AFTER 12.6 Kg LOAD TEST WITH 12Si 2C PIN
Fig. 142 - Bearing area analysis for disc after test with 12Si pin with 12.6 kg load

Fig. 143 - Bearing area analysis for disc after test with 12Si 2C pin with 12.6 kg load
Fig. 144 - RAPID PIN WEAR
- PIN DESTROYED

Fig. 145 - RAPID PIN WEAR
- MATERIAL DEPOSITED ON DISC
Fig. 146 - STEP WEAR

Fig. 147 - STEADY- RAPID WEAR ALTERATION
Fig. 148 - 4Si 2C STEP WEAR
CHART RECORDING (ACTUAL)
Fig. 149 - STEADY-RAPID WEAR TRANSITION
(12Si @ 17.2Kg)
(ALTERATION WEAR)
Fig. 150 - 4Si SEM FRACTURE SURFACE

Fig. 151 - 4Si 4C SEM FRACTURE SURFACE

Fig. 152 - 4Si 6C SEM FRACTURE SURFACE

Fig. 153 - 4Si 8C SEM FRACTURE SURFACE
Fig. 154 - 8Si
SEM FRACTURE SURFACE

Fig. 155 - 8Si 2C
SEM FRACTURE SURFACE

Fig. 156 - 8Si 4C
SEM FRACTURE SURFACE

Fig. 157 - 8Si 6C
SEM FRACTURE SURFACE
Fig. 158 - 12Si
SEM FRACTURE SURFACE

Fig. 159 - 12Si 2C
SEM FRACTURE SURFACE

Fig. 160 - 12Si GC
SEM FRACTURE SURFACE

Fig. 161 - 12Si 8C
SEM FRACTURE SURFACE
Fig. 162 - 16Si
SEM FRACTURE SURFACE
X 500

Fig. 163 - 16Si 2C
SEM FRACTURE SURFACE
X 500

Fig. 164 - 16Si 4C
SEM FRACTURE SURFACE
X 500

Fig. 165 - 16Si 8C
SEM FRACTURE SURFACE
X 500
Fig. 166 - RECIP. DIAMOND TEST, 8Si  200 STROKES  5kg LOAD

Fig. 167 - RECIP. DIAMOND TEST, 8Si 4C  200 STROKES, 5kg LOAD.
Fig. 168 - 4Si
SEM WORN SURFACE
(P.O.D. = 3.25 kg)

x90

Fig. 169 - 4Si
SEM WORN SURFACE
(P.O.D. = 3.25 kg)

x900

Fig. 170 - 4Si 8C
SEM WORN SURFACE
(P.O.D. = 3.25 kg)

x90

Fig. 171 - 4Si 8C
SEM WORN SURFACE
(P.O.D. = 3.25 kg)

x900
Fig. 172 - 8Si
(3.25 kg - P.O.D.)

Fig. 173 - 8Si
(3.25 kg - P.O.D.)

Fig. 174 - 8Si 6C
(3.25 kg - P.O.D.)

Fig. 175 - 8Si 6C
(3.25 kg - P.O.D.)
Fig. 176 - 12Si
(P.O.D. - 3.25 kg)

Fig. 177 - 12Si
(P.O.D. - 3.25 kg)

Fig. 178 - 12Si 8C
(P.O.D. - 3.25 kg)

Fig. 179 - 12Si 8C
(P.O.D. - 3.25 kg)
Fig. 180 - 16Si
(P.O.D. - 3.25 Kg)

Fig. 181 - 16Si
P.O.D. 3.25 Kg

Fig. 182 - 16Si 2C
(P.O.D. - 3.25 Kg)

Fig. 183 - 16Si 2C
(P.O.D. 3.25 Kg)
Fig. 184 - 8Si (P.O.D. - 7.8 kg) x 900

Fig. 185 - 8Si (P.O.D. - 12.6 kg) x 900

Fig. 186 - 8Si 8C (P.O.D. - 7.8 kg) x 900

Fig. 187 - 8Si 6C (P.O.D. - 12.6 kg) x 900
Fig. 188 - 4Si (P.O.D. - 12.6 kg)
X900

Fig. 189 - 4Si 2C (P.O.D. - 12.6 kg)
(STEP WEAR TEST TERMINATED WHEN \( \mu \) HIGH)
X900

Fig. 190 - 4Si 6C (P.O.D. - 12.6 kg)
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 191</td>
<td>12Si (P.O.D. - 12.6 kg) (Step wear test terminated when N low)</td>
</tr>
<tr>
<td>Fig. 192</td>
<td>12Si 2C (P.O.D. - 12.6 kg) (Step wear test terminated when N high)</td>
</tr>
<tr>
<td>Fig. 193</td>
<td>12Si 4C (P.O.D. - 12.6 kg) (Step wear test terminated when N low)</td>
</tr>
<tr>
<td>Fig. 194</td>
<td>12Si 6C (P.O.D. - 12.6 kg)</td>
</tr>
</tbody>
</table>

**Notes:**
- Figures 191 and 192 show the wear test results for 12Si and 12Si 2C respectively, with the step wear test being terminated under specific conditions.
- Figures 193 and 194 show similar tests for 12Si 4C and 12Si 6C, respectively, with notes on the termination criteria for the step wear test.
Fig. 195 - 16 Si
(P.O.D. - 12.6 Kg)

x 900

Fig. 196 - 16 Si 2C
(P.O.D. - 12.6 Kg)
(STEP WEAR-
TEST TERMINATED
WHEN N LOW)

x 900

Fig. 197 - 16 Si 8C
(P.O.D. - 12.6 Kg)

x 900
Fig. 198 - WEAR DEBRIS 16Si (P.O.D. - 12.6 kg) x1000

Fig. 199 - WEAR DEBRIS 16Si 2C (P.O.D. - 12.6 kg) x500

Fig. 200 - WEAR DEBRIS (P.O.D. - 12.6 kg) 16Si 4C x500
Fig. 201 - Areal Analysis of 16Si 4C Casting Section (Positions)
Fig. 202 - 12Si
MACHINED SURFACE

Fig. 203 - 12Si
CHIP

Fig. 204 - 12Si GC
MACHINED SURFACE

Fig. 205 - 12Si GC
CHIP
Fig. 206 - 16Si
MACHINED SURFACE

x 50

Fig. 207 - 16Si
CHIP

x 40

Fig. 208 - 16Si 2C
MACHINED SURFACE

x 50

Fig. 209 - 16Si 2C
CHIP

x 40
Fig. 210 - 8Si 4C - (ORIGINAL CASTING)
Fig. 211 - 8Si 4C (REPEAT CASTING No1)
Fig. 212 - 8Si: 4C (REPEAT CASTING No. 2)
Fig. 213 - 16Si 4C (ORIGINAL CASTING)
Fig. 214 - 16Si 4C (REPEAT CASTING No.1)
Fig. 215 - 16Si 4C (REPEAT CASTING N°2)