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THE EFFECT OF MATERIAL AND PARTICULATE PROPERTIES ON THE COMPACTION OF METAL POWDERS

by

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SYNOPSIS

This investigation attempts to assess quantitatively the influence of material and particulate characteristics upon the compaction behaviour of metal powders. The effects have been studied mainly by isostatic compaction to eliminate the effects of die-wall friction. A range of powders has been studied having a wide variation in material properties.

The application of the accurate data to existing pressure-density formulae resulted in only limited success. This necessitated the formulation of new relationships which were based upon stress-strain behaviour in solid metals. A formula has been proposed which successfully describes the isostatic compaction of metal powders to densities beyond the stage of maximum packing.
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LIST OF SYMBOLS

Ln - natural logarithm
P - compacting pressure (kg/mm²)
ρ - density (g/cm³)
D - fractional density
Dₐ - fractional apparent density
Dₜ - fractional tap density
D₀ - fractional density at zero pressure
β - relative volume
V - compact volume at pressure P
V₀ - compact volume at zero pressure
Vₜ - powder volume at tap density
V∞ - compact volume at theoretical density
A, B, C, K and z constants
X - elongation factor
Y - bulkiness factor
Z - surface factor
MH₁₀μm - microhardness (kg/mm²) referred to an indentation diagonal of 10 microns
1. INTRODUCTION

The process of compaction whereby a loose powder is pressed into a coherent mass is of fundamental importance to a large number of industries. The widespread use of the process has promoted a considerable amount of experimental study but a literature survey has revealed only isolated attempts at studying the underlying principles relating compact density and applied pressure. Moreover, a large number of these references are only concerned with the formulation of empirical relationships of compressibility with pressure whose applicability have been found to be very limited. The few attempts that have been made to correlate powder properties and compaction behaviour have resulted in only limited success.

The main objective of this work was to study the factors influencing the densification of metal powders particularly at the higher density levels. In the initial stages of compaction the amount of porosity is largely controlled by external characteristics of the particles such as their size, shape and surface conditions. However, as compaction proceeds the inherent material properties become the dominant factor controlling densification. For metals this means the ability of the particles to deform, the stress required for deformation, and the influence of strain hardening on the stress requirements for continued deformation. A range of powders was studied, therefore, having a wide variation in material properties. Isostatic compaction was selected initially in order to eliminate die-friction effects and uneven density distributions but several powders were die compacted for comparison.
There is a very limited amount of data available on accurate pressure-density relationships for isostatic compaction and even less data giving comparisons between die and isostatic compaction. Isostatic compaction must not be considered simply as being die-compaction without die-wall friction. Account must be taken of the relatively large area over which pressure is applied in isostatic compaction and the effect of this on entrapped air and pore closure.

The correlation between powder properties and compaction behaviour requires accurate pressure and density measurements particularly at the higher density levels where large pressure increases produce smaller density changes. Therefore, particular attention has been made to the accurate measurement of density and pressure.

The measurement of material properties of metal powders is extremely difficult. The number of material properties that can be determined on a particulate solid is clearly limited and although many more properties can be determined on the bulk material the results are not necessarily related to the original powder properties. Many workers have taken published values of bulk yield strength and related these to experimentally determined compaction behaviour but it can be shown that values can be selected to fit any data.

A material property which can be measured even on small particles is hardness (microhardness) which can be defined as the resistance of a material to indentation by another body under the action of any type of force.
For metals the property is simply a measure of their resistance to permanent or plastic deformation. The hardness is given by a force per unit area and defined in fact as a pressure and one would expect a relationship to exist between hardness and compaction behaviour. Moreover, the dependence of hardness on load should be indicative of how densification proceeds. Although microhardness testing is considered as a scientific research tool and to a large extent outside the field of standardisation, reproducible comparative hardness measurements can be readily made using accurate equipment.

The work has involved the design and manufacture of an isostatic compaction apparatus, a die-compaction tool set and the ancillary equipment and testing procedure necessary for the determination of accurate pressure-density relationships. The powders have been closely characterised and the compaction behaviour has been followed using metallographic techniques.

After obtaining accurate data the results were applied to various well known compaction equations and the influence of the powder variables assessed. In addition to only obtaining a limited fit with the majority of these equations, they were considered to be inadequate because the influence of strain hardening was largely neglected. Various equations were developed, therefore, correcting this omission based upon stress-strain behaviour in solid metals. The complexity of the stress-strain system in a powder compact necessitated the formulation of partially empirical equations.
2. PUBLISHED WORK

2.1 General

A very considerable amount of work has been published over the last fifty years concerned with powder compaction. A literature survey has revealed over 300 original papers closely related to compaction phenomena of which about 75% have been published in the last ten to fifteen years. Most of the recent papers have dealt with the compaction of metal powders, the ceramic and pharmaceutical fields contributing to a far lesser extent, which reflects the rapid expansion in the use of powder metallurgy.

A satisfactory relationship between pressure and density has been the aim of many workers and a considerable number of formulae relating these have been proposed. However, none of these formulae so far seem to be generally applicable and fit the experimental data only over a limited range of pressures.

Although many powders, particularly metals, were compacted\(^{(1,2,3,4)}\) in the 19th century the first formula relating pressure and density for these appears to have been made by Walker\(^{(5)}\) in 1923. He proposed the following relationship after studying the compaction of various salts and lead powder.
\[ \beta = K_1 - K_2 \ln P \]  

(2.1)

where

- \( P \) = pressure
- \( \beta \) = relative volume
- \( K_1 \) and \( K_2 \) are constants.

A similar formula to Walker's was proposed by Balshin (6) in 1938.

\[ \ln P = -A(\beta - 1) + C \]  

(2.2)

This formula has been extensively criticised (7,8,9) for its extension of Hooke's law to plastic deformation, its assumption that particle hardening does not occur, and the fact that the volume change refers not to the initial height of the compact but to the final height corresponding to zero porosity. A practical drawback is that the use of relative volume leads to insensitivity at high pressures.

According to Balshin (10,11) some metal and ceramic powders show a behaviour of the form

\[ \ln P = -A \ln \beta + \ln P_{\text{MAX}} \]  

(2.3)
This formula, which is similar to that for the compression of a gas, refers the compaction behaviour to the instantaneous volume and not to the extreme conditions of loose powder or non-porous solid. Relationships analogous to Equation (2.3) have been proposed by other authors (12,13).

In Equation (2.4), due to Zhdanovich, allowance is made for the effect of particle hardening (14).

\[ P = P_c \left[ \left( \frac{h_0}{h} \right)^n - 1 \right] \left[ \left( \frac{M}{\gamma_0} \right)^n - 1 \right] \]  

(2.4)

where

- \( h \) = compact height at pressure \( P \)
- \( h_0 \) = compact height at zero pressure
- \( \gamma_0 \) = density at zero pressure
- \( P_c \) = constant related to critical creep stress
- \( M \) = specific weight of metal

Meerson (7) has pointed out that according to the experimental data the exponent \( n \) for several metals (iron, copper, nickel, cobalt, tin and lead) is approximately equal to 4 and therefore with very little loss in accuracy Equation (2.4) can be transformed to

\[ \ln(P + K) = -n \ln\beta + \ln P_c \]  

(2.5)
Jones\textsuperscript{(15)} suggested that a linear relationship between \(\ln P\) and relative apparent density implies that the rate of change of density with pressure is inversely proportional to the pressure. Obviously this cannot be valid at high pressures since the relative apparent density will become greater than 1. Jones also points out that a plot of \(\ln P\) versus \(\beta^2\) is equally applicable over a similar limited range.

Smith\textsuperscript{(16)} has proposed the use of the following empirical relationship

\[
C_f = \frac{\rho - \rho_o}{P^{1/3}} \tag{2.6}
\]

where

- \(C_f\) is a constant called the compressibility factor
- \(\rho\) = compact density (g/cm\(^3\)) at pressure \(P\)
- \(\rho_o\) = apparent density (g/cm\(^3\))

The validity of Equation (2.6) has been questioned by several authors and does not appear applicable at high or low pressures.

Shapiro and Kolthoff\textsuperscript{(17)} after investigating silver bromide powders arrived at Equation (2.7) starting with the assumption that the powder mass could be treated as if it were a solid body subject to isostatic compression forces.
where

\[ D = \text{fractional density at pressure } P \]
\[ D_o = \text{fractional density at zero pressure} \]

This formula was also independently proposed by Konopicky (18) after studying the compaction of iron, steel, magnetite, quartz and magnesite powders. Several workers (19, 20, 21) have found Equation (2.7) applicable to density-pressure data of both metallic and non-metallic powders.

Athy (22) previously showed that the density of the earth's sedimentary rock crust is also described by Equation (2.7) where pressure is replaced by depth and \((1 - D_o)\) refers to the average porosity of surface clays.

In 1950 Heuberger (23) proposed a modification of Equation (2.7) in that an empirical value \((D_o)\) is used in place of true density

\[ \ln \frac{D - D_o}{D_o - D} = KP \] (2.8)
Deviations from Equation (2.7) at low pressures have been explained by Konopicky and later by Shapiro in terms of particle rearrangements involving the filling up of larger voids in the powder mass by particles sliding past each other. Deviations at higher pressures have been explained in terms of cold working effects (metal powders) and fragmentation (brittle powders).

In 1948 Torre (24) related the proportionality constant in Konopicky's formula to the upper yield stress of the metal. This concept was based upon the model of a hollow metal sphere, plastically deformed under a uniform pressure. Heckel (20) attempted to produce experimental evidence of Torre's relationship but this was criticised by Donachie and Burr (25) because an arbitrarily assigned value of yield strength had been given as defining K for all powders of a given metal.

Bockstiegel (26) applied Equation (2.7) to both isostatic and die-compacted iron powders and found the correlation completely invalid for his data. Moreover, deviation occurred over the whole range of pressures and it was not considered justifiable to divide the pressure into ranges representing different mechanisms of compaction. This is rather surprising in view of the large amount of support for Equation (2.7) but his conclusions must be seriously considered because of his accurate and careful
experimental techniques. Bockstiegel also criticised the derivation of Torre's formula which, he shows, is based upon mathematically unsound premises.

Cooper and Eaton\(^{(27)}\) introduced a new concept based upon the idea that the size of the pores relative to the size of the surrounding particles determines the kind of pore closing mechanisms. For the sake of simplicity they considered two broad classes of compaction mechanisms; the filling of large holes by particle sliding (involving only slight particle modification by fracture or plastic deformation) and the filling of small holes by plastic flow or fragmentation. From this study Equation (2.9) was developed.

\[
V^* = \frac{V_o - V}{V_o - V_\infty} = a_1 \exp \left(-\frac{K_1}{P}\right) + a_2 \exp \left(-\frac{K_2}{P}\right) \tag{2.9}
\]

where

- \(V^*\) = fractional volume contraction
- \(V_o\) = original volume
- \(V\) = volume at pressure \(P\)
- \(V_\infty\) = volume at theoretical density
- \(K_1\) and \(K_2\) are constants
- \(a_1\) and \(a_2\) are dimensionless coefficients indicating the fraction of theoretical compaction that would be achieved at infinite pressure by each mechanism.
Experimental data for four ceramic powders of markedly different hardnesses gave excellent fit to Equation (2.9).

In 1963 Shapiro\(^{(28)}\) found that his earlier relationship Equation (2.7), appeared satisfactory for plastic materials but did not apply to ceramic powders particularly at low pressures. Retaining the concept of Equation (2.7) he performed a curve-fitting exercise in which porosity was expressed by the general equation,

\[ 1 - D = A_1 e^{-K_1P} \]  \hspace{1cm} (2.10)

For thoria, silica and molybdenum disulphide mixtures he obtained fairly good "fits" using only two terms of Equation (2.10) e.g.

\[ 1 - D = a_1 e^{-K_1P} + a_2 e^{-K_2P} \]  \hspace{1cm} (2.11)

(where subscript 1 refers to the low pressure region and subscript 2 to the high pressure region)

Heckel\(^{(20)}\) arrived at Equation (2.7) by integrating Equation (2.12)

\[ \frac{dD}{dP} = K(1 - D) \]  \hspace{1cm} (2.12)
In 1966, Jovanovic\textsuperscript{(29)} proposed that Equation (2.13) was more applicable than Equation (2.12)

\[
\frac{dV}{dP} = zV
\]  \hspace{1cm} (2.13)

where $V$ is the volume of voids at any pressure $P$. Integrating Equation (2.13) and transforming to the notation of Equation (2.7) one obtains,

\[
\ln \frac{D}{1 - D} = zP + \ln \frac{D_0}{1 - D_0}
\]  \hspace{1cm} (2.14)

Jovanovic states that a better relationship than that obtained by Heckel exists between $z$ and the yield strength of the metal. However, Jovanovic obtained a large amount of his data from the work of Balshin\textsuperscript{(6)} and Kuzmick\textsuperscript{(30)} estimating most of the pressure-density values from published graphs.

Jovanovic also noted a third stage of compaction which he described in terms of fragmentation and deformation of agglomerates. Burr and Donachie\textsuperscript{(31)} had previously shown this stage to exist in the Shapiro equation.

Kawakita\textsuperscript{(32)} adopted a more general approach and proposed an equation of state for powder compression. This, he showed, to be applicable to a very wide range of particulate matter ranging from lead and tungsten to cocoa and sugar. Kawakita's relationship is,
\[ C = \frac{V_o - V}{V_o} = \frac{abP}{1 + bP} \quad (2.15) \]

where

\[ C \] = relative reduction in volume

\[ a \] is a constant related to initial porosity

\[ b \] is a second constant

Kawakita's equation has been shown to give an excellent fit over the widest range of pressures and its use and a possible derivation is given in Section 7. The only other published data using this equation is by Sheinburg\(^{(33)}\) who found it generally applicable except at very low pressures.

2.2 Compaction Stages

Seelig and Wulff\(^{(34)}\) considered the compaction process of powdered metals as consisting of three steps: (1) packing, (2) elastic and plastic deformation and (3) cold working (with or without fragmentation). The authors stressed that the extent and sequence of each step depended to a large extent on the plasticity of the powder. Many years later, Kurtz and Barduhn\(^{(35)}\) plotting \( \ln P \) against \( 1 - D \) produced a three segment plot which Burr and Donachie\(^{(25,31)}\) developed to explain the mechanisms of compaction.
Stage 1 was considered in terms of stacking adjustments leading to close packing and elimination of bridges. This stage ends at about 39% porosity which is not a unique property of metal powders but exhibited by most substances in particulate form. Burr and Donachie noted that surprisingly high pressures are required to reach this density level.

There are a large number of variables that control the initial packing of the particles which include particle shape, absolute size, size distribution and surface properties. Meldau and Stach found that after simple deposition spherical and near spherical particles pack to higher densities than irregular ones. However, at low pressures (or with the application of vibrations) higher comparative densities will be achieved which can be attributed to reorientation of particles.

In general, as the absolute size of the particles decrease the packing density also decreases as shown by Fraser and McGeary. This effect is most likely due to the increasing surface area of the particles affecting friction conditions between particles and contributing to bridging and arching.
Optimum size distributions can be selected whereby the interstices in a bed of particles are occupied by smaller particles thus reducing the overall porosity. Theoretical packing of this nature has been suggested by Furnas (40), Fraser (41) and White and Walton (42) reducing initial porosities to a low level. Bo, Freshwater and Scarlett (43) found that for powders of the same size limits the porosity of a packed bed decreases as the cumulative plot of the size distribution approaches linearity and also that powders of a wide range of sizes pack more closely than those of similar distribution but narrower size limits. McGeary (44) achieved experimentally the remarkably low porosity of 4.9% using a quaternary system with a sevenfold difference in size between individual components.

Donachie and Burr (25) suggested a generalised equation based upon three-stage compaction of the form:

$$D = f_1(P) + f_2(P) + f_3(P) + A$$  \hspace{1cm} (2.16)

where

$$f_1(P) = \text{a function of pressure applying to the region of transitional restacking}$$

$$f_2(P) = \text{a function of pressure applying to the area of local flow}$$
\[ f_3(P) = \text{a complex function of pressure applying to the area of isostatic (elastic plus plastic) compression} \]
\[ A = \text{a geometrical constant related to material shape, size, etc.} \]

As all of the functions are undefined it would appear to assist the development of compaction theory to only a very limited extent.

The extent of particle movement during compaction has recently been the subject of several investigations. Shapiro\(^{(28)}\) by taking photomicrographs during powder compression in a glass die could see no evidence of particle sliding. Bockstiegel\(^{(26)}\) precompacted an iron powder at low pressure (2.5 kg/mm\(^2\)), sintered the compact and found no change in the densification pattern as a result of the formation of strong interparticle bonds.

In 1968 Kostelnick, Kludt and Beddow\(^{(45)}\) published the results of an investigation into the initial stage of compaction. They defined this stage as the region where the density increases from the apparent density to the tap density and showed clearly the effects of particle shape on the extent of this stage. Even at the extremely low pressures employed (less than 0.001 kg/mm\(^2\)) fragmentation of electrolytic and flake copper powders occurred.
The general observation on the first stage as found by Lipson, (46) Sorokin, (47) and many others is that lower initial porosities produce lower relative porosities at high compaction pressures.

Plastic deformation has always been known to occur during compaction of metal powders but very few quantitative investigations have been made. Donachie and Burr (25) found no metallographic evidence of gross plastic deformation in brass powders compacted at pressures up to 70 kg/mm$^2$ and found very little x-ray line broadening after pressing commercial copper powders at similar pressures. However, more extensive deformation was found to occur during pressing if the powders were pressed immediately after annealing. The presence of lattice distortions in green compacts and their elimination by annealing has been qualitatively demonstrated on iron powder compacts by Bockstiegel (48) by means of x-ray back-reflections.

Hirschhorn and Garey (49) studied the extent of plastic deformation in several iron powders by measuring the increase in particle hardness resulting from work hardening. Tundermann (50) also found significant increases in particle hardness during powder compaction.
Numerous workers have shown the effect of an intermediate stress annealing operation on compaction. For example, Greenspan\(^{(51)}\) isostatically compacting beryllium at a constant pressure of 100 kg/mm\(^2\) reduced the porosity successively to 9\%, 3\% and 1\% by intermediate stress-annealing operations. Greenspan identified the importance of strain hardening by suggesting a porosity-pressure relationship of the form

\[
P = K \left( \frac{1 - D}{1 - D_0} \right)^n
\]

(2.17)

where

the "compaction exponent" 'n' is influenced by strain hardening.

2.3 Compaction Method

The majority of the published work on powder compaction has been made in a uni-directional manner in rigid dies; a subject which has recently been critically reviewed by Bockstiegel\(^{(52)}\).
Die-friction effects have not always been fully taken into account in compaction experiments although their magnitude and distribution have been investigated by numerous workers. The investigations can be divided into two general categories; experiments concerned with measurements made on or within the compact and experiments involving external measurements from applied pressure and die distortion.

Internal measurements have been made using hardness measurements\(^{(53,54,55)}\), sectioning and machining\(^{(53,56)}\), by radiography of lead grids\(^{(57,58)}\) and lead spheres\(^{(59)}\) and using coloured powders\(^{(60,61)}\). Kamm and Steinburg\(^{(57)}\) used a lead grid placed within the compact and by radiography observed its deformation. The technique yielded the density and deformation at various points in the compact and the stress trajectories and enabled calculation of the coefficient of friction at the die wall. Train\(^{(62)}\) measured the pressure distribution using a number of manganin coils and found that a close relationship existed between the pressure developed and the apparent density at a point within a compact. Aketa, Tanaka and Tsuwa\(^{(59)}\) assumed a hyperbolic function between pressure and density and obtained very good agreement between theoretical analysis of density distributions and experimental results on cylindrical compacts.
External measurements have been made by Long\textsuperscript{(63, 64)} and Bustamante and Sheinburg\textsuperscript{(65)} who found that the ratio of radial to applied pressure increases as the density increases and is dependent on material, component length and particle size. Long found that for materials such as aluminium that have a constant shear stress the ratio approaches unity (hydrostatic conditions). However, for materials such as copper of the Mohr type (when the yield stress is a function of the normal stress on the shear plane) the radial pressure remains less than the axial pressure.

Recent work by Bockstiegel and Hewing\textsuperscript{(66)} has shown that 60-70\% of the work consumed in the compaction process was required for the plastic deformation of powder particles while the remaining 30-40\% was expended to approximately equal parts on friction and on elastic deformation of the tool and the compact. By comparison with the work spent in torsional deformation of iron and copper rods they estimated the dislocation density in the deformed powder particles to be in the order of $5 \times 10^{11}$ cm$^{-2}$ which indicated a high degree of strengthening of the particles. This assumption was confirmed by the considerable increase in compressive yield strength of green compacts.
An important feature of isostatic compaction is that the effects of die-wall friction are absent, so that much more uniform densities are obtained. This was confirmed by Borok (67) who found only small density decreases towards the centre of isostatic compacts of iron and copper. Furthermore, density differences were not detectable in discs which formed the cross-sections of a cylinder with a length to cross-section ratio of $14.5 : 1$. Powell (68) found that at high densities both die and isostatic compaction produced similar green densities for iron and aluminium powders.
3. EXPERIMENTAL PROCEDURE

The experimental procedure may be divided into three sections describing experiments made before, during and after compaction. The first section involves characterization of the powders and the loose powder mass. Compaction techniques are described in the second section and the last section is concerned with measurements made on the powder compact.

3.1 Particle Characterization

3.1.1 Theoretical Density

It was noted that considerable errors could occur in the measurement of porosity without precise knowledge of the theoretical density at zero porosity. Values cannot be taken from the literature since metal powders contain amounts of non-metallic inclusions. These usually have lower densities than the metal powders and result in the maximum attainable density being lower than literature values for the density of the pure metals and alloys. Also the theoretical and particle densities would enable calculations of internal particle porosity. The presence of closed internal porosity in a large number of metal powders prevents the application of pycnometry.
The procedure for measurement of theoretical density involved the production (by die compaction) of cylindrical compacts of the respective powders. These compacts were thoroughly melted under an atmosphere of high purity argon in a tungsten arc furnace (except for the lead powder which was melted using a bunsen burner). After melting the buttons were cold pressed between flat platens to eliminate any internal shrinkage or gas porosity before annealing to remove the effects of cold work. The annealed buttons were accurately machined to symmetrical form to enable the calculation of their volumes.

3.1.2 Particle Density

The particle density was determined using a Helium/Air Pycnometer. This operates on the principle that the change in pressure of a non-absorbing pure gas within an enclosed vessel accompanying a discrete change in the volume of the vessel is a function of the volume of a solid object also in the vessel. The volume of the powder can be established from the functional relationship, and the density \( (g/cm^3) \) of the powder is then directly obtained by dividing its weight, as determined separately, by its volume.
This apparatus was found to give more consistent results than specific gravity bottle technique using a low viscosity liquid \(^{(69)}\).

### 3.1.3 Particle Hardness

A Reichert micro-hardness tester was used for measurement of particle hardness. This instrument is designed to replace the objective on a Reichert Universal camera-microscope with the measuring objective and pyramid indenter side by side on the top face of the upper moving section. Load is applied by operating the fine focus adjustment and reading the force on the calibrated scale seen in the measuring eyepiece as the diamond is pressed into the clamped specimen via a torsion balance. After indentation movement of the upper section brings the objective into the optical axis for measurement of the indent diagonals. The load scale and measurement scale were accurately calibrated using a set of weights and a graticule respectively.

The indenter is a diamond in the form of a square pyramid with an apex angle of \(136^\circ\) and the load can be varied up to 100g. The surface area of the pyramid shaped impression is calculated by measuring the diagonal of the square base.
The hardness is defined as the ratio between the force \( P \) acting on the indentor and the actual surface area \( M \) of the pyramid shaped permanent impression produced by this force.

If \( P \) is measured in kilograms and \( M \) is square millimetres the hardness \( H \) is calculated by the formula

\[
H = \frac{P}{M} \text{ kg/mm}^2
\]  

(3.1)

The surface area of the impression of apex angle \( \alpha \) and base diagonal \( d \) is given by

\[
M = \frac{d^2}{2 \sin \alpha/2} \text{ mm}^2
\]

(3.2)

\[
= \frac{d^2}{1.8544} \text{ mm}^2
\]

(3.3)

The hardness is given by substituting Equation (3.3) into Equation (3.1)

\[
H = 1.8544 \frac{P}{d^2} \text{ kg/mm}^2
\]

(3.4)
A small sample of the powder to be tested was mixed with -100 mesh bakelite powder and placed in a metallurgical mounting press with a bakelite preform. The powder was polished on successively finer grades of emery papers before final polishing with 6 micron and 1 micron diamond paste. Care was taken that exactly the same preparations were followed for each powder. A minimum of six indentations were made at each load which varied from 1.6g to 32g depending on the size of the particles and their hardness.

Meyer (70) found that the following relationship occurred between load and indentation diagonals:

\[ P = \frac{a d^n}{d} \]  

(3.5)

where

- \( P \) = load
- \( d \) = indentation diagonal
- \( n \) = Meyer exponent

Although this relationship has been disputed by Buckle (71) and other workers it is generally found to apply over a limited range. A log-log plot of load against average indentation diagonal was produced.
for each powder and the Meyer line determined using a least squares computer programme; the Meyer exponent being the slope of the Meyer line. The microhardness referred to an indentation diagonal of 10 microns was calculated from the graph according to:

\[ MH_{10\mu m} = 18.544 \cdot P \text{ kg/mm}^2 \quad (3.6) \]

3.1.4 Particle Size Analysis

The precise determination of particle size can only be made for spherical particles. For other particle shapes a precise determination is impossible, and represents an approximation only, dependent on the testing method.

Sieve analysis is the most widely used technique for size analysis and was used for preliminary examination of the powders. 100g of each powder was sieved for 15 mins. on a set of U.S. Standard sieves where the width of each consecutive opening was \( \sqrt{2} \) times the width of the previous sieve.

Sieving has a number of disadvantages for accurate size analysis including the minimum size limitation of 37 microns.
and the fact that although the particle cross-section must lie within the area of the sieve aperture there is no restriction on length.

This latter point became readily apparent when the examination of two adjacent sieve cuts of the elongated electrolytic iron powder showed the length of the particles to be comparable.

When considering a size analysis technique for research investigations it is important to assess the requirements because each technique measures a characteristic particle size. With the investigation of compaction and the role of particle deformation one could consider that the distance a particle separates surrounding particles is an important criterion. Bearing this in mind a direct microscope technique was used which measured the Feret diameter. This statistical diameter was defined by Feret (72) as follows:

"The most suitable measure is the mean for a sufficient number of particles of about the same size, of the distance between two tangents on opposite sides of the apparent outline of the particle, parallel to an arbitrary fixed direction and irrespective of the orientation of each particle with respect to this direction."
A Fleming Particle Size Micrometer and Analyser, which operates on a vibrating shear principle, was used as this semi-automatic instrument considerably reduces the time involved in microscopic measurements.

The complete batch of each powder was first reduced to a few grams using a rotary sampler and further reduced by liquid sampling. The final sample was evenly dispersed on a microscope and 1000 particles from a fixed area were measured for each powder.

A system of particles is characterised by the properties of total number, length, surface area and volume or weight if the density is uniform. Following the procedure given by Heywood(73) these properties can be expressed in terms of \( dN \), the number of particles in a group with size limits sufficiently close together for the mean size to be represented by \( X \); the property being \( dN \times X \) raised to the appropriate power. The total property for the whole system is the summation of the values for the individual groups and the mean diameters with nomenclature proposed by Heywood(74) shown in Table 1 can be derived.
TABLE 1

Derivation of Mean Diameters

<table>
<thead>
<tr>
<th>Nomenclature and Properties Concerned</th>
<th>Expression for means</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number length mean diameter</td>
<td>$\Sigma x dN/\Sigma dN$</td>
<td>$X_{nl}$</td>
</tr>
<tr>
<td>Length surface mean diameter</td>
<td>$\Sigma x^2 dN/\Sigma x dN$</td>
<td>$X_{ls}$</td>
</tr>
<tr>
<td>Surface volume mean diameter</td>
<td>$\Sigma x^3 dN/\Sigma x^2 dN$</td>
<td>$X_{sv}$</td>
</tr>
<tr>
<td>Volume moment mean diameter</td>
<td>$\Sigma x^4 dN/\Sigma x^3 dN$</td>
<td>$X_{vm}$</td>
</tr>
</tbody>
</table>

3.1.5 Particle Shape

Several methods have been proposed for the characterization of particle shape. Heywood\(^{(74,75,76)}\) has defined various shape coefficients involving the length, breadth and thickness of a particle and derived surface and volume coefficients. A sphericity shape coefficient was devised by Wadell\(^{(77)}\) but this requires knowledge of the surface area of the particle. Hausner,\(^{(78)}\) concerned with metal powders, has proposed three shape
coefficients which despite their shortcomings give three descriptive shape factors and these were adopted for the investigation.

Particle sections were projected onto a microscope screen at a magnification of 500X and the outlines of 25 random particles for each powder were traced. A rectangle of minimum area was drawn around each particle and the length and breadth measured. A planimeter was used to measure the area of each particle and an opisometer to make perimeter measurements. The following shape factors were then calculated for each particle and an average made for each powder.

Elongation factor \( X = \frac{a}{b} \)

where \( a \) is the length and \( b \) the breadth of the rectangle.

Bulkiness factor \( Y = \frac{a \times b}{A} \)

where \( A \) is the projected area of the particle.

Surface factor \( Z = \frac{C^2}{12\pi A} \)

where \( C \) is the perimeter of the projected particle.
The ratio of the sides of the rectangle providing an elongation factor has always been generally used and provides a good indication of whether a particle is equiaxed or to what extent it is elongated. The bulkiness factor will approach 1 as the particle fills the rectangle and the surface factor will be 1 for a sphere and increase as the surface roughness increases.

3.1.6 Surface Area Measurement

The specific surface which is the total surface area of 1 gram of powder is an important powder characteristic because it incorporates size, shape and surface conditions. Two techniques were used for its measurement involving gas adsorption and permeametry.

The first technique used was the well known BET method (79) based on the principle of covering the surface of a material with a monolayer of an absorbed gas. This is achieved by adsorption of nitrogen on a sample maintained at the temperature of liquid nitrogen, (-195°C) under which conditions the gas molecules form a uniform tightly packed monolayer. With the knowledge of the volume of gas adsorbed and the area covered by a single molecule the surface area can be calculated.
Whereas the BET technique measures the total surface area including blind pores, fissures etc., measurement by permeability methods will tend to give the 'envelope' surface area. However, this could be more indicative of the influence of surface area on compaction behaviour.

A Micromeritics Permeameter was used which operates at low pressures with an inert gas under conditions of molecular or Knudsen flow where the mean free path of the gas molecules are comparable with the pore diameter. Although slightly more complex than techniques based on the Kozeny-Carmen equation of laminar flow more reliable results are obtained.

3.1.7 Apparent Density

The apparent densities of the powders were determined according to MPIF Standard 4-45 where a dried amount of powder flows through a Standard Hall Flowmeter Funnel into a 25 cm³ density cup. For non-free flowing powders a Carney Funnel was used and the MPI Standard 28-59 adopted. A minimum of five determinations were made on each powder.
3.1.8 Tap Density

A similar procedure to 3.1.7 was adopted for the tap density measurements except that the density cup was tapped on the side. Tapping was continued until no further improvement in packing, shown by a constant maximum weight, was achieved.

3.2 Compaction Techniques

3.2.1 Isostatic Compaction

The requirement for the isostatic compaction apparatus is a high pressure vessel capable of withstanding fluid pressures up to 100-150 kg/mm², a method for generating these pressures and an accurate technique for pressure measurement. At these relatively high pressures the method of pressure generation considered most appropriate was using a plunger which applied pressure directly to a fluid in a closed vessel.

Pressure Vessel Design. In order to operate at relatively high pressures it was necessary to design and manufacture a compound cylinder. The outer cylinder which is 'shrunk on' produces residual compressive stresses in the inner cylinder and raises its working
pressure limit. The pressure vessel, Fig. 1, consists of a G110 maraging steel insert and an EN30 shrink ring. The calculations necessary for the design of the cylinder and safe operating pressures are given in Appendix I.

The cylinder was constructed by heating the EN30 in a furnace to 500°C and inserting the G110 maraging steel after cooling in liquid nitrogen. The bore of the EN30 was protected during heating by filling with cast iron chips.

Design of Pressure Seals. The top plunger and bottom plug are sealed by a Viton O-ring backed by a beryllium-copper (anti-extrusion) mitre ring. The tolerances on the plunger and die are made to BS1916D precision location.

The terminal seals for the Manganin pressure gauge are made from steel cones 6.35 mm long tapering from 3.17 mm to 1.59 mm. The steel cones are lapped into a conical ceramic insulator which is lapped into appropriate holes in the end of the top plunger. The internal and external leads are soldered to the steel terminal.
Pressure Transmission Fluids. The pressure transmitting medium should not 'freeze' at high pressures and should not be of extremely low viscosity. Lowe and Gould (80) studied the behaviour of several different liquids by subjecting them to increasing isostatic pressures and recording the output of a Manganin gauge. The applied punch pressure and the Manganin gauge pressures were found to be the same for all liquids at pressures up to about 80 kg/mm$^2$. Above this value considerable divergences occurred as shown by their results shown in Fig. 2.

Although pressures of only up to 100 kg/mm$^2$ were envisaged for the initial work castor oil was chosen as the pressure transmitting medium.

Wet Bag Tooling. Solid cylindrical compacts were chosen for isostatic compaction as these provide the easiest shape to compact. Latex rubber tubing 12.5 mm internal diameter and 1 mm wall thickness was used for the membrane containing the powder with a 5 mm section of a rubber stopper in each end. The powder volume in each bag is about 2.5 cm$^3$ and two compacts could be produced in the chamber at the same time.
Pressure Measurement. The pressure applied to the plunger indicates the pressure produced in the vessel with possible errors due to friction losses and efficiency of fluid pressure transmission. In order to exclude these possible errors a method of fluid pressure measurement was sought. The absence of commercial measuring devices in this pressure range necessitated the construction of Manganin coils which have been used by Bridgman \(^6\) up to 210 kg/mm\(^2\). After discussions with the National Engineering Laboratory gauges were made by winding 42 swg Manganin wire non-inductively on Perspex spools to give a total resistance of 100 ohms. Copper wires were attached to the Manganin wires through holes in the perspex spools to provide stronger fixing and the coils were subjected to maximum pressure before use. Two pressure gauges were wired in adjacent arms of a Wheatstone bridge, the unbalance being a measure of the pressure differential. The gauge outside the pressure vessel prevents zero wandering by compensating for ambient pressure and temperature variations.

An attempt was made to calibrate the Manganin pressure gauge in the compaction vessel as a high-pressure dead-weight tester was not readily available. The pressure on the plunger was measured using a 200 ton
Elliot load cell with an output of 2 mV/V
During pressure application the output of the load cell and the Manganin gauge were recorded simultaneously on a 2 channel potentiometric recorder. The applied punch pressure and the Manganin gauge output were found to be linear up to about 70 kg/mm$^2$ above which pressure increasing divergence occurred. The applied pressures and deduced internal pressures are given in Table 2.
In order to ensure complete pressure transmission through the rubber membrane a Manganin gauge was fitted inside the sealed membrane in a reservoir of oil. Repeated tests with and without the rubber end plug gave consistent Manganin gauge readings.
3.2.2 Die Compaction

The die-compaction apparatus shown schematically in Fig. 3 consists of a J36 die-block containing a cylindrical compaction cavity 215 mm$^2$ in area x 750 mm long. The die face was coated with a solution of zinc stearate in methylated spirits prior to each compaction cycle. The load applied to the top punch which was varied from 10 to 100 kg/mm$^2$ was measured using a load cell to an accuracy of about 1%.

3.3 Compact Measurements

3.3.1 Green Density

The accurate determination of density for die-pressed powder compacts is straightforward because the volume can be calculated from two or more direct linear measurements. However, due to the irregularity of isostatically pressed powder compacts it becomes necessary to use a displacement technique. These techniques can be extremely accurate for non-porous solids as shown by Nelson and Becker (82) but problems occur with powder compacts due to adsorption of the liquid during immersion. A thin coating of silicone grease was found sufficient to prevent adsorption and the experimental procedure outlined below was initially adopted:
1. Temperature (T)
2. Weight of compact + wire
3. Dry weight of wire (Mw)
4. Weight of compact (Ma) (2)-(3)
5. Weight of compact + grease + wire
6. Weight of compact in liquid
7. Weight of wire immersed in liquid
8. Density of liquid at temperature T (ρm)
9. Density of grease (ρg)
10. Density of wire (ρw)
11. Volume of compact, grease and wire
    \[ \frac{(5)-(6)}{8} \]
12. Volume of grease and wire
    \[ \frac{(5)-(2)+\frac{7}{8}}{(9)} \]
13. Volume of compact
    \[ (11)-(12) \]
14. Density of compact \[ \frac{14}{(13)} \]

Although this technique was found satisfactory and provided a useful comparison, it was considered unsuitable for the measurement of several hundred densities. One technique which appeared viable was the mercury displacement method. Stanworth\(^{(83)}\) modified this technique using a displacement cell comprising one arm of a U-tube, where the equivalent change in the level of the mercury in the other limb was measured by a capacitance technique using a modified De Sauty bridge. This method contained certain advantages but its accuracy of about 1% was not considered sufficient.
The availability of accurate top-pan balances has enabled the construction of the equipment shown in Fig. 4 which is based on Archimedes' Principle. As the compacts would tend to float on top of the mercury it becomes necessary to provide a sinker. It is concerned with this sinker that inaccuracies can occur and it was important to ensure a constant volume of sinker immersed in the mercury. This was achieved by a battery/light/mercury contact circuit and by having the minimum sinker wire diameter at the air/mercury interface.

The mercury balance was calibrated using polished and degreased steel balls of various diameters. Although both published and measured values for the density of mercury at 20°C were found to be 13.546 g/cm³ a value of 13.65 g/cm³ was consistently calculated from the upthrust produced from the steel balls of various known volumes. This error was thought to be due to a surface tension effect preventing the mercury from completely filling the volume at the contact of the specimen and the sinker. However, as the error was consistent the volumes were calculated using a value of 13.65 g/cm³ and the results for the steel balls are given in Table 3.
TABLE 3
Calibration of Density Apparatus

<table>
<thead>
<tr>
<th>Diameter of Ball (cms)</th>
<th>Measured Volume (cm$^3$)</th>
<th>Calculated Volume (cm$^3$)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2698</td>
<td>1.0715</td>
<td>1.0720</td>
<td>+0.05</td>
</tr>
<tr>
<td>1.1108</td>
<td>0.7171</td>
<td>0.7193</td>
<td>+0.31</td>
</tr>
<tr>
<td>0.9519</td>
<td>0.4511</td>
<td>0.4511</td>
<td>0.00</td>
</tr>
<tr>
<td>0.3124</td>
<td>0.2613</td>
<td>0.2627</td>
<td>+0.56</td>
</tr>
</tbody>
</table>

A minimum of three readings were taken for each compact and the mercury was regularly cleaned to ensure accurate results. The following procedure was finally adopted:

1. The weight of compact was measured using an Analytical balance to 0.0001g.

2. The sinker was lowered into the mercury until contact was indicated and then raised using the fine adjustment screw until the contact light just went out.
The balance was then tared to zero (the point of contact break was found to be more consistent than initial contact).

3. Procedure 2 was repeated until a zero reading was maintained. (This was necessary as each adjustment of the tare slightly altered the relative position of the balance pan.)

4. After swinging aside the top arm to enable the sinker to be rapidly removed the compact was placed on the mercury surface, and the sinker replaced. The point of contact break was found using the fine adjustment screw and the balance reading noted.

5. The volume was calculated by dividing the balance reading which gave the upthrust due to the compact by 13.65.

Although this technique is generally only applicable to metals which do not form an amalgam with mercury it was possible to measure the copper compacts. The immersion time of a few seconds was not sufficient to produce any reaction. However, the silver compacts reacted rapidly and various coatings proved unsatisfactory. The compacts, therefore, were machined to cylinders and the volumes measured directly.
3.3.2 **Metallographic Preparation**

Preliminary tests showed that very careful preparation is necessary in order to examine the true structure of green compacts. The final procedure which was used was based on a technique developed by B.C.U.R.A. for the impregnation and examination of coal structures. The apparatus, Fig. 5, is self explanatory but the following standard procedure was essential to obtain good results.

1. After placing the compacts in the moulds the apparatus was evacuated to less than 1 mmHg and heated to $150^\circ$C for about 30 mins.

2. During this time the Araldite resin was also evacuated until all of the air entrapped during mixing was removed.

3. After filling each mould in turn evacuation was continued for a further 30 mins.

4. The moulds were placed in an oven at $120^\circ$C for 2 hours in order to cure the Araldite resin before grinding back to the centre of the compact.

5. The ground surface was polished by wet grinding on rotating emery paper in successive steps using grit sizes of 220, 320, 400 and 600 mesh.
6. Final polishing was achieved using 6μm and 1μm diamond paste.

3.3.3 Compact Hardness

The measurement of compact hardness was made on selected specimens which had been prepared according to the previous section. The same procedure was followed as for the particle hardness (see section 3.1.3) a minimum of 100 random indentations being made on each specimen using a constant load of 8g.

3.3.4 Pore-size Determination

A preliminary investigation was made into the possibility of using the Quantimet (Q.T.M.) image analysing computer for measurements of pore characteristics. The specimen is placed on a microscope fitted with a beam splitting prism, which projects the image simultaneously into a conventional binocular eyepiece for direct viewing and into a television camera. The output from the camera is displayed on a monitor to give a television microscope display for focussing and for selecting appropriate fields. The camera output is also fed into an electronic detector which responds to the changes in output voltage as the scanning spot in the camera tube passes over features in the field. The discrimination can be set
to respond to areas darker or lighter than a selected threshold and the signals obtained from these areas are then fed into the computer which derives the required information and presents it on punch tape. One problem associated with powder metallurgy structures is the intensity threshold. This control selects the brightness intensity above or below which areas are detected by the detection circuitry. It became readily apparent that the selection of threshold level is rather arbitrary and the porosity can vary above or below the measured value. The Quantimet was set to measure the chord size distribution of the pores and the total area percentage. The measurements were made on fifty random fields on each specimen and the average chord size distribution calculated.

However, as mentioned above, the arbitrary positioning of the threshold level produces erroneous porosity measurements. There appears to be two possibilities to overcome these difficulties, firstly to continuously alter the threshold level until the average value for a large number of areas of a specimen corresponds to the measured average value. The second alternative is to consider the possibility of converting the results at a particular threshold setting to the correct results. The former would have taken up a large amount of instrument time and therefore the latter alternative was examined.
Consider the pore shown in Fig. 6, where the continuous outline is the true particle of Area $A$ and the dotted line the particle of larger area, $A_1$, due to a high threshold setting. If the particle is divided into a number of strips a small distance $dX$ apart then the area of one strip of length $L$ is given by Equation (3.6).

$$dA = LdX$$  \hspace{1cm} (3.6)

If $EL$ is the total length of strips, $dX$ is constant (and small), $n$ is the number of strips and $\bar{L}$ the mean length of strip then the total area $A$ is given by Equation (3.7) and total length by Equation (3.8).

$$A = \Sigma dA = \Sigma Ldx$$  \hspace{1cm} (3.7)

$$EL = n\bar{L}$$  \hspace{1cm} (3.8)

Substituting (3.8) in (3.7).

$$A = dXn\bar{L}$$  \hspace{1cm} (3.9)

For area $A_1$

$$A_1 = dXn\bar{L}_1$$  \hspace{1cm} (3.10)
dX and n are constant because the area only increases sideways. Dividing Equation (3.9) by Equation (3.10) gives

\[ \frac{A}{A_L} = \frac{L}{L_L} \] (3.11)

Therefore, for the total system, as \( L_L \) can be calculated from the chord size distribution, and the two areas are known, the true mean chord length \( \bar{L} \) can be calculated. The true chord length distribution can be obtained because each chord length will be in error by a constant amount \( (L_L - \bar{L}) \).
4. MATERIAL PROPERTIES

4.1 Powder Selection

The eight powders given in Table 4 were selected for the investigation covering a broad spectrum of material and particulate properties.

**TABLE 4**

General Description of Powders

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Material</th>
<th>Type</th>
<th>Grade or Batch</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iron</td>
<td>Sponge</td>
<td>MH100.24</td>
<td>Högandörs</td>
</tr>
<tr>
<td>2</td>
<td>Iron</td>
<td>Electrolytic</td>
<td>-100 mesh</td>
<td>Cohens</td>
</tr>
<tr>
<td>3</td>
<td>Copper</td>
<td>Atomised</td>
<td>H5076</td>
<td>B.S.A.</td>
</tr>
<tr>
<td>4</td>
<td>Nickel*</td>
<td>Hydrometallurgical Grade S</td>
<td>Sherritt Gordon</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>310L Stainless Steel</td>
<td>Atomised</td>
<td>N1621</td>
<td>B.S.A.</td>
</tr>
<tr>
<td>6</td>
<td>410L Stainless Steel</td>
<td>Atomised</td>
<td>N6937</td>
<td>B.S.A.</td>
</tr>
<tr>
<td>7</td>
<td>Lead</td>
<td>Atomised</td>
<td>-100 mesh</td>
<td>Hopkin &amp; Williams</td>
</tr>
<tr>
<td>8</td>
<td>Silver*</td>
<td>Electrolytic</td>
<td>Type EC</td>
<td>Johnson Matthey</td>
</tr>
</tbody>
</table>

* -100 +200 mesh used for experiments.
**Powder 1.** The sponge iron powder was selected as being representative of a type widely used in powder metallurgy parts production. It is produced by the reduction of magnetite concentrates with coke and limestone. After heating the resultant sponge iron cakes are separated from residual coke and ash, pulverised and annealed. The resultant powder is porous and contains an appreciable amount of impurities.

**Powder 2.** In comparison to the sponge iron the electrolytic iron was selected because it is virtually non-porous and has a lower level of impurities. The production process involves electrolytic deposition of iron from a ferrous chloride electrolyte at high current densities. The brittle deposit is stripped, comminuted by ball milling and annealed. The chemical composition of the two iron powders are given in Table 5.

### TABLE 5

**Chemical Composition of Powders 1 and 2**

<table>
<thead>
<tr>
<th>Powder</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sponge Iron</td>
<td>0.018</td>
<td>0.11</td>
<td>0.029</td>
<td>0.013</td>
<td>0.005</td>
</tr>
<tr>
<td>2. Electrolytic Iron</td>
<td>0.015</td>
<td>&lt;0.02</td>
<td>0.025</td>
<td>0.016</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Powder 3. The copper powder was produced by atomisation where a stream of the molten metal is disintegrated by jets of high pressure fluid. For the copper and stainless steel powders water was used as the atomising medium which cause the molten droplets to solidify with an irregular form. The powder was found to contain 99.2% copper.

Powder 4. The nickel powder is produced by the Sherritt Gordon Process (84) involving precipitation of nickel from nickel diammine sulphate solution onto special 'seed' powders. Hydrogen at about 200 lb/in$^2$ 'over pressure' is injected into autoclaves containing the heated purified solution. The resultant powder is very pure (99.8% nickel) and has a characteristic botryoidal shape. The copper and nickel powders were selected as examples of face-centred cubic metals for comparison with the body-centred cubic iron.

Powders 5 and 6. The two stainless steel powders were produced by water atomisation as described for powder 3. The austenitic stainless steel (310L) and the martensitic stainless steel (410L), were included to extend the range of hardness and yield strength and have different comparative work hardening rates. Their chemical compositions are given in Table 6.
Table 6

Chemical Compositions of Powders 5 and 6

<table>
<thead>
<tr>
<th>Powder</th>
<th>Cr</th>
<th>Ni</th>
<th>Si</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. 310L</td>
<td>24.2</td>
<td>20.5</td>
<td>1.28</td>
<td>0.085</td>
</tr>
<tr>
<td>6. 410L</td>
<td>12.8</td>
<td>-</td>
<td>0.63</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Powders 7 and 8. The two very soft, compressible powders lead and silver, are capable of compaction to higher densities than the other powders. The lead powder is probably air atomised where the cooling rate of the molten droplets is sufficiently slow for surface-tension forces to spheroidise them before solidification occurs. In contrast, the silver powder produced by electrolytic deposition is highly irregular.

4.2 Particle Hardness

The Meyer analysis of the microhardness results are shown in Figs 7 to 14. The microhardness determined for an indentation diagonal of 5μm, 10μm and 20μm and for a load of 5g are given together with the Meyer exponent in Table 7.
### TABLE 7

**Microhardness of Powders**

<table>
<thead>
<tr>
<th>Powder No.</th>
<th>Microhardness kg/mm²</th>
<th>Meyer Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5µm</td>
<td>10µm</td>
</tr>
<tr>
<td>1</td>
<td>211</td>
<td>168</td>
</tr>
<tr>
<td>2</td>
<td>182</td>
<td>143</td>
</tr>
<tr>
<td>3</td>
<td>133</td>
<td>115</td>
</tr>
<tr>
<td>4</td>
<td>178</td>
<td>148</td>
</tr>
<tr>
<td>5</td>
<td>267</td>
<td>222</td>
</tr>
<tr>
<td>6</td>
<td>363</td>
<td>276</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>62</td>
<td>58</td>
</tr>
</tbody>
</table>
4.3 Grain Size

The considerable variation in grain size of the powders is shown in Figs. 15 - 18. The water atomised powders (Powders 3, 5 and 6) typified by the 310L Stainless Steel powder, Fig. 18, have very fine grain sizes produced by the rapid quenching action of the water. This results in a tendency for the grain size to decrease with particle size. The two iron powders which are annealed as a final stage of their production have considerably larger grain sizes, Figs. 15 and 16.
5. PARTICLE CHARACTERISTICS

5.1 Powder Density

The published and experimentally determined theoretical densities and the particle densities and calculated porosities are given in Table 8.

**TABLE 8**

Density of Experimental Powders

<table>
<thead>
<tr>
<th>No.</th>
<th>Powder</th>
<th>Published Theoretical Density g/cm³</th>
<th>Determined Solid Density g/cm³</th>
<th>Particle Density g/cm³</th>
<th>Particle Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hoganas iron</td>
<td>$7.87^{(1)}$</td>
<td>$7.75_{4}$</td>
<td>7.32</td>
<td>5.60</td>
</tr>
<tr>
<td>2</td>
<td>Cohens iron</td>
<td>$7.87^{(1)}$</td>
<td>$7.84_{3}$</td>
<td>7.81</td>
<td>0.42</td>
</tr>
<tr>
<td>3</td>
<td>Copper</td>
<td>$8.96^{(1)}$</td>
<td>$8.83_{9}$</td>
<td>8.60</td>
<td>2.70</td>
</tr>
<tr>
<td>4</td>
<td>Nickel</td>
<td>$8.90^{(1)}$</td>
<td>$8.91_{4}$</td>
<td>8.83</td>
<td>0.94</td>
</tr>
<tr>
<td>5</td>
<td>310L</td>
<td>$7.81^{(2)}$</td>
<td>$7.76_{7}$</td>
<td>7.74</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>410L</td>
<td>$7.75^{(1)}$</td>
<td>$7.74_{9}$</td>
<td>7.71</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>Lead</td>
<td>$11.68^{(1)}$</td>
<td>$11.28_{0}$</td>
<td>11.20</td>
<td>0.71</td>
</tr>
<tr>
<td>8</td>
<td>Silver</td>
<td>$10.50^{(1)}$</td>
<td>$10.49_{7}$</td>
<td>10.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

5.2 **Particle Size Distribution**

5.2.1 **Sieve Analysis**

The sieve analyses of the powders are given in Table 9.

**TABLE 9**

**Sieve Analysis of Experimental Powders**

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>-70</td>
<td>-</td>
</tr>
<tr>
<td>-70 +100</td>
<td>-</td>
</tr>
<tr>
<td>-100 +140</td>
<td>19.1</td>
</tr>
<tr>
<td>-140 +200</td>
<td>30.8</td>
</tr>
<tr>
<td>-200 +270</td>
<td>23.3</td>
</tr>
<tr>
<td>-270 +400</td>
<td>15.1</td>
</tr>
<tr>
<td>-400</td>
<td>11.7</td>
</tr>
</tbody>
</table>

5.2.2 **Microscope Method for Particle Size Analysis**

The particle size distribution converted to weight % are given in Table 10 and frequency diagrams shown in Fig. 19.
<table>
<thead>
<tr>
<th>Size Class (microns)</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>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>0.42</td>
<td>0.02</td>
<td>0.20</td>
<td>-</td>
<td>0.18</td>
<td>0.10</td>
<td>0.91</td>
<td>0.01</td>
</tr>
<tr>
<td>20-40</td>
<td>4.68</td>
<td>0.31</td>
<td>1.12</td>
<td>-</td>
<td>5.72</td>
<td>0.73</td>
<td>9.38</td>
<td>0.31</td>
</tr>
<tr>
<td>40-60</td>
<td>11.65</td>
<td>1.70</td>
<td>4.01</td>
<td>-</td>
<td>12.42</td>
<td>1.89</td>
<td>26.55</td>
<td>1.31</td>
</tr>
<tr>
<td>60-80</td>
<td>15.59</td>
<td>3.38</td>
<td>10.66</td>
<td>0.36</td>
<td>18.61</td>
<td>4.64</td>
<td>14.19</td>
<td>2.63</td>
</tr>
<tr>
<td>80-100</td>
<td>23.02</td>
<td>6.29</td>
<td>11.70</td>
<td>8.71</td>
<td>21.23</td>
<td>8.88</td>
<td>10.05</td>
<td>3.42</td>
</tr>
<tr>
<td>100-120</td>
<td>13.33</td>
<td>9.97</td>
<td>11.82</td>
<td>24.68</td>
<td>13.68</td>
<td>18.37</td>
<td>14.68</td>
<td>5.10</td>
</tr>
<tr>
<td>120-140</td>
<td>11.85</td>
<td>13.13</td>
<td>15.76</td>
<td>39.82</td>
<td>10.04</td>
<td>23.19</td>
<td>24.25</td>
<td>12.00</td>
</tr>
<tr>
<td>140-160</td>
<td>10.40</td>
<td>22.09</td>
<td>19.60</td>
<td>22.63</td>
<td>5.78</td>
<td>24.66</td>
<td>-</td>
<td>43.98</td>
</tr>
<tr>
<td>180-200</td>
<td>5.28</td>
<td>18.87</td>
<td>11.71</td>
<td>0.72</td>
<td>3.92</td>
<td>5.57</td>
<td>-</td>
<td>3.94</td>
</tr>
</tbody>
</table>
The particle size distribution of the three size fractions of Powder 2 are given in Table 11.

### TABLE 11

**Particle Size Analysis of Powder 2 Size Fractions**

<table>
<thead>
<tr>
<th>Size Class (microns)</th>
<th>Weight % 2A</th>
<th>Weight % 2B</th>
<th>Weight % 2C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-100 +140</td>
<td>-170 +200</td>
<td>-270 +400</td>
</tr>
<tr>
<td>0-20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20-40</td>
<td>-</td>
<td>0.40</td>
<td>2.09</td>
</tr>
<tr>
<td>40-60</td>
<td>0.11</td>
<td>3.45</td>
<td>14.52</td>
</tr>
<tr>
<td>60-80</td>
<td>0.35</td>
<td>6.95</td>
<td>17.60</td>
</tr>
<tr>
<td>80-100</td>
<td>2.13</td>
<td>12.17</td>
<td>13.54</td>
</tr>
<tr>
<td>100-120</td>
<td>20.00</td>
<td>21.03</td>
<td>20.41</td>
</tr>
<tr>
<td>120-140</td>
<td>23.95</td>
<td>17.11</td>
<td>15.55</td>
</tr>
<tr>
<td>140-160</td>
<td>21.44</td>
<td>10.51</td>
<td>11.94</td>
</tr>
<tr>
<td>160-180</td>
<td>17.29</td>
<td>13.12</td>
<td>4.35</td>
</tr>
<tr>
<td>180-200</td>
<td>14.72</td>
<td>15.26</td>
<td>-</td>
</tr>
</tbody>
</table>

The mean diameters calculated according to Table 1 (Section 3.1.4) and standard deviations are given in Table 12.
### TABLE 12

**Mean Diameters and Standard Deviations of Experimental Powders**

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Number-Length Mean Diameter</th>
<th>Length-Surface Mean Diameter</th>
<th>Surface-Volume Mean Diameter</th>
<th>Volume-Moment Mean Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_{nl}$</td>
<td>$\sigma$</td>
<td>$X_{ls}$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>1.</td>
<td>28.9</td>
<td>27.4</td>
<td>54.8</td>
<td>37.8</td>
</tr>
<tr>
<td>2</td>
<td>70.3</td>
<td>54.0</td>
<td>111.8</td>
<td>68.1</td>
</tr>
<tr>
<td>3</td>
<td>34.8</td>
<td>38.1</td>
<td>76.5</td>
<td>56.5</td>
</tr>
<tr>
<td>4</td>
<td>116.9</td>
<td>20.8</td>
<td>120.6</td>
<td>21.1</td>
</tr>
<tr>
<td>5</td>
<td>37.0</td>
<td>27.8</td>
<td>57.9</td>
<td>34.8</td>
</tr>
<tr>
<td>6</td>
<td>45.2</td>
<td>46.2</td>
<td>92.3</td>
<td>66.0</td>
</tr>
<tr>
<td>7</td>
<td>23.9</td>
<td>21.1</td>
<td>42.5</td>
<td>28.1</td>
</tr>
<tr>
<td>8</td>
<td>83.1</td>
<td>55.1</td>
<td>119.7</td>
<td>66.1</td>
</tr>
<tr>
<td>2A</td>
<td>126.1</td>
<td>29.3</td>
<td>132.9</td>
<td>30.1</td>
</tr>
<tr>
<td>2B</td>
<td>79.4</td>
<td>38.5</td>
<td>98.1</td>
<td>42.8</td>
</tr>
<tr>
<td>2C</td>
<td>56.8</td>
<td>27.5</td>
<td>70.1</td>
<td>30.6</td>
</tr>
</tbody>
</table>
5.3 Particle Shape

Particle sections are shown in Figs. 20 to 27 which have been prepared according to Section 3.3.2. The average particle shape characteristics measured from the particle sections are given in Table 13; the complete data being given in Appendix 2.

**TABLE 13**

Shape Characteristics of Powders

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Elongation Factor X</th>
<th>Bulkiness Factor Y</th>
<th>Surface Factor Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.46</td>
<td>0.55</td>
<td>4.15</td>
</tr>
<tr>
<td>2</td>
<td>2.59</td>
<td>0.68</td>
<td>2.06</td>
</tr>
<tr>
<td>3</td>
<td>1.37</td>
<td>0.62</td>
<td>2.85</td>
</tr>
<tr>
<td>4</td>
<td>1.19</td>
<td>0.70</td>
<td>1.21</td>
</tr>
<tr>
<td>5</td>
<td>1.49</td>
<td>0.58</td>
<td>2.54</td>
</tr>
<tr>
<td>6</td>
<td>1.58</td>
<td>0.64</td>
<td>1.77</td>
</tr>
<tr>
<td>7</td>
<td>1.34</td>
<td>0.75</td>
<td>1.24</td>
</tr>
<tr>
<td>8</td>
<td>1.54</td>
<td>0.58</td>
<td>3.90</td>
</tr>
</tbody>
</table>
5.4 Specific Surface

The specific surface (m²/g) of the eight powders determined by Permeatry and B.E.T. Methods are given in Table 14.

TABLE 14

Specific Surface of the Experimental Powders

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Specific Surface (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B.E.T.</td>
</tr>
<tr>
<td>1</td>
<td>0.0902</td>
</tr>
<tr>
<td>2</td>
<td>0.0301</td>
</tr>
<tr>
<td>3</td>
<td>0.0675</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.0850</td>
</tr>
<tr>
<td>6</td>
<td>0.0805</td>
</tr>
<tr>
<td>7</td>
<td>0.1025</td>
</tr>
<tr>
<td>8</td>
<td>0.0425</td>
</tr>
</tbody>
</table>
5.5 Bulk Densities

The apparent and tap densities of the powders, calculated fractional densities and bulk density ratios are given in Table 15.

TABLE 15
The Apparent and Tap Densities of the Experimental Powders

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Apparent Density g/cm³</th>
<th>Tap Density g/cm³</th>
<th>Fractional Apparent Density ( D_a )</th>
<th>Fractional Tap Density ( D_T )</th>
<th>( D_T/D_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.42</td>
<td>3.25</td>
<td>0.312</td>
<td>0.419</td>
<td>1.34</td>
</tr>
<tr>
<td>2</td>
<td>3.06</td>
<td>3.91</td>
<td>0.390</td>
<td>0.499</td>
<td>1.28</td>
</tr>
<tr>
<td>3</td>
<td>2.98</td>
<td>3.66</td>
<td>0.337</td>
<td>0.414</td>
<td>1.23</td>
</tr>
<tr>
<td>4</td>
<td>4.10</td>
<td>4.79</td>
<td>0.460</td>
<td>0.537</td>
<td>1.17</td>
</tr>
<tr>
<td>5</td>
<td>2.46</td>
<td>3.37</td>
<td>0.317</td>
<td>0.439</td>
<td>1.37</td>
</tr>
<tr>
<td>6</td>
<td>2.90</td>
<td>3.73</td>
<td>0.374</td>
<td>0.481</td>
<td>1.29</td>
</tr>
<tr>
<td>7</td>
<td>4.95</td>
<td>7.04</td>
<td>0.439</td>
<td>0.624</td>
<td>1.42</td>
</tr>
<tr>
<td>8</td>
<td>2.10</td>
<td>2.58</td>
<td>0.200</td>
<td>0.246</td>
<td>1.23</td>
</tr>
<tr>
<td>2A</td>
<td>3.34</td>
<td>3.90</td>
<td>0.426</td>
<td>0.497</td>
<td>1.17</td>
</tr>
<tr>
<td>2B</td>
<td>2.94</td>
<td>3.70</td>
<td>0.375</td>
<td>0.472</td>
<td>1.26</td>
</tr>
<tr>
<td>2C</td>
<td>1.84</td>
<td>3.50</td>
<td>0.235</td>
<td>0.447</td>
<td>1.90</td>
</tr>
</tbody>
</table>
6. COMPACTION RESULTS

6.1 Isostatic Compaction

The results of the isostatic compaction experiments are given in Tables 16 to 23. The compaction curves of fractional density and pressure for all the powders are shown in Fig. 28.

TABLE 16

Isostatic Compaction of Powder 1: Högans
MH100 24 Iron Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td>7.377</td>
<td>1.379</td>
<td>5.35₉</td>
<td>0.690</td>
</tr>
<tr>
<td>31.5</td>
<td>7.454</td>
<td>1.190</td>
<td>6.25₉</td>
<td>0.808</td>
</tr>
<tr>
<td>47.3</td>
<td>7.428</td>
<td>1.108</td>
<td>6.70₉</td>
<td>0.864</td>
</tr>
<tr>
<td>63.0</td>
<td>7.435</td>
<td>1.063</td>
<td>6.99₉</td>
<td>0.902</td>
</tr>
<tr>
<td>78.8</td>
<td>7.422</td>
<td>1.037</td>
<td>7.15₉</td>
<td>0.923</td>
</tr>
<tr>
<td>94.5</td>
<td>7.353</td>
<td>1.015</td>
<td>7.2₄₉</td>
<td>0.93₉</td>
</tr>
</tbody>
</table>
### TABLE 17

**Isostatic Compaction of Powder 2: Cohens Electrolytic Iron Powder**

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td>7.376</td>
<td>1.262</td>
<td>5.84</td>
<td>0.745</td>
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<tr>
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<td>7.406</td>
<td>1.114</td>
<td>6.64</td>
<td>0.848</td>
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<tr>
<td>47.3</td>
<td>7.423</td>
<td>1.053</td>
<td>7.01</td>
<td>0.899</td>
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<td>1.042</td>
<td>7.25</td>
<td>0.921</td>
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<tr>
<td>78.8</td>
<td>7.428</td>
<td>1.011</td>
<td>7.34</td>
<td>0.937</td>
</tr>
<tr>
<td>94.5</td>
<td>7.421</td>
<td>0.996</td>
<td>7.45</td>
<td>0.950</td>
</tr>
</tbody>
</table>

### TABLE 18

**Isostatic Compaction of Powder 3: B.S.A. Atomised Copper Powder**

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td>7.465</td>
<td>1.126</td>
<td>6.62</td>
<td>0.750</td>
</tr>
<tr>
<td>31.5</td>
<td>7.302</td>
<td>0.964</td>
<td>7.57</td>
<td>0.857</td>
</tr>
<tr>
<td>47.3</td>
<td>7.473</td>
<td>0.926</td>
<td>8.07</td>
<td>0.914</td>
</tr>
<tr>
<td>63.0</td>
<td>7.419</td>
<td>0.892</td>
<td>8.31</td>
<td>0.944</td>
</tr>
<tr>
<td>78.8</td>
<td>7.478</td>
<td>0.884</td>
<td>8.45</td>
<td>0.957</td>
</tr>
<tr>
<td>94.5</td>
<td>7.335</td>
<td>0.859</td>
<td>8.53</td>
<td>0.966</td>
</tr>
</tbody>
</table>
### TABLE 19

Isostatic Compaction of Powder 4: Sherritt Gordon Nickel Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.6</td>
<td>9.090</td>
<td>1.270</td>
<td>7.158</td>
<td>0.803</td>
</tr>
<tr>
<td>30.5</td>
<td>9.412</td>
<td>1.258</td>
<td>7.482</td>
<td>0.839</td>
</tr>
<tr>
<td>39.4</td>
<td>9.478</td>
<td>1.221</td>
<td>7.763</td>
<td>0.871</td>
</tr>
<tr>
<td>47.3</td>
<td>9.478</td>
<td>1.181</td>
<td>7.969</td>
<td>0.894</td>
</tr>
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<td>55.1</td>
<td>9.431</td>
<td>1.166</td>
<td>8.089</td>
<td>0.907</td>
</tr>
<tr>
<td>63.0</td>
<td>9.320</td>
<td>1.134</td>
<td>8.219</td>
<td>0.922</td>
</tr>
<tr>
<td>70.9</td>
<td>9.512</td>
<td>1.149</td>
<td>8.279</td>
<td>0.929</td>
</tr>
<tr>
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<td>9.499</td>
<td>1.136</td>
<td>8.362</td>
<td>0.938</td>
</tr>
<tr>
<td>86.6</td>
<td>9.492</td>
<td>1.127</td>
<td>8.423</td>
<td>0.945</td>
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<td>94.5</td>
<td>9.520</td>
<td>1.125</td>
<td>8.463</td>
<td>0.949</td>
</tr>
</tbody>
</table>

### TABLE 20

Isostatic Compaction of Powder 5: B.S.A. Atomised 310L Stainless Steel Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td>6.785</td>
<td>1.361</td>
<td>4.985</td>
<td>0.642</td>
</tr>
<tr>
<td>31.5</td>
<td>7.403</td>
<td>1.281</td>
<td>5.779</td>
<td>0.774</td>
</tr>
<tr>
<td>47.3</td>
<td>7.253</td>
<td>1.155</td>
<td>6.279</td>
<td>0.808</td>
</tr>
<tr>
<td>63.0</td>
<td>7.403</td>
<td>1.131</td>
<td>6.542</td>
<td>0.843</td>
</tr>
<tr>
<td>78.8</td>
<td>7.110</td>
<td>1.082</td>
<td>6.842</td>
<td>0.882</td>
</tr>
<tr>
<td>94.5</td>
<td>7.547</td>
<td>1.077</td>
<td>7.004</td>
<td>0.902</td>
</tr>
</tbody>
</table>
### TABLE 21

**Isostatic Compaction of Powder 6: B.S.A. Atomised 410L Stainless Steel Powder**

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td>6.783</td>
<td>1.351</td>
<td>5.02</td>
<td>0.648</td>
</tr>
<tr>
<td>31.5</td>
<td>7.441</td>
<td>1.300</td>
<td>5.72</td>
<td>0.740</td>
</tr>
<tr>
<td>47.3</td>
<td>7.729</td>
<td>1.253</td>
<td>6.16</td>
<td>0.800</td>
</tr>
<tr>
<td>63.0</td>
<td>7.634</td>
<td>1.185</td>
<td>6.41</td>
<td>0.831</td>
</tr>
<tr>
<td>78.8</td>
<td>7.361</td>
<td>1.092</td>
<td>6.74</td>
<td>0.870</td>
</tr>
<tr>
<td>94.5</td>
<td>7.592</td>
<td>1.101</td>
<td>6.89</td>
<td>0.890</td>
</tr>
</tbody>
</table>

### TABLE 22

**Isostatic Compaction of Powder 7: Lead Powder**

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>14.581</td>
<td>1.389</td>
<td>10.56</td>
<td>0.937</td>
</tr>
<tr>
<td>6.6</td>
<td>13.613</td>
<td>1.239</td>
<td>10.98</td>
<td>0.974</td>
</tr>
<tr>
<td>9.8</td>
<td>14.481</td>
<td>1.302</td>
<td>11.12</td>
<td>0.986</td>
</tr>
<tr>
<td>13.3</td>
<td>13.582</td>
<td>1.215</td>
<td>11.17</td>
<td>0.991</td>
</tr>
<tr>
<td>16.4</td>
<td>14.528</td>
<td>1.297</td>
<td>11.20</td>
<td>0.993</td>
</tr>
<tr>
<td>20.0</td>
<td>14.366</td>
<td>1.280</td>
<td>11.22</td>
<td>0.995</td>
</tr>
</tbody>
</table>
TABLE 23

Isostatic Compaction of Powder 8: Silver Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.6</td>
<td>5.151</td>
<td>0.544</td>
<td>9.46</td>
<td>0.902</td>
</tr>
<tr>
<td>31.5</td>
<td>5.490</td>
<td>0.523</td>
<td>9.773</td>
<td>0.931</td>
</tr>
<tr>
<td>39.4</td>
<td>5.229</td>
<td>0.521</td>
<td>10.036</td>
<td>0.956</td>
</tr>
<tr>
<td>47.3</td>
<td>5.504</td>
<td>0.450</td>
<td>10.194</td>
<td>0.971</td>
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<tr>
<td>55.1</td>
<td>5.250</td>
<td>0.514</td>
<td>10.215</td>
<td>0.973</td>
</tr>
<tr>
<td>63.0</td>
<td>5.210</td>
<td>0.508</td>
<td>10.267</td>
<td>0.977</td>
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<td>70.9</td>
<td>5.175</td>
<td>0.503</td>
<td>10.288</td>
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<td>78.8</td>
<td>5.103</td>
<td>0.494</td>
<td>10.330</td>
<td>0.984</td>
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</tbody>
</table>

6.2 Die-Compaction

The details of the die-compaction experiments are given in Table 24 to 28.
### TABLE 24

Die-Compaction of Powder 1: Hoganas MH100.24 Iron Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm(^2))</th>
<th>Weight (g)</th>
<th>Volume (cm(^3))</th>
<th>Density (g/cm(^3))</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.4</td>
<td>7.476</td>
<td>1.495</td>
<td>5.002</td>
<td>0.645</td>
</tr>
<tr>
<td>27.3</td>
<td>7.573</td>
<td>1.317</td>
<td>5.748</td>
<td>0.742</td>
</tr>
<tr>
<td>38.0</td>
<td>7.517</td>
<td>1.212</td>
<td>6.203</td>
<td>0.807</td>
</tr>
<tr>
<td>47.4</td>
<td>7.574</td>
<td>1.158</td>
<td>6.543</td>
<td>0.838</td>
</tr>
<tr>
<td>59.4</td>
<td>7.621</td>
<td>1.123</td>
<td>6.781</td>
<td>0.872</td>
</tr>
<tr>
<td>71.0</td>
<td>7.473</td>
<td>1.275</td>
<td>6.951</td>
<td>0.894</td>
</tr>
<tr>
<td>83.0</td>
<td>7.539</td>
<td>1.061</td>
<td>7.105</td>
<td>0.911</td>
</tr>
<tr>
<td>101.9</td>
<td>7.498</td>
<td>1.039</td>
<td>7.272</td>
<td>0.937</td>
</tr>
</tbody>
</table>

### TABLE 25

Die-Compaction of Powder 2: Cohens Electrolytic Iron Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm(^2))</th>
<th>Weight (g)</th>
<th>Volume (cm(^3))</th>
<th>Density (g/cm(^3))</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
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<td>11.8</td>
<td>7.585</td>
<td>1.429</td>
<td>5.30</td>
<td>0.677</td>
</tr>
<tr>
<td>23.6</td>
<td>7.502</td>
<td>1.240</td>
<td>6.05</td>
<td>0.771</td>
</tr>
<tr>
<td>35.7</td>
<td>7.473</td>
<td>1.146</td>
<td>6.52</td>
<td>0.831</td>
</tr>
<tr>
<td>49.8</td>
<td>7.589</td>
<td>1.104</td>
<td>6.87</td>
<td>0.876</td>
</tr>
<tr>
<td>59.2</td>
<td>7.539</td>
<td>1.066</td>
<td>7.07</td>
<td>0.902</td>
</tr>
<tr>
<td>71.0</td>
<td>7.527</td>
<td>1.047</td>
<td>7.18</td>
<td>0.917</td>
</tr>
<tr>
<td>83.0</td>
<td>7.532</td>
<td>1.027</td>
<td>7.33</td>
<td>0.935</td>
</tr>
<tr>
<td>99.5</td>
<td>7.470</td>
<td>1.011</td>
<td>7.38</td>
<td>0.942</td>
</tr>
</tbody>
</table>
### TABLE 26

Die—Compaction of Powder 3 : B.S.A.
Atomised Copper Powder

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>7.519</td>
<td>1.321</td>
<td>5.69</td>
<td>0.644</td>
</tr>
<tr>
<td>23.6</td>
<td>7.477</td>
<td>1.106</td>
<td>6.76</td>
<td>0.765</td>
</tr>
<tr>
<td>35.4</td>
<td>7.459</td>
<td>1.012</td>
<td>7.37</td>
<td>0.834</td>
</tr>
<tr>
<td>47.2</td>
<td>7.448</td>
<td>0.950</td>
<td>7.84</td>
<td>0.887</td>
</tr>
<tr>
<td>59.0</td>
<td>7.480</td>
<td>0.928</td>
<td>8.06</td>
<td>0.912</td>
</tr>
<tr>
<td>70.8</td>
<td>7.512</td>
<td>0.911</td>
<td>8.24</td>
<td>0.933</td>
</tr>
<tr>
<td>82.7</td>
<td>7.506</td>
<td>0.894</td>
<td>8.39</td>
<td>0.950</td>
</tr>
<tr>
<td>94.4</td>
<td>7.453</td>
<td>0.883</td>
<td>8.44</td>
<td>0.955</td>
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<tr>
<td>106.2</td>
<td>7.509</td>
<td>0.876</td>
<td>8.57</td>
<td>0.970</td>
</tr>
</tbody>
</table>

### TABLE 27

Die—Compaction of Powder 5 : B.S.A.
310L Atomised Stainless Steel

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>7.692</td>
<td>1.715</td>
<td>4.48</td>
<td>0.577</td>
</tr>
<tr>
<td>23.6</td>
<td>7.698</td>
<td>1.480</td>
<td>5.20</td>
<td>0.670</td>
</tr>
<tr>
<td>35.4</td>
<td>7.677</td>
<td>1.342</td>
<td>5.72</td>
<td>0.736</td>
</tr>
<tr>
<td>47.2</td>
<td>7.550</td>
<td>1.238</td>
<td>6.09</td>
<td>0.785</td>
</tr>
<tr>
<td>59.0</td>
<td>7.567</td>
<td>1.184</td>
<td>6.39</td>
<td>0.823</td>
</tr>
<tr>
<td>70.8</td>
<td>7.584</td>
<td>1.150</td>
<td>6.59</td>
<td>0.849</td>
</tr>
<tr>
<td>82.7</td>
<td>7.638</td>
<td>1.125</td>
<td>6.78</td>
<td>0.874</td>
</tr>
<tr>
<td>94.4</td>
<td>7.649</td>
<td>1.104</td>
<td>6.92</td>
<td>0.892</td>
</tr>
<tr>
<td>106.2</td>
<td>7.583</td>
<td>1.078</td>
<td>7.03</td>
<td>0.906</td>
</tr>
</tbody>
</table>
TABLE 28

Die-Compaction of Powder 6 : B.S.A.
410L Atomised Stainless Steel

<table>
<thead>
<tr>
<th>Compacting Pressure (kg/mm²)</th>
<th>Weight (g)</th>
<th>Volume (cm³)</th>
<th>Density (g/cm³)</th>
<th>Fractional Density (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>7.725</td>
<td>2.039</td>
<td>3.78⁹</td>
<td>0.489</td>
</tr>
<tr>
<td>23.6</td>
<td>7.614</td>
<td>1.441</td>
<td>5.28⁹</td>
<td>0.682</td>
</tr>
<tr>
<td>35.4</td>
<td>7.687</td>
<td>1.346</td>
<td>5.71⁹</td>
<td>0.737</td>
</tr>
<tr>
<td>47.2</td>
<td>7.583</td>
<td>1.258</td>
<td>6.02⁸</td>
<td>0.778</td>
</tr>
<tr>
<td>59.0</td>
<td>7.580</td>
<td>1.193</td>
<td>6.35⁴</td>
<td>0.820</td>
</tr>
<tr>
<td>82.7</td>
<td>7.598</td>
<td>1.122</td>
<td>6.71²</td>
<td>0.874</td>
</tr>
<tr>
<td>94.5</td>
<td>7.575</td>
<td>1.096</td>
<td>6.91²</td>
<td>0.892</td>
</tr>
<tr>
<td>106.2</td>
<td>7.544</td>
<td>1.076</td>
<td>7.01²</td>
<td>0.905</td>
</tr>
</tbody>
</table>

6.3 Particle Size Effect

The fractional densities of four different size fractions of powder 2 (Cohns Electrolytic Iron) isostatically compacted at various pressures are given in Table 29 and shown in Fig. 29. The highest densities are achieved with the 'as received' powder; the density level decreasing progressively as the particle size decreases.
### TABLE 29

The Isostatic Compaction of Four Size Fractions of Powder 2: Cohens Electrolytic Iron

<table>
<thead>
<tr>
<th>Compacting Pressure $P$ (kg/mm$^2$)</th>
<th>Fractional Density $D$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As received</td>
</tr>
<tr>
<td>17.3</td>
<td>0.762</td>
</tr>
<tr>
<td>25.0</td>
<td>0.819</td>
</tr>
<tr>
<td>29.5</td>
<td>0.844</td>
</tr>
<tr>
<td>32.7</td>
<td>0.859</td>
</tr>
<tr>
<td>36.7</td>
<td>0.872</td>
</tr>
<tr>
<td>40.3</td>
<td>0.883</td>
</tr>
<tr>
<td>49.0</td>
<td>0.904</td>
</tr>
<tr>
<td>70.8</td>
<td>0.933</td>
</tr>
</tbody>
</table>
6.4 Compact Hardness

The microhardness of compacts produced from two narrow size fractions of Powder 2 (Cohens Electrolytic Iron Powder) are given in Tables 30 and 31. Fig. 30 shows the hardness progressively increasing as the density increases; the finer powder increasing initially at the highest rate. The range of hardness values for a given pressure, as indicated by the coefficient of variation, increases to a maximum level at about 80% density and then falls off as densification proceeds.

**TABLE 30**

Microhardness Survey of Powder 2A
(-100 +140 mesh) Compacts

<table>
<thead>
<tr>
<th>Ocular Reading</th>
<th>Compacting Pressure (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>46-48</td>
<td>-</td>
</tr>
<tr>
<td>49-51</td>
<td>-</td>
</tr>
<tr>
<td>52-54</td>
<td>4</td>
</tr>
<tr>
<td>55-57</td>
<td>8</td>
</tr>
<tr>
<td>58-60</td>
<td>26</td>
</tr>
<tr>
<td>61-63</td>
<td>40</td>
</tr>
<tr>
<td>64-66</td>
<td>18</td>
</tr>
<tr>
<td>67-69</td>
<td>4</td>
</tr>
</tbody>
</table>

Mean Size 61.2 58.7 56.2 54.5 52.6 52.0 51.3
Standard Deviation 3.29 3.05 3.91 3.35 2.68 2.28 2.02
Coef. of Variation % 5.26 5.20 6.95 6.15 5.10 4.40 5.46

Microhardness MH₈g kg/mm² 147 160 175 186 199 204 210
### TABLE 31

**Microhardness Survey of Powder 2C**

*(-270 +400 mesh*) **Compacts**

<table>
<thead>
<tr>
<th>Ocular Reading</th>
<th>Compacting Pressure kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>46-48</td>
<td>-</td>
</tr>
<tr>
<td>49-51</td>
<td>-</td>
</tr>
<tr>
<td>52-54</td>
<td>26</td>
</tr>
<tr>
<td>55-57</td>
<td>18</td>
</tr>
<tr>
<td>58-60</td>
<td>24</td>
</tr>
<tr>
<td>61-63</td>
<td>40</td>
</tr>
<tr>
<td>64-66</td>
<td>16</td>
</tr>
<tr>
<td>67-69</td>
<td>2</td>
</tr>
</tbody>
</table>

| Mean Size     | 60.8     | 54.9  | 53.9  | 51.6  |
| Standard Deviation | 3.06    | 3.22  | 2.61  | 2.70  |
| Coeff. of Variation % | 5.05    | 5.90  | 4.95  | 5.25  |

| Microhardness MH₈g (kg/mm²) | 149 | 183 | 197 | 207 |
6.5 Annealing and Repressing Results

The effect of an intermediate anneal on the density achieved on repressing compacts produced from Powders 1 and 5 are given in Table 32 and 33. A large density increase is achieved with Powder 1 by repressing after annealing at the original compaction pressure.

TABLE 32

Powder 1 (MHL00.24 Iron Powder), Isostatically Repressed at Specified Pressures after Annealing 10 mins. at 800°C in Hydrogen

<table>
<thead>
<tr>
<th>Preform Pressure (kg/mm²)</th>
<th>Repressing Pressure (kg/mm²)</th>
<th>0</th>
<th>15.8</th>
<th>31.5</th>
<th>47.3</th>
<th>63.0</th>
<th>78.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td></td>
<td>0.689</td>
<td>0.775</td>
<td>0.874</td>
<td>0.922</td>
<td>0.936</td>
<td>0.955</td>
</tr>
<tr>
<td>31.5</td>
<td></td>
<td>0.806</td>
<td>0.830</td>
<td>0.884</td>
<td>0.925</td>
<td>0.944</td>
<td>0.958</td>
</tr>
<tr>
<td>47.3</td>
<td></td>
<td>0.862</td>
<td>-</td>
<td>0.907</td>
<td>0.922</td>
<td>0.960</td>
<td>0.964</td>
</tr>
<tr>
<td>63.0</td>
<td></td>
<td>0.900</td>
<td>-</td>
<td>-</td>
<td>0.907</td>
<td>0.947</td>
<td>0.957</td>
</tr>
<tr>
<td>78.8</td>
<td></td>
<td>0.921</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.959</td>
<td>0.965</td>
</tr>
<tr>
<td>94.5</td>
<td></td>
<td>0.932</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.956</td>
</tr>
</tbody>
</table>
TABLE 33

Powder 5 (B.S.A. 310L)
Isostatically Repressed at Specified Pressures after Annealing 10 mins. at 800°C in Hydrogen

<table>
<thead>
<tr>
<th>Preform Pressure (kg/mm²)</th>
<th>Repressing Pressure (kg/mm²)</th>
<th>0</th>
<th>15.8</th>
<th>31.5</th>
<th>47.3</th>
<th>63.0</th>
<th>78.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.8</td>
<td></td>
<td>0.642</td>
<td>0.668</td>
<td>0.750</td>
<td>0.815</td>
<td>0.848</td>
<td>0.884</td>
</tr>
<tr>
<td>31.5</td>
<td></td>
<td>0.744</td>
<td>0.744</td>
<td>0.764</td>
<td>0.820</td>
<td>0.855</td>
<td>0.886</td>
</tr>
<tr>
<td>47.3</td>
<td></td>
<td>0.808</td>
<td>-</td>
<td>0.808</td>
<td>0.822</td>
<td>0.856</td>
<td>0.890</td>
</tr>
<tr>
<td>63.0</td>
<td></td>
<td>0.843</td>
<td>-</td>
<td>-</td>
<td>0.844</td>
<td>0.867</td>
<td>0.897</td>
</tr>
<tr>
<td>78.8</td>
<td></td>
<td>0.882</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.887</td>
<td>0.910</td>
</tr>
<tr>
<td>94.5</td>
<td></td>
<td>0.902</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.904</td>
</tr>
</tbody>
</table>

6.6 Quantimet Results

The accumulative number of chord intersections above a given chord size for pores in compacts produced from Powder 2 are given in Table 34 and 35. The number of chords given and the pore volume % is the average of 50 fields.
### TABLE 34

**Chord Size Distribution of Powder 2A**  
*Cohens Electrolytic Iron (-100 + 140 mesh)*

<table>
<thead>
<tr>
<th>Pressure $\text{kg/mm}^2$</th>
<th>Accumulative number of chord intersections above given chord size</th>
<th>Total Pore Volume $%$</th>
<th>Measured Pore Volume $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>1024 532 337 221 143 104 20 24.6 25.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.3</td>
<td>951 444 261 163 96 67 8 16.6 19.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>891 392 226 138 82 59 7 14.8 16.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.5</td>
<td>821 406 261 181 123 95 18 17.6 14.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.7</td>
<td>687 316 183 110 64 44 6 11.3 13.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.7</td>
<td>712 315 162 98 55 37 4.7 10.7 12.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.3</td>
<td>673 253 135 60 44 31 1.2 9.5 9.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49.0</td>
<td>423 141 65 33 17 9.5 0.1 5.1 7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 35

Chord Size Distribution of Powder 2C
Cohens Electrolytic Iron (-270 +400 mesh)

<table>
<thead>
<tr>
<th>Pressure kg/mm²</th>
<th>Accumulative number of chord intersections above given chord size</th>
<th>Total Pore Volume %</th>
<th>Measured Pore Volume %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total 8µm 16µm 24µm 32µm 40µm 80µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.3</td>
<td>1833 795 416 226 122 76 4.5</td>
<td>27.8</td>
<td>27.8</td>
</tr>
<tr>
<td>32.7</td>
<td>1515 449 176 79 37 20 2.6</td>
<td>15.8</td>
<td>16.5</td>
</tr>
<tr>
<td>49.0</td>
<td>1218 333 127 54 22 11 0</td>
<td>11.9</td>
<td>11.0</td>
</tr>
<tr>
<td>70.8</td>
<td>866 170 49 17 6 3.4 0</td>
<td>6.6</td>
<td>7.9</td>
</tr>
</tbody>
</table>

The mean chord size calculated from Table 34 is given in Table 36 together with the mean chord size corrected as given in Section 3.3.4.
### TABLE 36

Calculated and Corrected Mean Chord Sizes of Powder 2A (-100 +140 mesh)

<table>
<thead>
<tr>
<th>Pressure kg/mm²</th>
<th>Calculated Mean Chord Size μm</th>
<th>Corrected Mean Chord Size μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.3</td>
<td>16.9</td>
<td>19.7</td>
</tr>
<tr>
<td>25.0</td>
<td>14.1</td>
<td>16.4</td>
</tr>
<tr>
<td>29.5</td>
<td>13.4</td>
<td>15.1</td>
</tr>
<tr>
<td>32.7</td>
<td>17.4</td>
<td>14.6</td>
</tr>
<tr>
<td>36.7</td>
<td>13.7</td>
<td>16.2</td>
</tr>
<tr>
<td>40.3</td>
<td>12.7</td>
<td>14.8</td>
</tr>
<tr>
<td>49.0</td>
<td>11.0</td>
<td>11.5</td>
</tr>
<tr>
<td>70.8</td>
<td>9.4</td>
<td>12.9</td>
</tr>
</tbody>
</table>

6.7 **Metallography**

Compact sections of various powders were examined metallographically to follow the compaction process and to study particle deformation and particle contacts. Figs. 30A, 30B and 30C show compact sections of Powder 2A (-100 +140 mesh Cohens electrolytic iron powder) compacted at 17.3, 32.7 and 70.8 kg/mm².
7. EXISTING PRESSURE–DENSITY RELATIONSHIPS

In order to relate quantitatively powder properties to compaction behaviour it is necessary to express pressure-density data in mathematical terms. The accurate compaction results were applied to several existing formulae and their validity assessed.

7.1 Balshin

The application of the compaction results to Balshin's equation (Equation 2.2) is shown in Fig. 31. The Figure shows a series of curves where the curvature increases as the hardness decreases. Therefore, the equation does not appear applicable to the compaction of metal powders at relatively high pressures, but might apply over a limited low pressure range particularly with harder powders.

7.2 Smith

The experimental data applied to the relationship according to Smith (Equation 2.6) is shown in Fig. 32 which reveals its inapplicability to describe the data for any of the powders or pressures studied.

7.3 Shapiro-Konopicky

The compaction results for four powders applied to the Shapiro-Konopicky equation are shown in Fig. 33.
The graphs can be divided into three segments except for the stainless steel powder (Powder 5) where it would appear that the third (high density) stage was not reached at the maximum pressure used. An approximate analysis of the results is given in Table 37 where $K_2$, $K_3$, $\text{Lnln/1-D}_2$ and $\text{Lnln/1-D}_3$ refer to the slopes and intercepts respectively of the second and third stages.

**TABLE 37**

*Analysis of Data Following Shapiro-Konopicky*

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>$K_2$</th>
<th>$K_3$</th>
<th>$\text{Lnln/1-D}_2$</th>
<th>$\text{Lnln/1-D}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.021</td>
<td>0.011</td>
<td>1.00</td>
<td>1.68</td>
</tr>
<tr>
<td>2</td>
<td>0.026</td>
<td>0.011</td>
<td>1.10</td>
<td>1.72</td>
</tr>
<tr>
<td>3</td>
<td>0.025</td>
<td>0.018</td>
<td>0.80</td>
<td>1.70</td>
</tr>
<tr>
<td>4</td>
<td>0.023</td>
<td>0.014</td>
<td>1.12</td>
<td>1.65</td>
</tr>
<tr>
<td>5</td>
<td>0.016</td>
<td></td>
<td>0.89</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.013</td>
<td></td>
<td>0.99</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.45</td>
<td>0.10</td>
<td>1.00</td>
<td>3.35</td>
</tr>
<tr>
<td>8</td>
<td>0.046</td>
<td>0.02</td>
<td>1.25</td>
<td>2.52</td>
</tr>
</tbody>
</table>

The second stage slope, $K_2$, is inversely proportional to the hardness as shown in Table 38. This is in agreement with the relationship proposed by Heckel (20) if the hardness is considered analogous to yield stress.
TABLE 38

Relationship Between Slope and Hardness

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>MH$_{10\mu m}$</th>
<th>$\frac{1}{K_2}$</th>
<th>$K_2 \times MH_{10\mu m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11</td>
<td>2.2</td>
<td>4.95</td>
</tr>
<tr>
<td>8</td>
<td>58</td>
<td>21.7</td>
<td>2.67</td>
</tr>
<tr>
<td>3</td>
<td>115</td>
<td>40.0</td>
<td>2.88</td>
</tr>
<tr>
<td>2</td>
<td>143</td>
<td>38.5</td>
<td>3.72</td>
</tr>
<tr>
<td>4</td>
<td>148</td>
<td>43.5</td>
<td>3.40</td>
</tr>
<tr>
<td>1</td>
<td>168</td>
<td>47.6</td>
<td>3.53</td>
</tr>
<tr>
<td>5</td>
<td>222</td>
<td>62.5</td>
<td>3.54</td>
</tr>
<tr>
<td>6</td>
<td>276</td>
<td>76.9</td>
<td>3.59</td>
</tr>
</tbody>
</table>

The third stage slope, parameter $K_3$, follows the same trend of being inversely proportional to hardness as the second stage but at a lower value of $K$.

The values of the intercepts from the two stages are so similar and of insufficient accuracy to form any conclusions as to a possible relationship with particle characteristics.
7.4 Jovanovic

The compaction results applied to Jovanovic's equation, Fig. 34, show the same general trends as the Shapiro-Konopicky analysis (section 7.3). An analysis of the results is given in Table 39 where $K_2$ and $K_3$ refer to the slopes of the second and third stages and $\ln D_2 / (1-D_2)$ and $\ln D_3 / (1-D_3)$ to the respective intercepts.

**TABLE 39**

**Analysis of Data Following Jovanovic**

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>$K_2$</th>
<th>$K_3$</th>
<th>$\ln D_2 / (1-D_2)$</th>
<th>$\ln D_3 / (1-D_3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.025</td>
<td>0.013</td>
<td>0.62</td>
<td>1.40</td>
</tr>
<tr>
<td>2</td>
<td>0.029</td>
<td>0.014</td>
<td>0.92</td>
<td>1.62</td>
</tr>
<tr>
<td>3</td>
<td>0.039</td>
<td>0.019</td>
<td>0.55</td>
<td>1.57</td>
</tr>
<tr>
<td>4</td>
<td>0.028</td>
<td>0.015</td>
<td>0.77</td>
<td>1.57</td>
</tr>
<tr>
<td>5</td>
<td>0.018</td>
<td></td>
<td>0.60</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.015</td>
<td></td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.45</td>
<td>0.10</td>
<td>1.25</td>
<td>3.25</td>
</tr>
<tr>
<td>8</td>
<td>0.056</td>
<td>0.021</td>
<td>0.85</td>
<td>2.45</td>
</tr>
</tbody>
</table>
The second stage slope, $K_2$, is inversely proportional to the hardness, Table 40, similar to that found for the Shapiro-Konopicky relationship although in this case there is a slightly better fit between the data.

**TABLE 40**

Relationship Between Slope and Hardness

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>$\text{MH}_{10\mu m}$</th>
<th>$\frac{1}{K_2}$</th>
<th>$K_2 \times \text{MH}_{10\mu m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11</td>
<td>2.2</td>
<td>4.95</td>
</tr>
<tr>
<td>8</td>
<td>58</td>
<td>17.9</td>
<td>3.29</td>
</tr>
<tr>
<td>3</td>
<td>115</td>
<td>25.6</td>
<td>4.49</td>
</tr>
<tr>
<td>2</td>
<td>143</td>
<td>34.5</td>
<td>4.15</td>
</tr>
<tr>
<td>4</td>
<td>148</td>
<td>35.7</td>
<td>4.15</td>
</tr>
<tr>
<td>1</td>
<td>168</td>
<td>40.0</td>
<td>4.20</td>
</tr>
<tr>
<td>5</td>
<td>222</td>
<td>55.6</td>
<td>4.00</td>
</tr>
<tr>
<td>6</td>
<td>276</td>
<td>66.7</td>
<td>4.14</td>
</tr>
</tbody>
</table>
7.5 **Kawakita**

The empirical formula proposed by Kawakita (Equation 2.15) may be transformed to Equation (7.1) to produce a linear plot.

\[
\frac{P}{C} = \frac{1}{ab} + \frac{1}{a}(P) \tag{7.1}
\]

The results of the isostatic compaction experiments applied to equation (7.1) are shown in Fig. 35. A computer programme was written (see Appendix 3) to calculate the constants in Kawakita's equation and the results are given in Table 41 together with the initial porosity values.

**TABLE 41**

<table>
<thead>
<tr>
<th>Powder</th>
<th>Initial Porosity (I-D)₀</th>
<th>Calculated Constants</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>1</td>
<td>0.688</td>
<td>0.697</td>
<td>0.235</td>
</tr>
<tr>
<td>2</td>
<td>0.610</td>
<td>0.618</td>
<td>0.220</td>
</tr>
<tr>
<td>3</td>
<td>0.663</td>
<td>0.676</td>
<td>0.284</td>
</tr>
<tr>
<td>4</td>
<td>0.540</td>
<td>0.554</td>
<td>0.147</td>
</tr>
<tr>
<td>5</td>
<td>0.683</td>
<td>0.697</td>
<td>0.164</td>
</tr>
<tr>
<td>6</td>
<td>0.626</td>
<td>0.628</td>
<td>0.122</td>
</tr>
<tr>
<td>7</td>
<td>0.561</td>
<td>0.564</td>
<td>5.463</td>
</tr>
<tr>
<td>8</td>
<td>0.800</td>
<td>0.804</td>
<td>1.364</td>
</tr>
</tbody>
</table>
Kawakita indicated that the constant 'a' was related to initial porosity and the results obtained here show that they are not only related but almost identical. However, it should be noted that the volume reduction was calculated using the initial porosities derived from apparent density measurements according to equation (7.2).

\[
C = \frac{V_0 - V}{V_0} = 1 - \frac{D_0}{D}
\]  

(7.2)

where

- \( C \) = relative reduction in volume
- \( V_0 \) = initial volume
- \( V \) = volume of pressure \( P \)
- \( D_0 \) = apparent density
- \( D \) = density at pressure \( P \)

There is a tendency for the constant \( b \) to increase as the hardness decreases, Fig. 36A, but variations in this inverse relationship appear to follow variations in initial porosity, i.e. Powders 1, 5, and 8 above the line have the highest initial porosities and Powder 4 below the line has the lowest initial porosity.

In another paper referring to the compression of spherical glass powders, Kawakita (85) uses Equation (7.3).
\[- \frac{d(l - D)}{dP} = K(l - D)^x \quad (7.3)\]

where \(K\) and \(x\) are constants.

Considering the special case given by Equation (7.4) when the decrease in porosity with pressure is proportional to the \((\text{porosity})^2\).

\[- \frac{d(l - D)}{dP} = \beta(l - D)^2 \quad (7.4)\]

This equation (7.4) can be rearranged and integrated between porosity and pressure limits to give (7.5).

\[\int_{1 - D_0}^{P_0} \frac{1 - D}{(1 - D)^2} \, d(1 - D) = \beta \int_{P}^{P_0} dP \quad (7.5).\]

where
\[
\begin{align*}
1 - D_0 &= \text{initial porosity} \\
1 - D &= \text{porosity at pressure } P
\end{align*}
\]
Equation (7.5) can be transformed to equation (7.6).

\[
\begin{bmatrix}
\frac{1}{1-D} \\
\frac{1}{1-D_0}
\end{bmatrix} \frac{1-D}{1-D_0} = \beta \begin{bmatrix} P \end{bmatrix}_{P_0}^P
\] (7.6)

This can be transformed to equation (7.8)

\[
\frac{D - D_0}{(1-D)(1-D_0)} = \beta P
\] (7.8)

From equation (7.2).

\[
\frac{V - V_0}{V_0} = \frac{D - D_0}{D}
\] (7.9)

Substituting equation (7.9) in (7.8).

\[
\frac{C D}{(1-D)(1-D_0)} = \beta P
\] (7.10)

Let \((1-D_0) = a\)
Then:

\[
\frac{C \cdot D}{(1 - D)} = a \cdot SP
\]  \hspace{1cm} (7.11)

From equation (7.7),

\[
\frac{1}{1 - D} = SP + \frac{1}{a} = \frac{aSP + 1}{a}
\]  \hspace{1cm} (7.12)

or

\[
1 - D = \frac{a}{1 + aSP}
\]  \hspace{1cm} (7.13)

and

\[
D = \frac{(1-a) + aSP}{1 + aSP}
\]  \hspace{1cm} (7.14)

dividing equation (7.14) by equation (7.13).

\[
C = \frac{a^2 \cdot SP}{(1-a) + aSP}
\]  \hspace{1cm} (7.15)

or

\[
C = \frac{a^2 \cdot SP}{(1-a)(1 + (\frac{a}{1-a})SP)}
\]  \hspace{1cm} (7.16)

Let

\[
b = \frac{aSP}{1-a}
\]  \hspace{1cm} (7.18)

and substituting in (7.17).
Thus it is possible to arrive at Kawakita's equation (7.19) starting from equation (7.4).

The original proportionality constant $\beta$ can be obtained from the constants $a$ and $b$ from equation (7.19).

$$\beta = \frac{b(1-a)}{a}$$  \hspace{1cm} (7.20)

If $\beta$ is used as a material constant a better inverse relationship exists, Fig. 36B. Moreover, if particle hardening is taken into account by having the hardness inversely proportionally to $\beta$ times the Meyer Exponent then the relationship is further improved, Fig. 36C.

The proportionality constants for the values shown in Fig. 36A, 36B, 36C are given in Table 42.
TABLE 42
Proportionality Constants Relating Kawakita's Constants and Particle Hardness

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Proportionality Constant</th>
<th>Proportionality Constant</th>
<th>Proportionality Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_1$ ($b \times MH_{10u}$)</td>
<td>$K_2$ ($b \times MH_{10u}$)</td>
<td>$K_3$ ($b \times MH_{10u} \times M.E.$)</td>
</tr>
<tr>
<td>1</td>
<td>39.4</td>
<td>17.2</td>
<td>29.2</td>
</tr>
<tr>
<td>2</td>
<td>31.4</td>
<td>19.4</td>
<td>32.1</td>
</tr>
<tr>
<td>3</td>
<td>32.7</td>
<td>15.6</td>
<td>29.0</td>
</tr>
<tr>
<td>4</td>
<td>17.3</td>
<td>13.9</td>
<td>30.8</td>
</tr>
<tr>
<td>5</td>
<td>36.4</td>
<td>16.4</td>
<td>29.3</td>
</tr>
<tr>
<td>6</td>
<td>33.7</td>
<td>19.9</td>
<td>31.8</td>
</tr>
<tr>
<td>7</td>
<td>61.1</td>
<td>45.8</td>
<td>67.2</td>
</tr>
<tr>
<td>8</td>
<td>78.3</td>
<td>19.3</td>
<td>37.7</td>
</tr>
</tbody>
</table>

The Shapiro-Konopicky and Jovanovic equations are only of limited use because of the narrow density ranges over which they apply. Kawakita's equation would appear valid as an empirical equation of state but its usefulness in describing compaction behaviour for studying the effect of powder variables is clearly limited.

Existing pressure-density formulae would appear to fall down because they largely ignore the most important compaction mechanism of particle deformation and the resultant particle hardening.
8. THE FORMULATION OF PRESSURE-DENSITY RELATIONSHIPS

The importance of plastic deformation and the influence of strain hardening suggests the application of a stress-strain formula to the compaction of metal powders. The stress distribution around individual pores is complex but essentially pore closure will be influenced by the stress required for particle deformation which is controlled by the compacting pressure.

8.1 Stress-Strain

The general form of the stress-strain curve for metals can be represented after Ludwick, Nadai and others by the logarithmic expression

\[ \sigma = K \varepsilon^n \]  

(8.1)

where

- \( \sigma \) = true stress
- \( \varepsilon \) = true strain
- \( K \) = stress when \( \varepsilon = 1.0 \)
- \( n \) = strain hardening coefficient

The true stress is given by the load divided by the instantaneous cross-sectional area and the true strain is the change in dimensions referred to the instantaneous length. As plastic deformation
is the most important mechanism in the compaction of metal powders one might expect an expression analogous to the true stress-true strain power law to apply to metal powder compaction.

In the compaction of metal powders the cross-sectional area changes as densification proceeds. Initially, the pressure will be applied over an extremely small contact area and deformation will occur at particle contacts. As deformation proceeds and the pressure increases the particle contact cross-section also increases.

8.2 Simple Strain Formula

As an initial simplification the stress was represented by the compaction pressure and the strain represented by the porosity as given by equation (8.2)

\[ P = K(1 - D)^n \]  

(8.2)

where

- \( P \) = compaction pressure
- \( 1 - D \) = fractional porosity
- \( K \) and \( n \) are constants.
The data represented by equation (8.2) is shown in Figs. 37 to 44 and the continuous lines show the good fit obtained at porosity levels below about 15%. An analysis of the results is given in Table 43 where K and n values have been calculated using a least squares computer programme.

**TABLE 43**

*Analysis of Data From Equation (8.2)*

<table>
<thead>
<tr>
<th>Powder</th>
<th>K</th>
<th>n</th>
<th>S</th>
<th>((1 - D)S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.45</td>
<td>-0.93</td>
<td>38-44</td>
<td>0.145-0.174</td>
</tr>
<tr>
<td>2</td>
<td>4.76</td>
<td>-1.00</td>
<td>25-31</td>
<td>0.151-0.186</td>
</tr>
<tr>
<td>3</td>
<td>7.23</td>
<td>-0.76</td>
<td>24-28</td>
<td>0.166-0.200</td>
</tr>
<tr>
<td>4</td>
<td>5.88</td>
<td>-0.23</td>
<td>33-38</td>
<td>0.132-0.151</td>
</tr>
<tr>
<td>5</td>
<td>12.89</td>
<td>-0.85</td>
<td>51-56</td>
<td>0.166-0.182</td>
</tr>
<tr>
<td>6</td>
<td>11.86</td>
<td>-0.94</td>
<td>58-63</td>
<td>0.178-0.195</td>
</tr>
<tr>
<td>7</td>
<td>0.48</td>
<td>-0.71</td>
<td>1-3*</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>5.17</td>
<td>-0.66</td>
<td>12-18*</td>
<td>-</td>
</tr>
</tbody>
</table>

* by extrapolation.
The value of $S$ and $(1 - D)S$ refer to the pressure and porosity respectively at the point where deviation from a straight line occurs. A range of values are given covering the positions where the inflexion could occur between experimental points.

The values of $K$ do not appear to be related to any of the measured powder properties but the values of $S$ are closely related to particle hardness as shown in Fig. 45; the calculated line being given by equation (8.3).

$$S = 0.24 \frac{MH_{10\mu m}}{10\mu m}$$ \hspace{1cm} (8.3)

The slope of the log-log plot $n$ is related to the Meyer Exponent as given in equation (8.4).

$$n = \text{Meyer Exponent} - 2.62$$ \hspace{1cm} (8.4)

The values of Meyer Exponent and the experimental and calculated values using equation (8.4) of $n$ are given in Table 44.
### TABLE 44

**Meyer Exponent and n Values**

<table>
<thead>
<tr>
<th>Powder</th>
<th>Meyer Exponent</th>
<th>n experimental</th>
<th>n calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.70</td>
<td>-0.93</td>
<td>-0.92</td>
</tr>
<tr>
<td>2</td>
<td>1.65</td>
<td>-1.00</td>
<td>-0.97</td>
</tr>
<tr>
<td>3</td>
<td>1.85</td>
<td>-0.76</td>
<td>-0.77</td>
</tr>
<tr>
<td>4</td>
<td>1.76</td>
<td>-0.93</td>
<td>-0.86</td>
</tr>
<tr>
<td>5</td>
<td>1.78</td>
<td>-0.85</td>
<td>-0.84</td>
</tr>
<tr>
<td>6</td>
<td>1.60</td>
<td>-0.94</td>
<td>-1.02</td>
</tr>
<tr>
<td>7</td>
<td>1.88</td>
<td>-0.71</td>
<td>-0.76</td>
</tr>
<tr>
<td>8</td>
<td>1.96</td>
<td>-0.66</td>
<td>-0.66</td>
</tr>
</tbody>
</table>

### 8.3 Instantaneous Strain Formula

In compaction unlike metal deformation (except in the elastic region) a volume change occurs. If one considers this volume change to be related to the natural strain in compression then the following formula can be deduced.
where

\[ \varepsilon = \text{true strain} \]

\[ V = \text{volume of compact} \]

\[ V_\infty = \text{volume at theoretical density} \]

In terms of fractional density equation (8.5) can be transformed to

\[ \ln \frac{V}{V_\infty} = \ln \frac{1}{D} = -\ln D \quad (8.6) \]

Taking \(-\ln D\) to be indicative of compaction strain, equation (8.2) becomes

\[ p = K' (-\ln D)^n' \quad (8.7) \]
The experimental data applied to equation (8.7) is shown in Figs. 46 to 53. A better fit of the data is obtained using equation (8.7) compared with equation (8.2) and it extends over a slightly greater density range. The point of inflexion shown in Figs. 46 to 53 where the continuous and broken lines intercept was found to be a constant fraction of particle hardness given by

\[ P_S = 0.20 \cdot H_{10\mu m} \]  

(8.8)

The value of \( P_S \), called the consolidation pressure, and \( D_S \), the density at pressure \( P_S \) together with the compaction exponent \( n' \) are given in Table 45.
TABLE 45

Analysis of Data From Equation (8.7)

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Compaction Exponent ( n' )</th>
<th>Consolidation Pressure ( P_S )</th>
<th>Consolidation Density ( D_S )</th>
<th>Compaction Strain ( -\text{Ln}D_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.90</td>
<td>33.8</td>
<td>0.819</td>
<td>0.200</td>
</tr>
<tr>
<td>2</td>
<td>-0.96</td>
<td>28.6</td>
<td>0.835</td>
<td>0.180</td>
</tr>
<tr>
<td>3</td>
<td>-0.73</td>
<td>23.4</td>
<td>0.795</td>
<td>0.230</td>
</tr>
<tr>
<td>4</td>
<td>-0.92</td>
<td>29.6</td>
<td>0.831</td>
<td>0.185</td>
</tr>
<tr>
<td>5</td>
<td>-0.84</td>
<td>44.4</td>
<td>0.787</td>
<td>0.240</td>
</tr>
<tr>
<td>6</td>
<td>-0.98</td>
<td>52.2</td>
<td>0.815</td>
<td>0.205</td>
</tr>
<tr>
<td>7</td>
<td>-0.70</td>
<td>2.2</td>
<td>0.887</td>
<td>0.120</td>
</tr>
<tr>
<td>8</td>
<td>-0.64</td>
<td>11.6</td>
<td>0.705</td>
<td>0.350</td>
</tr>
</tbody>
</table>

At densities above the consolidation density, \( D_S \), equation (8.7) becomes

\[
P = P_S \left( \frac{-\text{Ln}D}{-\text{Ln}D_S} \right)^{n'}
\]

(8.9)
The relationship between compaction exponent \( n' \) and Meyer Exponent is

\[
n' = \text{Meyer Exponent} - 2.60 \quad (8.10)
\]

The consolidation density \( D_S \) is related to the tap density \( D_T \), Fig. 54, by the following formula

\[
D_S = 0.46D_T + 0.60 \quad (8.11)
\]

Computer analysis of the equation (8.11) is given in Table 46.
TABLE 46

Computer Analysis of Relationship between Tap Density \( (D_T) \) and Consolidation Density \( (D_S) \)

\[
D_S = A \ D_T + B
\]

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Expected Value</th>
<th>95 pct Confidence Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.6014</td>
<td>0.5586 0.6443</td>
</tr>
<tr>
<td>B</td>
<td>0.4590</td>
<td>0.3604 0.5497</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( D_T ) actual</th>
<th>( D_S ) actual</th>
<th>( D_S ) estim.</th>
<th>95 pct Confidence Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.246</td>
<td>0.705</td>
<td>0.714</td>
<td>0.693 0.736</td>
</tr>
<tr>
<td>0.414</td>
<td>0.795</td>
<td>0.791</td>
<td>0.782 0.800</td>
</tr>
<tr>
<td>0.419</td>
<td>0.819</td>
<td>0.794</td>
<td>0.785 0.803</td>
</tr>
<tr>
<td>0.439</td>
<td>0.787</td>
<td>0.803</td>
<td>0.795 0.811</td>
</tr>
<tr>
<td>0.447</td>
<td>0.811</td>
<td>0.807</td>
<td>0.799 0.815</td>
</tr>
<tr>
<td>0.472</td>
<td>0.824</td>
<td>0.818</td>
<td>0.810 0.826</td>
</tr>
<tr>
<td>0.481</td>
<td>0.815</td>
<td>0.822</td>
<td>0.814 0.830</td>
</tr>
<tr>
<td>0.497</td>
<td>0.830</td>
<td>0.830</td>
<td>0.821 0.838</td>
</tr>
<tr>
<td>0.499</td>
<td>0.835</td>
<td>0.831</td>
<td>0.822 0.839</td>
</tr>
<tr>
<td>0.537</td>
<td>0.831</td>
<td>0.848</td>
<td>0.838 0.858</td>
</tr>
<tr>
<td>0.624</td>
<td>0.887</td>
<td>0.888</td>
<td>0.871 0.904</td>
</tr>
</tbody>
</table>

Substituting equation (8.8), (8.10) and (8.11) in equation (8.9) one obtains the following relationship

\[
P = 0.2 \ \text{MH}_{10\mu m} \ \dfrac{-\ln D}{-\ln(0.46D_T + 0.60)} n' - 2.6 \ (8.12)
\]
8.4 Compaction Strain Formula

After the initial success in relating compaction behaviour to hardness and tap density it was thought that this might be carried a step further by incorporating tap density into the strain function. After various attempts the strain function given in equation (8.13) was found to be the most appropriate.

\[
\varepsilon = \ln \left( \frac{V_T - V}{V_T - V_\infty} \right) = \ln \left( \frac{D - D_T}{D(1 - D_T)} \right) \quad (8.13)
\]

where

- \( V_T \) = volume at tap density
- \( V \) = volume at pressure \( P \)
- \( V_\infty \) = volume at theoretical density

Equation (8.2) now becomes

\[
P = K \ln \left[ \frac{D - D_T}{D(1 - D_T)} \right]^{n''} \quad (8.14)
\]
Equation (8.14) applied to the isostatic compaction of the eight powders is shown in Fig. 55 where all the powders can be represented by straight lines over the pressure range covered.

The intercept $K$ is related to particle hardness, Fig. 56, and the slope $n''$ to the Meyer Exponent, Fig. 57, by the following expressions

\[
\frac{n''}{K} = \text{Meyer Exponent} - 2.57 \tag{8.15}
\]

\[
K = 0.054 \text{MH}_{10\mu m} \tag{8.16}
\]

The values of $n''$ and $K$ are given in Table 47 together with the values calculated using equation (8.15) and (8.16).

**TABLE 47**

Analysis of Data From Equation (8.14)

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Measured</th>
<th></th>
<th>Calculated</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n''$</td>
<td>$K$</td>
<td>$n''$</td>
<td>$K$</td>
</tr>
<tr>
<td>1</td>
<td>0.87</td>
<td>7.2</td>
<td>0.87</td>
<td>9.0</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>7.4</td>
<td>0.92</td>
<td>7.7</td>
</tr>
<tr>
<td>3</td>
<td>0.73</td>
<td>6.6</td>
<td>0.72</td>
<td>6.2</td>
</tr>
<tr>
<td>4</td>
<td>0.83</td>
<td>9.8</td>
<td>0.81</td>
<td>8.0</td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>12.5</td>
<td>0.79</td>
<td>12.0</td>
</tr>
<tr>
<td>6</td>
<td>0.93</td>
<td>13.4</td>
<td>0.97</td>
<td>14.9</td>
</tr>
<tr>
<td>7</td>
<td>0.68</td>
<td>0.6</td>
<td>0.69</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>0.62</td>
<td>2.9</td>
<td>0.61</td>
<td>3.1</td>
</tr>
</tbody>
</table>
The values of \( n'' \) and \( K \) for the sieve fractions of powder 2 are given in Table 48.

**TABLE 48**

K and \( n'' \) values for Sieve Fractions of Powder 2

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Mesh Size</th>
<th>( n'' )</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>As received</td>
<td>-0.87</td>
<td>7.4</td>
</tr>
<tr>
<td>2A</td>
<td>-100 +140</td>
<td>-0.84</td>
<td>8.2</td>
</tr>
<tr>
<td>2B</td>
<td>-170 +200</td>
<td>-0.84</td>
<td>7.7</td>
</tr>
<tr>
<td>2C</td>
<td>-270 +400</td>
<td>-0.82</td>
<td>7.7</td>
</tr>
</tbody>
</table>

A successful description of compaction behaviour has been achieved by the application of a stress-strain formula. Moreover, quantitative relationships have been obtained between material properties and constants in the pressure-density formula.
As expected lower densities were achieved by die-compaction even when the compact height was kept to a minimum to reduce the effect of die-wall friction. The pressure difference required for a given density between die and isostatic compaction increases as the density increases reaching a maximum at about 90% of the theoretical density. Above this density level the pressure difference decreases and similar densities are achieved by die and isostatic compaction.

The die compaction results applied to the instantaneous strain formula (equation 8.7) are shown in Figs. 58 and 59. The compaction exponents (n') and the consolidation strains (-LnD_s) were found to be very similar to the values given in Table 43 for isostatic compaction. However, at high densities Powders 1, 2 and 3 show a deviation where the die and isostatic results converge. The consolidation pressure (P_s) for die compaction is higher than for isostatic compaction as given in Table 47.
TABLE 47

The Consolidation Pressure ($P_c$) for Die and Isostatic Compaction

<table>
<thead>
<tr>
<th>Powder Number</th>
<th>Consolidation Pressure (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Die</td>
</tr>
<tr>
<td>1</td>
<td>41.5</td>
</tr>
<tr>
<td>2</td>
<td>35.9</td>
</tr>
<tr>
<td>3</td>
<td>30.2</td>
</tr>
<tr>
<td>5</td>
<td>49.8</td>
</tr>
<tr>
<td>6</td>
<td>58.1</td>
</tr>
</tbody>
</table>

The relationship between consolidation pressure and particle hardness for isostatic and die compaction, Fig. 60, shows that the difference in consolidation pressure for the two compaction methods decreases as the particle hardness increases.

The compaction strain formula (equation 8.14) applied to the isostatic and die compaction of Powders 2 and 3 is shown in Figs. 61 and 62. Whereas the isostatic compaction results transform to a linear relationship over the complete pressure range studied the die compaction results break down into three stages. In the first stage, beginning at the same value, the die compaction results diverge until the middle stage is reached which covers the widest density range and has the same slope ($n''$) as the isostatic compaction results. At the upper pressure ranges the die compaction results appear to converge towards the isostatic compaction line.
10. DISCUSSION

10.1 General

The experimental results suggest that for the materials used and the pressure range studied the isostatic compaction behaviour can be described as a two-stage process. The first stage is concerned with the initial packing of the particles and the second stage with particle deformation. The factors affecting the two stages are summarised in Table 49.

**TABLE 49**

Factors Affecting Isostatic Compaction of Metal Powders

<table>
<thead>
<tr>
<th>Compaction Stage</th>
<th>Controlling Factors</th>
<th>Measured Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial Packing</td>
<td>Particle Size Distribution</td>
<td>Tap Density</td>
</tr>
<tr>
<td></td>
<td>Mean Size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Particle Shape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface Conditions</td>
<td></td>
</tr>
<tr>
<td>2. Particle Deformation</td>
<td>Structure</td>
<td>Particle Hardness</td>
</tr>
<tr>
<td></td>
<td>Purity</td>
<td>and</td>
</tr>
<tr>
<td></td>
<td>Grain Size</td>
<td>Meyer</td>
</tr>
<tr>
<td></td>
<td>Plasticity</td>
<td>Exponent</td>
</tr>
<tr>
<td></td>
<td>Elasticity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice Defects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas Content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alloy Additions</td>
<td></td>
</tr>
</tbody>
</table>
There will of course be a certain amount of overlapping between the factors affecting the two stages. For instance, the particle factors will determine the pore size distribution and therefore the amount of deformation required for densification.

10.2 Stage 1

The tap density is taken as the measured property indicative of the extent of Stage 1. Pelzel(85) has shown that the particle contact area at high porosity levels is exceedingly small and therefore deformation of particle asperities probably occurs at very low applied pressures. This means that the surface topography could influence the extent of Stage 1; the tap density being correct for smooth spherical particles but giving a low value in the case of rough, spiky, irregular particles.

The apparent density, although of enormous commercial importance, does not appear to directly influence compaction behaviour. However, as shown in Table 15, the tendency is for higher apparent densities to give higher tap densities. The initial density of the powder in isostatic compaction is difficult to measure accurately because the filling is difficult to control, the container is flexible and sealing of the bag may give some precompaction, but it is undoubtedly higher than the value of the apparent density as measured by a standard test.
The large variation in particle characteristics prevents a straightforward assessment of their effect on packing behaviour; the effects of particle size distribution being masked by changes in particle shape. In general, the results indicate that maximum packing is achieved with a high bulkiness factor and a low surface factor. The isolated effect of particle size for narrow size fractions of Powder 2 shows that the packing density increases as the particle size increases but the maximum packing is achieved with the wide size range of the 'as received' powder.

10.3 Stage 2

The second stage is controlled by plastic deformation of particles which has been quantitatively measured in terms of the particle hardness taken as a measure of yield strength and the Meyer Exponent, which is taken to be indicative of work hardening. The particle hardness indicates the pressure requirement for the commencement of Stage 2 and the Meyer Exponent indicates the rate at which densification proceeds. Quantitative relationships have been produced relating hardness and Meyer Exponent to densification but it must be emphasised that the hardness refers to an indentation diagonal of 10 microns. Furthermore, the Meyer Exponent has a value which is unique to the narrow range of loads used for the hardness analysis and cannot be compared with Meyer Exponents determined by macrohardness measurements.
The amount of strain hardening is indicated by the large increase in hardness of the green compacts and the beneficial effect of an intermediate anneal during compaction. The annealing and repressing experiments on Powder 1 (MH100.24 Iron Powder) showed that the powder was strain hardened in the 'as received' condition which probably accounts for its high predicted K value in the compaction strain formula, Fig. 56.

The effect of particle size on compaction during Stage 2 would appear to be relatively small as indicated by the small amount of scatter in the relationship between particle hardness and compaction constant, Fig. 56. The compaction strain formula does however isolate the effect of particle size on initial packing as shown by comparing Fig. 29 and Table 46 for Powder 2. The finer powders produce a lower density for a given pressure compared with the coarser size fractions but require a similar amount of compaction strain. Table 48 does indicate a slight increase in the value of K as particle size increases which might account for the high value of K for Powder 4, Fig. 56.

The particle size distribution affects the pore size distribution as shown by the Quantimet results (Section 6.6). Bockstiegel(26) has shown theoretically that smaller pores require higher
pressures for pore closure and experimentally that pores disappear strictly in order of size beginning with the largest. However it is possible that the larger amount of deformation required for the closure of large pores counteracts the effect of a lower pressure requirements.

10.4 Die-Compaction

The limited number of die compaction experiments have shown that initially densification proceeds in a similar manner to isostatic compaction except for a higher pressure requirement due to the effect of die-friction. However, at high pressures the density achieved by die compaction approaches the levels obtained by isostatic compaction. A possible explanation based on the theory proposed by Long (63) is that at high pressures hydrostatic conditions, where the ratio of radial to applied pressure approaches unity, can exist in die compaction. However, this excluded material of the Mohr type such as copper which in this investigation show the same phenomenon. At high pressures the shape of the pores could be important in determining the pressure required for their closure. In this respect the more elliptical pores found in unidirectionally pressed compacts might require less pressure compared with their more spherical isostatically produced counterparts.
11. CONCLUSIONS

A wide range of metal powders has been compacted isostatically to avoid the effects of die friction and accurate pressure-density data have been obtained. The results have been applied to existing pressure-density relationships but generally because of their empirical derivation and their failure to isolate the effects of die friction only limited success has been obtained.

The relationship between material properties and densification has been successfully analysed in terms of stress-strain behaviour. The following general expression for stress-strain has been adapted to describe the compaction of metal powders.

\[ P = K \varepsilon^n \]

where

- \( P \) = compacting pressure
- \( \varepsilon \) = compaction strain
- \( K \) and \( n \) are material constants

The most suitable expression for compaction strain was derived from the instantaneous change in volume from the tap density to the final density, viz.

\[ \varepsilon = \ln \left[ \frac{D - D_T}{D(1 - D_T)} \right] \]

where

- \( D \) = fractional density at pressure \( P \)
- \( D_T \) = fractional tap density
The constants $K$ and $n$ have been related to micro-hardness and Meyer exponent values produced under specified experimental conditions and have the following values when the pressure is expressed in kg/mm$^2$.

$$K = 0.054 \text{ MH}_{10\mu m}$$

$$n = \text{Meyer exponent} - 2.57$$

The limited amount of die compaction data has shown the effects of die friction in reducing densification at low pressures. However, at higher pressures similar densities have been obtained by the two compaction techniques suggesting that a different controlling mechanism occurs in die-compaction at high density levels.
12. **RECOMMENDATIONS**

The findings of this work have provided a powerful tool for studying powder compaction. The equations relating compacting pressure and density are obeyed with a high degree of precision and furthermore have a sound basis relating to the plastic deformation of metals.

It is considered that it would be valuable to extend the present work in several directions. The more important being:

1. An extension of the low pressure range to cover densification from the onset of plastic deformation.

2. A more detailed investigation of the effects of die-friction and the differences between uni-directional and isostatic compaction behaviour.

3. The study of the effects of powder variables on inter-particle friction and its effect on pressure transmission in isostatic compaction.
Grateful acknowledgement is made to Mr. R. L. Sands for his efforts in initiating this work and for his advice and encouragement together with Mr. P. J. James during the work. The support of the B.S.A. Group Research Centre and in particular Mr. D. A. Oliver, C.B.E., Director of Research is acknowledged. Thanks must go to Mr. T. Allmand who operated the Quantimet and Mr. E. Lilley who helped in the design of the pressure chamber. Concerning the preparation of the thesis thanks must go to Mrs. R. Fry, Miss M. Simpkin and Mrs. B. Hancox; and last but not least, to the forbearance and encouragement of my wife.
REFERENCES


41. See Ref. 38.
44. See Ref. 39.
76. H. Heywood - Chem. and Ind. 56, 149, (1937).


FIG. 1

ISOSTATIC PRESSING APPARATUS

1000 TON HYDRAULIC PRESS
TOP PLATEN

200 TON LOAD CELL
TO: PRESSURE RECORDER

TOP PLUNGER

EN30 CYLINDER

PRESSURE CHAMBER 35 mm. dia. x 70 mm. WORKING LENGTH

VITON O-RING

BOTTOM PLUG

GI10 MARAGING STEEL COIL
Be/Cu MITRE RING
MANGANIN COIL
PRESSURE TRANSMITTING FLUID
POWDER SAMPLE IN RUBBER MEMBRANE

SCALE: 1/2 FULL SIZE
FIG. 2

BEHAVIOUR OF VARIOUS TRANSMITTING FLUIDS

(LOWE AND GOOLD)
FIG. 3
DIE COMPACTION APPARATUS

SCALE: \( \frac{1}{2} \) FULL SIZE
FIG. 4

APPARATUS FOR DENSITY MEASUREMENT
OF IRREGULAR POROUS COMPACTS

- Fine Adjustment Screw
- Contact Indication Light
- Battery Isolation Switch
- Mercury Contact
- Sample
- Top Pan Balance
  0-800g, Adjustable Tare
  Accuracy 0.01g.
FIG. 5
APPARATUS FOR VACUUM IMPREGNATION OF POWDER COMPACTS.

[Diagram showing the apparatus for vacuum impregnation of powder compacts, with labeled parts: Resin, Position of Heater, Valve, Resin Inlet, Metal Tray, Mould, Pyrex Glass Tube, TO VACUUM PUMP, Winding Device.]
FIG. 6

THE EFFECT OF THRESHOLD SETTING ON PORE AREA

AREA A
(AREA A₁ INCLUDING DOTTED AREA)
FIG. 7

MICROHARDNESS OF POWDER 1

**MEYER EXPONENT = 1.70**

- \( \text{MH}_{5\mu m} = 211 \text{ kg/mm}^2 \)
- \( \text{MH}_{10\mu m} = 168 \text{ kg/mm}^2 \)
- \( \text{MH}_{20\mu m} = 143 \text{ kg/mm}^2 \)

**LOAD \( P \) (g)** vs. **INDENTATION DIAGONAL \( d \) (MICRONS)**
FIG. 8
MICROHARDNESS OF POWDER 2

MEYER EXPONENT = 1.65

MH$_{5 \mu m}$ = 182 kg/mm$^2$

MH$_{10 \mu m}$ = 143 kg/mm$^2$

MH$_{20 \mu m}$ = 111 kg/mm$^2$
FIG. 9
MICROHARDNESS OF POWDER 3

MEYER EXPONENT = 1.85

MH5μm = 133 kg/mm²
MH10μm = 115 kg/mm²
MH20μm = 95 kg/mm²

LOAD P (g)

1 2 3 4 5 6

5 10 15 20 25 30

MICRONES (kg/mm²)

2 5 10 20 40

INDENTATION DIAGONAL d (MICRONS)
FIG. 10
MICROHARDNESS OF POWDER 4

MAYER EXPONENT = 1.76

MH₅µm = 178 kg/mm²
MH₁₀µm = 148 kg/mm²
MH₂₀µm = 121 kg/mm²

LOAD P (g)

INDENTATION DIAGONAL d (MICRONS)

MICROHARDNESS (kg/mm²)
**FIG. II**

**MICROHARDNESS OF POWDER 5**

![Graph showing microhardness data for Powder 5.](image)

- **Meyer Exponent = 1.78**
- **$\text{MH}_{5\mu m} = 267 \text{ kg/mm}^2$**
- **$\text{MH}_{10\mu m} = 222 \text{ kg/mm}^2$**
- **$\text{MH}_{20\mu m} = 181 \text{ kg/mm}^2$**

The graph illustrates the relationship between load ($P$) and indentation diagonal ($d$) for different sizes of indentations.
FIG. 12
MICROHARDNESS OF POWDER 6

MEYER EXPONENT = 1.60

LOAD P (g)

30
20
10
5

363 kg/mm²
MH₅μm

276 kg/mm²
MH₉O μm

222 kg/mm²
MH₂O μm

MICROHARDNESS (kg/mm²)

350
300
250
200
150
100
50
0

INDENTATION DIAGONAL d (MICRONS)

2 5 10 20 40
FIG. 13
MICROHARDNESS OF POWDER 7

Load P (g)

Indentation Diagonal d (microns)

Meyer Exponent = 1.88

MH₅µm = 12.2 kg/mm²
MH₁₀µm = 11.2 kg/mm²
MH₂₀µm = 10.3 kg/mm²
FIG. 14
MICROHARDNESS OF POWDER 8

MEYER EXPONENT = 1.96
Fig. 15  Grain structure of Powder 1.
Hoganas MH100.24 iron
etched in 2% Nital.  x 500

Fig. 16  Grain structure of Powder 2.
Cohens electrolytic iron
etched in 2% Nital.  x 500
Fig. 17  Grain structure of Powder 4
Sherritt Gordon Nickel etched
in aqua regia.  x 500

Fig. 18  Grain structure of Powder 5
B.S.A. 310L stainless steel
etched in aqua regia.  x 500
FIG. 19
PARTICLE SIZE DISTRIBUTION OF METAL POWDERS
(MICROSCOPIC DETERMINATION)
Fig. 20  Particle sections of Powder 1
Hoganas MH100.24 Iron  x 150

Fig. 21  Particle sections of Powder 2
Cohens Electrolytic Iron  x 150
Fig. 22  Particle sections of Powder 3
E.S.A. Atomised Copper  x 150

Fig. 23  Particle sections of Powder 4
Sherritt Gordon Nickel  x 150
Fig. 24  Particle sections of Powder 5  
B.S.A. 310L stainless steel.  x 150

Fig. 25  Particle sections of Powder 6  
B.S.A. 410L stainless steel.  x 150
Fig. 26  Particle sections of Powder 7  Lead Powder  x 150

Fig. 27  Particle sections of Powder 8  Silver Powder  x 150
FIG. 28

ISOSTATIC PRESSURE - DENSITY RELATIONSHIPS

![Graph showing isostatic pressure-density relationships for various metals and materials.](image)
FIG. 29

THE EFFECT OF PARTICLE SIZE ON THE ISOSTATIC PRESSURE-DENSITY RELATIONSHIP OF POWDER 2: COHENS ELECTROLYTIC IRON

[Graph showing the relationship between compaction pressure (kg/mm²) and density (% solid) for different mesh sizes: -100 + 140 mesh, -170 + 200 mesh, -270 + 400 mesh, and as received.]
FIG. 30

THE EFFECT OF DENSIFICATION ON THE HARDNESS

FOR TWO SIZE FRACTIONS OF POWDER 2

![Graph showing the effect of densification on hardness for two size fractions of powder 2. The graph plots mean particle hardness (MPH) in kg/mm² against fractional density (D). The data points for two size fractions are indicated: -100 + 140 mesh (solid line) and -270 + 400 mesh (dashed line).]
Fig. 30A  Compact section of Powder 2A compacted at 17.3 kg/mm². × 500

Fig. 30B  Compact section of Powder 2A compacted at 32.7 kg/mm². × 500
Fig. 30C  Compact section of Powder 2A
Compacted at 70.8 kg/mm²  x 500
FIG. 31
ISOSTATIC COMPACTION PRESSURE-DENSITY DATA
RELATIONSHIP ACCORDING TO BALSHIN
FIG. 32
ISOSTATIC COMPACTION PRESSURE–DENSITY DATA
RELATIONSHIP ACCORDING TO SMITH

\[ \frac{1}{p^3} \]

![Graph showing isostatic compaction pressure-density data relationship according to Smith. The graph includes data points for Powder 1, Powder 3, Powder 5, and Powder 8.](image-url)
FIG. 33

ISOSTATIC COMPACTION PRESSURE–DENSITY DATA RELATIONSHIP ACCORDING TO SHAPIRO AND KOLTHOFF, KONOPICKY, ATHY, TORRE AND HECKEL

\[ \ln \frac{1}{1-D} \]

\[ P \text{ (kg/mm}^2) \]

\( \Delta \) POWDER 1
\( \Delta \) POWDER 3
\( X \) POWDER 5
\( \square \) POWDER 8
FIG. 34

ISOSTATIC COMPACTION PRESSURE - DENSITY DATA

RELATIONSHIP ACCORDING TO JOVANOVIC
FIG. 35
ISOSTATIC COMPACTION PRESSURE - DENSITY DATA
RELATIONSHIP ACCORDING TO KAWAKITA

![Graph of isostatic compaction pressure vs. density data according to Kawakita.](image-url)
FIG. 36
THE EFFECT OF PARTICLE HARDNESS ON CONSTANTS DERIVED FROM KAWAKITA'S EQUATION

FIG. 36a

FIG. 36b

FIG. 36c

PARTICLE HARDNESS

MICROHARDNESS

$\beta \times MEYER EXponent$
FIG. 37

ISOSTATIC COMPACTION OF POWDER I

HÖGANÄS MH 100.24 IRON POWDER

[Graph showing compaction pressure (P) vs. porosity (1 - D).]

COMPACTING PRESSURE (P) kg/mm²

POROSITY (1 - D)
FIG. 38

ISOSTATIC COMPACITION OF POWDER 2
COHENS ELECTROLYTIC IRON POWDER

![Diagram showing compaction pressure (P) vs. porosity (1-D)].

- Compacting Pressure (P) vs. Porosity (1-D)
- Units: kg/mm²
FIG. 39
ISOSTATIC COMPACTION OF POWDER 3
B.S.A. ATOMISED COPPER POWDER

![Graph showing compaction pressure (P) vs. porosity (1 - D).]
FIG. 40

ISOSTATIC COMPACTION OF POWDER 4

SHERRITT GORDON NICKEL POWDER

![Graph showing the relationship between compacting pressure (P) and porosity (1-D)].
FIG. 41

ISOSTATIC COMPACTION OF POWDER 5
B.S.A. ATOMISED STAINLESS STEEL 310 L

![Graph showing compaction pressure (P) vs. porosity (1 - D)]
FIG. 42

ISOSTATIC COMPACTION OF POWDER 6
B.S.A. ATOMISED STAINLESS STEEL 410L

![Graph showing the relationship between compacting pressure (p) and porosity (1 - D).]
FIG. 43

ISOSTATIC COMPACTION OF POWDER 7

LEAD POWDER

![Graph showing compaction pressure (P) vs. porosity (i-D).]
FIG. 44

ISOSTATIC COMPACTION OF POWDER B

SILVER POWDER

COMPACTING PRESSURE (P) k.g./cm²

POROSITY (1 - D)
FIG. 45
THE EFFECT OF PARTICLE HARDNESS ON THE CONSOLIDATION PRESSURE

![Diagram showing the relationship between consolidation pressure and particle hardness for different materials: Lead, Silver, Copper, Nickel, Iron (electrolytic), and Iron (sponge). The consolidation pressure is measured in kg/mm², and the particle hardness is measured in kg/100μm.](image-url)
FIG. 46

ISOSTATIC COMPACTION OF POWDER I

HÖGANÄS MH100.24 IRON POWDER

![Graph showing isostatic compaction of powder I with data points and linear trend line.](image-url)
FIG. 47
ISOSTATIC COMPACTION OF POWDER 2
COHENS ELECTROLYTIC IRON POWDER

COMPACTION PRESSURE $P$ kg/mm$^2$

$-\ln D$

0.05 0.1 0.25 0.5
FIG. 48

ISOSTATIC COMPACTION OF POWDER 3

B.S.A. ATOMISED COPPER POWDER

![Graph showing isostatic compaction of powder 3]
FIG. 49
ISOSTATIC COMPACTION OF POWDER 4
SHERRITT GORDON NICKEL POWDER
FIG. 50

ISOSTATIC COMPACTION OF POWDER S
B.S.A. 310L STAINLESS STEEL
FIG. 51
ISOSTATIC COMPACTION OF POWDER 6
B.S.A. 410L STAINLESS STEEL

COMPACITION PRESSURE $P$ kg/m$^2$

$-\ln D$

0.05 0.1 0.25 0.5
FIG. 52
ISOSTATIC COMPACTION OF POWDER 7
LEAD POWDER

![Graph showing compaction pressure vs. -ln D](image)
FIG. 53

ISOSTATIC COMPACTION OF POWDER 8

SILVER POWDER

COMPACT PRESSURE $P$, kg/mm²

$-\ln D$
FIG. 54

THE RELATIONSHIP BETWEEN TAP DENSITY AND CONSOLIDATION DENSITY

\[ D_s = 0.46D_t + 0.60 \]
FIG. 55
THE RELATIONSHIP BETWEEN COMPACTION PRESSURE AND COMPACTION STRAIN

![Graph showing the relationship between compaction pressure and compaction strain.](image-url)
FIG. 56

THE RELATIONSHIP BETWEEN PARTICLE HARDNESS AND COMPACTION CONSTANT K

$K = 0.054 \times MH_{10\mu m}$

[Graph showing the relationship between particle hardness (MH_{10\mu m}) and compaction constant K.]
FIG. 57
THE RELATIONSHIP BETWEEN MEYER EXPONENT AND
COMPACtion EXPONENT $\eta''$

$n'' = M.E. - 2.57$
FIG. 58

DIE COMPACTION OF POWDER 1, POWDER 2
AND POWDER 5

\[
\text{COMPACTION PRESSURE } P \quad \text{kg/mm}^2
\]

\[
\text{vs. } -\ln D
\]
FIG. 59

DIE COMPACTION OF POWDER 3 AND POWDER 6

- COMPACTION PRESSURE $P \text{ kg/mm}^2$
- $-\ln D$

- Dot markers for data points:
  - $0.05$
  - $0.1$
  - $0.25$
  - $0.5$

- Line markers for pressure trends:
  - Solid line for powder 3
  - Dashed line for powder 6
FIG. 60
THE RELATIONSHIP BETWEEN CONSOLIDATION PRESSURE AND PARTICLE HARDNESS FOR ISOSTATIC AND DIE COMPACTION

---

![Graph showing the relationship between consolidation pressure and particle hardness for isostatic and die compaction.](image)
FIG. 61
THE RELATIONSHIP BETWEEN COMPACTION PRESSURE AND
COMPACTION STRAIN FOR POWDER 2

![Diagram showing the relationship between compactation pressure and strain for Powder 2. The graph includes data points for both isostatic and die compaction methods.](image-url)
FIG. 62

THE RELATIONSHIP BETWEEN COMPACTION PRESSURE AND COMPACTION STRAIN FOR POWDER 3

\[ \ln \left( \frac{D - D_T}{D(1 - D_T)} \right) \]

- ISOSTATIC
- DIE

COMPACTION PRESSURE (kg/mm²)

0.0 0.025 0.05 0.1 0.15 0.2 0.25 0.5 1.0

80 60 40 20 10
APPENDIX 1

The stresses in the compound cylinder produced by an internal pressure of 65 ton/in² (about 100 kg/mm²) calculated according to Timoshenko (Strength of Materials Vol. 2) are as follows.

A. For shrink fit of two cylinders

\[
P = \frac{E\delta (b^2 - a^2)(c^2 - b^2)}{2b^2(c^2 - a^2)}
\]  

\(P\) = pressure existing after assembly of the two rings  
\(E\) = Young's Modulus (\(E\) taken as average for the two materials)  
\(\delta\) = initial difference in radius  
\(a\) = radius of inner bore  
\(b\) = inner radius of EN30  
\(c\) = outer radius of EN30

for \(c = 4\) in., \(b = 1.75\) in., \(a = 0.688\) in.,  
\(\delta = 0.004\) in., \(E = 28 \times 10^6\) lb/in².  

\(P = 22,500\) lbf/in² (7.07 kg/mm²).
B. Stresses due to shrink fit. Consider each ring separately subjected to this pressure.

(i) For outer cylinder (subject to internal pressure only)

\[ \sigma_r = \frac{a^2 P_i}{(b^2 - a^2)} \left( 1 - \frac{b^2}{r^2} \right) \quad (2) \]

\[ \sigma_t = \frac{a^2 P_i}{(b^2 - a^2)} \left( 1 + \frac{b^2}{r^2} \right) \quad (3) \]

where

- \( \sigma_r \) = radial stress
- \( \sigma_t \) = tangential stress
- \( a \) = internal radius
- \( b \) = external radius
- \( r \) = radius at any point in the ring
- \( P_i \) = internal pressure.

Taking

- \( a = 1.75 \text{ in.} \)
- \( b = 4 \text{ in.} \)
- \( P_i = 22,500 \text{ lbf/in}^2 \)

In (2) \[ \sigma_{ra} = -22,500 \text{ lbf/in}^2 \quad (r = a) \]
\[ \sigma_{ta} = 0 \text{ lbf/in}^2 \quad (r = b) \]

In (3) \[ \sigma_{ta} = 33,200 \text{ lbf/in}^2 \quad (r = a) \]
\[ \sigma_{tb} = 10,650 \text{ lbf/in}^2 \quad (r = b) \]
(ii) For inner cylinder (subject to external pressure only)

\[
\sigma_r = \frac{-P_0 b^2}{(b^2 - a^2)} \left(1 - \frac{a^2}{r^2}\right) \quad (4)
\]

\[
\sigma_t = \frac{-P_0 b^2}{(b^2 - a^2)} \left(1 + \frac{a^2}{r^2}\right) \quad (5)
\]

taking

\[
a = 0.688 \text{ in.}, \ b = 1.75 \text{ in.}, \ P_0 = 22,500 \text{ lbf/in}^2
\]

In (4) \(\sigma_{rb} = -22,500 \text{ lbf/in}^2 \) (r = b)

\(\sigma_{ra} = 0 \text{ lbf/in}^2 \) (r = a)

In (5) \(\sigma_{tb} = -33,500 \text{ lbf/in}^2 \) (r = b)

\(\sigma_{ta} = -58,000 \text{ lbf/in}^2 \) (r = a)

Treating the compound cylinder as a whole and subjected to 65 tonf/in\(^2\) pressure.

Case 1.

taking \(a = 0.688 \text{ in.}, \ b = 4 \text{ in.}, \ P_i = 65 \text{ tonf/in}^2\)

\(\sigma_{ta} = 69.1 \text{ tonf/in}^2 \) (r = a)

\(\sigma_{tb} = 3.98 \text{ tonf/in}^2 \) (r = b)

\(\sigma_{rl.75} = -8.38 \text{ tonf/in}^2\)

\(\sigma_{tl.75} = 12.4 \text{ tonf/in}^2\)
APPENDIX 2

Shape Characteristics of Powder 1 (Hoganas MH100.24)

<table>
<thead>
<tr>
<th>No.</th>
<th>Elongation Factor $X$</th>
<th>Bulkiness Factor $Y$</th>
<th>Surface Factor $Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.64</td>
<td>0.43</td>
<td>6.15</td>
</tr>
<tr>
<td>2</td>
<td>1.76</td>
<td>0.54</td>
<td>7.30</td>
</tr>
<tr>
<td>3</td>
<td>1.79</td>
<td>0.60</td>
<td>1.73</td>
</tr>
<tr>
<td>4</td>
<td>2.60</td>
<td>0.45</td>
<td>2.93</td>
</tr>
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<td>1.25</td>
<td>0.59</td>
<td>7.79</td>
</tr>
<tr>
<td>6</td>
<td>1.06</td>
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<td>2.15</td>
<td>0.56</td>
<td>6.70</td>
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<td>0.51</td>
<td>5.72</td>
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<td>9</td>
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<td>0.55</td>
<td>3.69</td>
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<td>1.22</td>
<td>0.63</td>
<td>5.55</td>
</tr>
<tr>
<td>11</td>
<td>1.16</td>
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<td>0.59</td>
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<td>1.05</td>
<td>0.26</td>
<td>7.59</td>
</tr>
<tr>
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Shape Characteristics of
Powder 4 (Sherritt Gordon Nickel)

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Shape Characteristics of Powder 5 (B.S.A. Atomised 310L)

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\[ \bar{X} = 1.49 \quad \bar{Y} = 0.58 \quad \bar{Z} = 2.54 \]
# Shape Characteristics of Powder 6 (B.S.A. Atomised 410L)

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\[ \bar{X} = 1.58 \quad \bar{Y} = 0.64 \quad \bar{Z} = 1.77 \]
Shape Characteristics of Powder 7 (Lead Powder)

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Shape Characteristics of Powder 8 (Silver Powder).

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$\bar{X} = 1.54 \quad \bar{Y} = 0.58 \quad \bar{Z} = 3.90$
APPENDIX 3

Computer Programme For Calculation
Of Kawakita's Constants

50 PRINT "COMPRESSION OF POWDERS"
60 PRINT "FOLLOWING KAWAKITA"
70 LET S1=S2=S3=S4=S5=9.3
80 PRINT
90 PRINT "P", "P/C", "DENSITY", "C"
100 FOR I=1 TO N
110 READ P, R
120 LET C1=1-R3/R
130 LET C=P/C1
140 LET S1=S1+C
150 LET S2=S2+C
160 LET S3=S3+C
170 LET S4=S4+C
180 LET S5=S5+C
190 PRINT P, C, R, C1
200 NEXT I
210 LET D=N*S4-S2*S2
220 LET M=(N*S3-S1*S2)/D
230 LET D9=(N*S5-S1*S1)/D
240 LET R9=(N*S3-S1*S2)/SQR(D9)
250 LET C=(S1*S4-S2*S3)/D
260 LET A=1/M
270 LET B=1/(A*C)
280 PRINT
290 PRINT "P/C=K+M*P WHERE K=" TO I01"M=" TO I03
300 PRINT "WITH A CORRELATION OF " TO I04"R9"
310 PRINT
320 PRINT "THE CONSTANTS IN KAWAKITA'S EQUATION"
330 PRINT "ARE=" TO I01"B=" TO I03