Dynamic mechanical properties of austenitic stainless steel

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DYNAMIC MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS

by

S.H. Ellwood, B.Sc.

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University of Technology

June 1983

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'When I went to the bar as a very young man,

Said I to myself, said I,

"I'll work on a new and original plan",

Said I to myself, said I!'

W.S. Gilbert, 1836 - 1911.
ACKNOWLEDGEMENTS

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ABSTRACT

The principal aim of the research is to determine the stress/strain characteristics of stainless steels at high rates of strain (> 100sec\(^{-1}\)), and so to investigate the effects of changing strain rate on yield point and plastic flow stress. The material properties obtained in this work are intended for use in the analysis of explosive tests on model fast breeder reactor containment vessels. The experimental technique used is the split Hopkinson pressure bar method in which stress pulses are used to produce high rates of loading in the sample.

Practical problems with pulse measurement and sample preparation are discussed, and recommendations are made to improve the reliability and accuracy of tests. New techniques described include the use of a transient recorder and micro-computer for improving pulse recording and analysis, pulse-shaping to control the strain rate of tests and a modification of the basic Hopkinson bar to enable a simple conversion to be made from compressive to tensile testing.

The results of extensive testing of samples from 321 stainless steel bar in compression and tension over a wide range of strain rates (static and 100 to 2000sec\(^{-1}\)), testing temperatures (20 to 600\(^{\circ}\)C); and different annealing temperatures are reported. Results of tests on 304, 316, 321 and 325 stainless steel rod are also presented. Comparison with previous empirical and theoretical material constitutive equations is discussed.
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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

A car crash, an earthquake, penetration of a projectile and explosive forming of sheet metal components are all situations where materials are deformed dynamically. Less obvious cases are in the regions near to a moving fracture tip or a metal cutting tool, and in the forging or extrusion of materials. Any complete analysis or understanding of these processes involve knowledge about how materials behave when deformed rapidly.

The mechanical behaviour of a material is normally displayed as a stress against strain curve obtained in a uniaxial test. Consider a tensile sample loaded by a force $F$ and of initial cross sectional area $A$. The engineering sample stress is given by:

$$\sigma_s = \frac{F}{A}$$  \hspace{1cm} (1.1)

The original length was $l$ and the increase after load applied $dl$. The engineering sample strain is given by:

$$\epsilon_s = \frac{dl}{l}$$  \hspace{1cm} (1.2)

Although engineering stress and strain have been defined here, true stress and strain will be calculated for all experimental results, this enables direct comparison of tensile and compressive values.

The curve in Figure 1.1 is a stress against strain curve of the type obtained in the testing of many metals. O-Y is the
FIGURE 1.1 Typical Stress Against Strain Curve

FIGURE 1.2 Effect of Increasing Strain Rate
elastic region, where the strain is fully recovered if the load is removed. In this linear region the slope is normally referred to as Young's modulus or the elastic modulus (E). Y-F is the plastic region and strain is not now fully recovered; the point at Y is known as the yield point and \( \sigma_y \) as the yield stress. If the stress at A is released the strain recovers along a line of slope E to show permanent strain \( E_B \). If the material at B is loaded again it will remain elastic up to A and so has increased its yield point, this process being known as strain hardening. The plastic straining can continue until a point F is reached where the sample fractures.

Whenever such a test is carried out many parameters have to be recorded to give it any relevance. Temperature, material type, grade and previous history, and sample dimensions all need to be recorded. The main factor to be discussed in this thesis is the strain rate:

\[
\varepsilon_s = \frac{d\varepsilon_s}{dt}
\]  

(1.3)

It is often not recorded, but can have a significance on the result of the test. In general, it has no effect on elastic behaviour, but does affect the plastic behaviour. Figure 1.2 indicates the trend that might be obtained from tests on metallic samples, and shows an increase in the stress for a given strain and a higher yield point with increasing strain rate.

Mechanical properties of materials are used by engineers and designers, and strain rate has to be considered whenever plastic flow is involved. In practical situations strain rate can vary over many orders of magnitude. Strain rates (from \( 10^{-9} \)
to $10^{-5}\text{s}^{-1}$) are encountered where a high load is maintained for a long period. Inelastic deformation can take place at stresses below the 'normal' yield point, a process known as creep. Most tests and loading situations are at 'quasi-static' rates (between $10^{-5}$ and $10^{-1}\text{sec}^{-1}$). The dynamic range includes strain rates of $10\text{sec}^{-1}$, up to $10^4-10^5\text{sec}^{-1}$ in shock loading conditions. The figures above refer to macroscopic strain rates which are normally measured; microscopic strain rates can be several orders of magnitude higher in the regions around moving dislocations (Gilman (1969)). In many situations the distribution of strain rate is complex, and large variations can occur in a small region. However, material properties are often not strongly dependent on strain rate so only an order of magnitude (Johnson (1972)), or range of values may be needed to characterise a particular situation.

The tests carried out by the present author were mainly on 321 austenitic stainless steel, in collaboration with the COVA (C0de-VAlidation) programme carried out by the United Kingdom Atomic Energy Authority. The COVA programme was designed to provide information for the validation of computer programmes designed to simulate the effects of accidents within fast breeder reactors. The experimental programme was carried out at Ispra in Italy, and within the UK at UKAEA Winfrith and AWRE Foulness. The tests were performed by the detonation of an explosive charge within a scale model reactor contaminant vessel (Figure 1.3). The models were not of specific reactor designs, but were intended to model the effects of various design features. At each of the three establishments a series of approximately twenty tests have been performed, starting with right cylindrical
FIGURE 1.3 Arrangement for COVA Test FT17
vessels with rigid walls and proceeding to deformable vessels (some with hemispherical ends). Later tests included internal tanks, diagrids and a model neutron shield. All models were water filled to simulate the effects of stress waves propagating through a coolant. Whilst the final deformation was the most important aspect of the tests, the models were well instrumented with resistance strain gauges and piezo-electric pressure transducers. The output of these (up to 100 channels) were recorded on high speed (120 i.p.s.) magnetic tape recorders. The data was digitised at a later date by replaying the tapes at a lower speed into a computer and plots of pressure or strain against time were plotted.

For comparison with computer simulations, material data at the strain rates encountered in the model tests (50-250sec\(^{-1}\)) were required. The deformable vessels were made from 321 stainless steel sheet, except for the hemispherical ends which had to be made from 304 stainless steel. 321 stainless steel was chosen as it was readily obtainable, easily welded (electron beam welding used) and because of a desire to use a single well-defined material throughout the tests. It is unlikely that it will be used in full scale containment vessels. Dynamic stress against strain data was available for 304, but there was little on 321 in the literature. Most of the material data used in the project was provided by Albertini and Montagnani (1979) from dynamic tensile tests carried out on offcut material saved from the fabrication of the vessels. The author entered the project towards the end of the experimental stage, and observed and assisted with the final model tests at Foulness. Many of the material tests reported later in this thesis were carried out
on samples of 321 stainless steel prepared at Foulness. They comprised an extensive series of tests, both in tension and compression, at a wide range of strain rates (static and 80-2000sec\(^{-1}\)) and temperatures (20-600°C).

Most of the author's work has been to develop techniques to enable the tests to be carried out on the split Hopkinson bar apparatus at Loughborough. The initial task was to develop a computer system (Chapter 2) for the analysis of results. This comprised of a transient recorder, for recording stress pulses, interfaced with a microcomputer which carries out calculations, plots graphs and produces tabulated results. Other techniques developed were pulse shaping, (Chapter 3) which was devised in order to enable tests to be carried out at the lower dynamic strain rates required for use in the COVA programme. As no dynamic tensile testing apparatus existed at Loughborough a simple modification of the Hopkinson bar was developed (Chapter 4) to enable tensile tests to be carried out.

Much of the work carried out on dynamic material properties is concerned with the development of constitutive equations:

\[
\sigma = F(\varepsilon, \dot{\varepsilon}, T)
\]  

(1.4)

Many such equations have been developed, (see Chapter 7) most of these are empirical and can be made to fit for a limited range of conditions for particular materials. No generally successful theory of plastic flow has yet been developed, but again equations based on existing theories can be made to fit particular situations, and are successful in describing many of the features observed in practice. These equations are usually based on dislocation theory.
1.2 Stress Waves

When loads are applied at high speeds, rigid body mechanics no longer apply and propagation of stress waves has to be considered. Most of the techniques used for the determination of material properties involve the propagation of stress waves (or pulses) through material samples. Reviews of the properties of stress waves in solids appear in the books by Kolsky (1963), Johnson (1972) and Walsley (1973).

1.2.1 Stress Waves in Infinite Media

The earliest study of stress waves considered the transmission medium as being perfectly elastic, and further simplification can be obtained by assuming an isotropic medium. Work in the last century by Stokes, Poisson, Rayleigh and Kelvin established the theory of stress waves in infinite media. For an infinite isotropic medium two types of wave are propagated: equivoluminal waves (S or shake waves) with velocity

\[ C_t = \sqrt{\frac{G}{\rho}} \]  \hspace{1cm} (1.5)

and irrotational (P or push waves) with velocity

\[ C_d = \sqrt{\frac{\lambda + 2G}{\rho}} \]  \hspace{1cm} (1.6)

where \( \lambda \) is wavelength, \( G \) shear modulus, \( \rho \) density and \( \nu \) Poisson's ratio.

Note that from 1.5 and 1.6

\[ \frac{C_d}{C_t} = \sqrt{2 + \frac{\lambda}{G}} \]  \hspace{1cm} (1.7)

and so \( C_d > C_t \).
For a fluid medium the shear modulus equals zero and so only
dilational waves of velocity $\sqrt{\lambda/\rho}$ are possible.

The terms equivoluminal and irrotational were first applied
by Lord Kelvin in 1899 but the recognition of the two types is
attributed to Stokes.

Rayleigh in 1887 showed that a third type of wave could
exist on the surface of a semi-infinite medium. These waves
are a surface effect, and at a depth of one wavelength the
amplitude is only 0.19 of that at the surface. Like the body
waves the Rayleigh waves are non-dispersive. The velocity varies
from $0.92C_t$ to $0.96C_t$, for $0.25 < \nu < 0.5$. Surface waves
propagated from earthquakes were analysed by Love who took into
account the variation in density and elasticity of the earth's
crust with depth.

1.2.2 Waves in Rods

The Hopkinson bar technique used by the author makes use of
the propagation of longitudinal stress pulses through long stain-
less steel bars. The simple, one-dimensional equation of motion
for an element of a rod leads to a wave equation where the
velocity of longitudinal waves, $C_o$, is given by

$$C_o = \sqrt{E/\rho}$$

(1.8)

This equation is accurate for $\lambda/a > 10$, where a is bar radius.
Love and Rayleigh derived an approximate equation to allow for
transverse radial motion of the element. Rayleigh's solution
leads to a phase velocity, $C_p$, where

$$C_p = C_o \left(1 - \nu \frac{a^2}{\lambda} \right)$$

(1.9)
This solution is reasonable for $\lambda/a > 1.4$ but can lead to large errors for short wavelengths.

Inclusion of radial motion in longitudinal waves due to Poisson coupling predicts a ripple in the top of the rectangular pulse given by a one-dimensional analysis. Waves other than longitudinal can be propagated along a rod.

Simple analysis of the torsional forces on a bar element leads to a velocity for torsional waves of

$$C_T = \sqrt{G/\rho_o}$$

(1.10)

This velocity is exactly correct as no inertial effects have been neglected, unlike in the simple case for longitudinal waves.

Flexural or bending waves can also be propagated along bars. Rayleigh derived a phase velocity of

$$C_F = C_o/(\lambda/\pi a)$$

(1.11)

for bars of circular cross-section. This implies that infinitely short waves travel at infinite speed and only fits experimentally derived results for long wavelengths, $\lambda/a > 10$. Better solutions to the wave equation have been found, particularly by Timoshenko who included a term to allow for the distortion of cross-sectional elements by shear forces.

Pochhammer and Chree independently derived exact equations to describe infinite wave trains in circular cross-section bars by applying equations of motion using cylindrical co-ordinates. These equations are useful when short wavelength, longitudinal, torsional or flexural waves are considered and can be used to
study the distortion of a pulse due to the differing velocities of its Fourier components (Davies (1956)).

This dispersion produces an increase in the rise time of a pulse and a tail due to a delay in the recovery of strain after a pulse.

1.2.3 Plastic Waves

When a suddenly applied stress exceeds the material's elastic limit \( \sigma'_y \), propagation of the stress level is dependent on the shape of the stress/strain curve,

\[
C_p = \sqrt{\frac{\partial \sigma}{\partial \varepsilon}} / \rho
\]  \hspace{1cm} (1.12)

Plastic waves therefore travel at much slower speeds than elastic waves and the overall pulse shape can change quite rapidly as the plastic component lags behind the elastic wave front. For materials (e.g. annealed copper in compression), whose stress against strain curve is concave upwards, high stresses are propagated faster than lower ones and so a shock can build up at the wave front. Shock fronts can also be generated in solids by very high velocity impacts (1-5km/S). A recent review of shock propagation in solids is given by Harding (1976).

1.3 Techniques for High Strain Rate Tests on Materials

Any process involving high speed deformation could, in principle, be used to determine dynamic mechanical properties. However, in many situations measured results may be insensitive to material properties, or the influence of inertial effects, or inhomogeneity of stress and strain make the analysis difficult.
One of the first attempts to measure dynamic material properties was by J Hopkinson (1872) who measured the tensile strength of steel wires. The load was applied by a falling weight with a hole through the centre, the wire being threaded through the hole. The weight was released from a known height and struck a stopper at the end of the wire. He found that the minimum height from which the weight had to be released to break the wire was independent on the mass of the weight; in other words, it was the velocity of impact \( v_0 \) that determined the stress in the wire. He explained this in terms of a stress waves propagated in the wire with an initial amplitude of

\[
\sigma_0 = \rho v_0 C_0
\]  

He found that the wire generally broke at the top where the maximum stress of the first reflection would be \( 2\rho v_0 C_0 \). These tests were repeated in 1905 by his son B Hopkinson who included a means of measuring the maximum strain at the top of the wire. He showed that the dynamic tensile strength of the wires was greater than that obtained in static tests. Taylor (1946) showed that the maximum stress was, in fact, at the third reflection where the maximum stress was \( 2.15\rho v_0 C_0 \) and this helped to further emphasise the importance of dynamic properties.

One of the most common forms of impact test is the Charpy test in which a notched specimen is subjected to a three point bending. The load is supplied by a swinging anvil and the energy absorbed in the impact and fracture can be measured by the reduction in height of swing caused by the specimen. Similar tests on notched specimens by application of drop weights, explosives or gas gun are also used. Such tests can achieve a
strain rate of approximately 200 sec$^{-1}$ but cannot produce a stress against strain curve or even a value for the yield stress. Parameters such as fracture toughness and null-ductility temperatures can be measured. Such tests can only be comparative, but can be used as a measure for quality control of materials where resistance to impact is required in a final product.

The propagation of elastic-plastic waves has been studied by many workers Malvern (1951), Bertholf and Karnes (1969), Kolsky and Douch (1962) and Bell (1968). The dynamic material properties obtained from other techniques can give good prediction of the propagation of plastic waves, particularly for high rate resistance materials such as iron (Watson (1969)). However, in many cases the accurate determination of dynamic stress against strain curves is not really possible as with this technique the wave front profile is not sufficiently sensitive to variations in plastic flow stress.

To obtain stress against strain diagrams of materials hydraulically driven machines, often with axial and torsional loading, have been used (Randall and Campbell (1972) and Lindholm et al (1971)). Strain rates of up to 100s$^{-1}$ have been achieved with specimens of high strength steel with very short gauge lengths. Albertini and Montagnani (1972) described pneumatic and hydraulic/pneumatic machines with no feedback. Strain rates are controlled by the use of calibrated orifices and constant rates of between 10 and 100 sec$^{-1}$ can be achieved. Strain is measured by displacement transducer and load by a strain gauge on an elastic stress bar. The machines are started
by puncturing a membrane.

Many workers have made use of a cam plastometer. First used by Orowan (1950) who made a compression machine, one of the platens being driven by a logarithmically shaped cam to produce a constant true strain rate. Many tests have been carried out (see review by Bitans and Witten 1972) on a wide range of metals and temperatures at strain rates between 0.1 and 200 sec\(^{-1}\).

Most of the work on dynamic stress against strain in the range between \(10^2\) and \(10^6\) sec\(^{-1}\) has been done by apparatus derived from what is now generally known as the split Hopkinson pressure bar, or sometimes as the Kolsky bar.

B. Hopkinson (1914) was one of the first to experimentally investigate propagation of stress pulses generated by the detonation of high explosives or impact of bullets. All previous work was on acoustic and seismic waves. As there was no electronic detection or recording equipment available he used a technique based on a 'time-piece', a short length of bar which was wrung into one end of a steel bar. The impact or explosion took place at the other end and a compressive stress pulse was propagated along the bar without distortion (pulse much longer than the bar diameter and maximum stress within its elastic limit). When the pulse reached the far end of the bar it entered the time-piece and was reflected from its free end as a pulse of tension. When the tensile front of the pulse reached the main bar again, it acted to detach the time-piece which flew off the main
bar with a momentum given by a portion of the pulse of duration $\Delta t$ given by:

$$\Delta t = \frac{2I}{c_0}$$  \hspace{1cm} (1.14)

where $I$ is the length of the time-piece. The momentum of the time-piece was measured by capture in a ballistic pendulum and the momentum remaining in the bar was obtained from the maximum amplitude of swing of the bar. The use of a series of time-pieces of differing lengths enables the shape of the pulse to be measured. The drawback with this technique is that unless the rise or fall time of the pulse can be determined from other means the shape of the pulse from a set of tests (on one type of pulse) is not uniquely defined. The technique does however, enable the amplitude and duration of a pulse to be found, but the tension required to break the time-piece from the bar introduces an unknown variable and makes the method unsuitable for pulses of low amplitude.

In 1948 R M Davies replaced the time-piece arrangement with a condenser unit. The free end of the bar acts as one plate of a parallel plate capacitor which, with suitable circuitry, produces a voltage proportional to its displacement which can be recorded on an oscilloscope. The resulting trace can be differentiated to produce a pressure time curve for the pulse. Two alternative arrangements are described by Davies, both with cylindrical tubes placed around the bar. One is placed part way along the bar and detects radial displacement, the other at the far end of the bar also detects longitudinal displacement. This has the advantage over the parallel plate arrangement of giving a linear response even when displacements
are large. J P Owen and Davies (1949) measured torsional waves photographically by the reflection of light from an optically polished flat on the surface of a bar.

The earliest attempts to produce stress/strain curves were made by Taylor (1946), E Volterra (1948) and Kolsky (1949). Taylor and Volterra used a photographic method in which the specimen, in the form of short cylinders were placed on the end of a ballistic pendulum in the form of a long bar. Another bar was swung so as to impact onto the specimen. The strain could be derived directly but the stress required a double differentiation of the displacement of the ballistic pendulum. Samples of rubbers and other polymers were tested using this technique. Volterra also developed a modification of the Davies bar in which a cylindrical specimen is placed between the end of a bar and an anvil. A .22" bullet is fired at the anvil and the stress pulse recorded in the bar gives the stress against time cycle for the sample. The measurement of strain in the sample requires the firing of a second bullet at the anvil with no sample present and the subtraction of the two pulses. The two methods above suffer from inaccuracies due to a double differentiation, subtraction of two pulses and the length of the specimen.

Kolsky is generally acknowledged as the first to produce a practical apparatus for measuring stress against strain. His advance was to sandwich a short cylindrical specimen between two long bars. At the far end of the first was an anvil and a detonation was used for the production of the incident stress pulse. At the far end of the second was a
parallel plate capacitor which measured the stress pulse transmitted through the sample and thus directly measured the stress against time. Mid-way along the first bar was a cylindrical capacitor which could measure the pulse incident on the sample and also reflected pulse from which the strain against time curve could be produced. The samples used by Kolsky were short, and so effects due to axial inertia and pulse propagation within the sample could be neglected. He made some correction for the radial inertia of the sample but the short length compared with the radius meant that frictional effects gave an over estimation of the sample stress (Davies and Hunter 1963).

The split Hopkinson pressure bar has now been applied to a wide range of materials (see Section 1.4) and many analyses have been carried out (see Section 2.1) which confirm that with some care valid stress against strain curves can be obtained for strain rates of up to 5000sec\(^{-1}\). The capacitive deflection transducers have in most cases been replaced by the use of resistive strain gauges attached to the bars either side of the specimen (Billington and Brissenden 1971), which detect the reflected and transmitted pulses. Watson (1970) described the system whereby a strain gauge is attached directly to a specimen to produce sample strain against time. Sample stress is measured by two slices of quartz crystal sandwiched between the sample and bars.

Several optical techniques have been used for measuring sample stress. Stevenson and Campbell (1975) etched a grid onto a torsion specimen. This was illuminated over a small
area (less than grid spacing), and the oscillating light output whilst the sample is straining recorded on an oscilloscope. Isozski and Oba (1979) used a similar technique using a copper grid and an electrical contact to measure tensile strain. Albertini and Montagnani (1977) and Gorham (1979) have used high speed photography on sample images to directly measure strain, and also strain distribution. Bell (1966) used a diffraction grating ruled directly onto a specimen to measure both stress and strain distribution. He points out that the use of long specimens by earlier workers can lead to questionable results. Griffiths and Martin (1974) use a system in which shutters are attached to the bars adjacent to the samples. Photo multipliers are used to detect their movement and strain can be measured directly while sample stress is obtained from a differentiation of the displacement of the shutter on the second bar.

Many workers have produced versions of the Hopkinson bar to produce other modes of deformation. Torsional apparatus are in wide use (Duffy 1974) as the specimen geometry remains constant during testing and pulses are propagated with no dispersion. Harding and Huddart (1979) describe a technique using a double notched specimen to produce very high strain rates in shear. Some of the tensile techniques used will be described in Section 4.1.

Much higher rates of strain can be achieved in techniques whereby an explosive charge is detonated in contact with a sample. Exploding wire techniques (Derwish 1979) are being investigated, in which a copper wire is vaporised along the
axis of a tubular specimen by the discharge of a high energy capacitor bank. Strains can be measured by optical detection of the deflection of the outer surface. Stresses can be measured by Schlieren techniques or by use of quartz crystal pressure gauges. Flying plate techniques can produce plane shock waves in plates accelerated by explosive charges, on impact with an anvil. Analyses of such situations is not simple as stress and strain are not obtained directly and iteration to assumed constitutive relations has to be employed.

1.4 Reported Material Properties

Many papers have been published in the past thirty years describing the results of tests on materials at high rates of strain. Most results of strain rates above $10^2 \text{sec}^{-1}$ were obtained on versions of the split Hopkinson pressure bar. Results below $10^2 \text{sec}^{-1}$ were mainly obtained by use of hydraulic actuators with feedback for the lower strain rates ($<1 \text{sec}^{-1}$) and by use of calibrated orifices for the intermediate rates. Much earlier work (Kolsky (1949), Davies and Hunter (1963)) concentrated on simple materials such as copper and aluminium. The use of such elemental materials was an attempt to use well-defined materials for which results could be compared, and also to limit the stress required to produce plastic deformation. Tests were also carried out on single crystal specimens also simplifying the interpretation of results on the microscopic scale. Attempts by the present author to compare results from different workers for aluminium under similar conditions
were hampered due to differences in initial material states specification, annealing, and in strain rate (and probably strain rate history) during testing. Similar comparisons in review papers rarely show close agreement (e.g. Duffy (1979)). Trends can emerge from a large number of results and are more reliable than those for a single series of tests. Comparison of material tests will always be difficult as properties can vary within a single specification, even from the same supplier, or within a single piece.

Much of the early work on dynamic material testing was carried out on iron as it is an example of a material whose properties are strongly dependent on strain rate. Mild steel has also been studied by many workers due to its wide application, and effects of strain rate on the stress drop at yielding are of great interest. Whilst most of the work has been carried out on metallic specimens, many tests have been carried out on non-metals. Polymers, such as rubber, polythene and perspex, have been tested but the interpretation of results is complicated by visco elastic effects. This problem is also present when composite materials such as glass or carbon fibre are tested due to the properties of the resin matrix materials normally used. Such materials are further complicated by a strong anisotropy which depends on fibre orientation. Other non-metallic materials that have been examined are bone (also anisotropic), granite, concrete and even frozen foods.

Most of the work carried out is with some particular application in mind, and so many of the technologically
important materials have been tested. However, the author's work on 321 stainless steel for the COVA project was instigated as there is little data available in the literature. Tests on 304 and 316 stainless steel are reported by Albertini and Montagnani (1974) by Isozaki and Oba (1979) and by Nicholas (1981). Tests on some of the ferritic and austenitic stainless steels have also been performed. In any case, definitive results for many materials are not available, and material data for a particular application are best obtained by performing tests on representative samples of the actual material used. Some of the unpublished results produced by Albertini and Montagnani on tests from the offcut 321 material from the COVA vessels have been supplied to the author and will be used later (Chapter 6) for comparison with the results obtained at Loughborough.

Parameters that are varied or measured in dynamic mechanical tests are stress and strain, strain rate and temperature. Other parameters that can be measured, or deduced from stress against strain curves are yield point, ductility ultimate tensile strength, work hardening rate and resistance to notches. Factors that can affect behaviour are composition, grain size, dislocation density, and presence of imperfections or a heat affected zone. Stress and strain can be in compression, tension or shear and have to be presented in a form suitable for further interpretation and analysis. Effective stress and strain may have to be calculated for use in bi- or tri-axial situations, and true stress and strain determined from uni-axial tests to allow for change in cross-sectional area. Strain rate can be a difficult parameter to
measure as it can vary throughout the test. This is especially so near the yield point of the material where the transition from elastic to plastic straining takes places and the strain rate can increase by at least an order of magnitude (at most strain rates) if no steps (such as feedback) are taken to control it. Strain rate is often defined as the plastic strain rate in the test. Strain rate can also vary within a sample as in bending or near the fracture tip in an instrumented Charpy test. Temperature can normally be precisely measured and made constant over a specimen, but as most dynamic loading situations are considered as adiabatic in a plastically deforming material there is a temperature rise. This is often not enough to significantly alter the result of a test, but is a factor that sometimes has to be considered. It is interesting to note that this effect will act to decrease strength with increasing strain rate and was thought to dominate in early theories of dynamic material behaviour.

Yield point could be defined as the limit of proportionality of the stress strain curve (i.e. Figure 1.1), but this is often not sharply defined and it is usually measured as the stress required to produce a permanent deformation of 0.2% (0.2% proof stress). The stress at a strain of 0.5% or 1.0% is often more easily measured and can be more reliable as it is not so sensitive to minor perturbations in the shape of the stress against strain curve that can occur in practice. Care has to be taken in some cases to ensure that comparison between different yield points are made on the basis of the same definition. The most common form of presentation of dynamic mechanical properties of materials is the stress
against strain curve obtained in a Hopkinson pressure bar test. These generally have characteristic strain rates quoted, and "static" and "dynamic" curves are often presented on the same axis for comparison. In general, they show that for increasing strain rates the yield point increases, ductility (strain to fracture) decreases, and the work hardening rate often remains unchanged. The increasing strength with strain rate is often shown in the form of graphs of yield point (or stress at a given strain level) against strain rate. The review article by Lindholm (1974) contains a few alternative forms of presentation often used. Strain rate and temperature are often combined from thermal activation equations in the form of an effective temperature \( (T^*) \) given by:

\[
T^* = kT \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right)
\]

(1.15)
as increasing temperature is considered equivalent to decreasing strain rate. Plots of stress against strain for changing effective temperature can then be plotted. The ratio of dynamic to static yield points can also be considered against parameters such an annealing temperature (see Chapter 5) or strain, Duffy (1979). Other composite parameters such as \( \frac{\Delta \sigma}{\sigma} - \Delta \ln \dot{\varepsilon} \) (rate sensitivity parameter) and \( \frac{d\sigma}{d\ln \dot{\varepsilon}} \) can also be plotted and are useful in discussion of rate controlling mechanisms.

1.5 Properties of Stainless Steels

The initial forms of stainless steels were developed in Germany by Strauss and Maurer at the Krupp Laboratories and in Britain by Brearly around the period 1909 to 1912. They
added 12% chromium to steels and found that this was sufficient to produce an alloy which was resistant to corrosion. This type of steel was used in stainless cutlery, and other alloys (17% chromium) were used for industrial applications. These early stainless steels had good corrosion resistance but were difficult to fabricate.

The need for a stainless steel that is easily formed, machined and welded has led to the development of austenitic stainless steels. Pure iron at room temperature has a body centred cubic polycrystalline structure and is termed ferrite or α-iron. The solubility of carbon in ferrite is very low (less than 0.00005% by weight at 20°C). If the temperature of iron is raised above about 910°C it transforms spontaneously into a face centred cubic structure. This form is known as austenite, it is more compact (greater density), non-magnetic, more easily worked and the solubility of carbon is greater. This transition also takes place with the simple chromium-iron alloy steels but unfortunately the austenite form is not stable at room temperature. Rapid cooling of the austenite leads to the formation of a structure intermediate between the face and the body centred cubic forms, known as martensite. This material is magnetic, stable at room temperature, and as the carbon is locked in solution has a high yield point.

Stainless steels of all these forms of carbon steel can be made stable at room temperature, by various heat treatments and mechanical working, but mainly by the use of the addition of alloying elements to the steel. The Schaeffler diagram, figure 1.4 shows the effect of nickel and chromium equivalent on the structure of stainless steels. The nickel equivalent
A = Austenite
M = Martensite
$\delta F$ = Delta Ferrite

**FIGURE 1.4** Effect of Nickel and Chromium equivalents on constitution of Stainless Steel (Schaeffler diagram) Pickering (1976)

**FIGURE 1.5** Effect of Nickel Content on True Stress - True Strain Curve Pickering (1976)
is given by:

\[
\text{Ni (eq)} = (\text{Ni}) + (\text{Co}) + 0.5(\text{Mn}) + 0.3(\text{Cu}) + 25(\text{N}) + 30(\text{C})
\]

(1.16)

and the chromium equivalent by:

\[
\text{Cr (eq)} = (\text{Cr}) + 2(\text{Si}) + 1.5(\text{Mo}) + 5(\text{V}) + 5.5(\text{Al}) + 1.75(\text{No}) + 1.5(\text{Ti}) + 0.75(\text{W})
\]

(1.17)

where the brackets indicate the percentage by weight of the alloying element. Many of the combinations produce a material containing two or even three phases in steels quenched from elevated temperatures.

Stainless steels with a completely ferritic structure have a wide application, as due to the absence (or very low proportion) of nickel they are more economical. Unfortunately they can be rather brittle, and the carbon content has to be low (below 0.03%) to produce a useful product. This can be achieved with modern steel making techniques such as argon-oxygen refining. These steels show good resistance to corrosion (improves with increasing chromium content or addition of molybdenum) and are used in many applications such as kitchen ware, trim and industrial containers and pipes. In general ferritic stainless steels have higher yield points than austenitic steels but as they work harden less rapidly have similar ultimate tensile strengths. They cannot be formed as easily as austenitic steels due to their low ductility but are suitable for cold forging and spinning. Grain growth in a heat affected zone due to welding can cause problems in this single phase material, but alloys with small amounts of niobium and titanium can be welded successfully. Steels
containing 12-17% chromium, 0-4% nickel, 0.1-1% carbon and other additions are austenitic at 950-1000°C but even when air cooled in large sections transform completely to a martensitic structure. Such steels have lower ductility but much higher strengths than ferritic or austenitic steels. They can be used in applications where high strength, even at high temperatures, is important e.g. turbine blades and in aircraft structures and engines. The harder, higher carbon forms are useful for tools, bearings and cutlery.

Besides the three main stainless steel types containing nominally one phase there are several less widely used types. Duplex steels containing austenitic and ferritic structures have some applications as they are stronger than austenitic steels and exhibit some useful mechanical properties; they can be made to exhibit superplasticity and are resistant to solidification cracking. One such grade (IN744) has a composition of 26% chromium, 6.5% nickel, 0.05% carbon and 0.3% titanium, and can be seen to fit in the A + 6F region in figure 1.4. Two special types make use of the transformation of metastable austenite into martensite and so combine the benefits of both. They are very expensive to manufacture and they require very fine control of composition and temperature to be successful. Controlled transformation stainless steels can be worked as austenite and transformed into martensite by refrigeration below the martensite transformation temperature (typically to -78°C) or by low temperature heat treatment (approximately 450°C) to destabilise the austenite. Transformation induced plasticity steels (TRIP) use plastic deformation to
transform the metastable austenite into martensite. A typical composition for this type of steel is 9\% chromium, 8.5\% nickel, 0.3\% carbon, 4\% molybdenum, 2\% silicon and 2\% manganese. Such a steel after working could have a yield point of over 1400 MNm\(^{-2}\) with an elongation to fracture of 50\% and ultimate tensile strength of 1500 MNm\(^{-2}\).

Typical stress against strain curves for stainless steels containing 17\% chromium and differing amounts of nickel, shown in figure 1.5. For steels of 13\% nickel content and above, the austenite is stable. For many 'austenitic' steels therefore the austenite is not truly stable and can transform into martensite at high strain levels. Most of the austenitic stainless steels contain portions of other phases (e.g. ferrite, martensite, carbides) the structure of any particular sample is very dependent on composition, heat treatment and degree of work hardening.

Austenitic steels are often referred to as 18/8 steels, as the addition of 18\% chromium and 8\% nickel is the basis for most of the austenitic compositions and represent the minimum of alloying additions for a basically austenitic structure after air cooling.

In the United Kingdom stainless steels are specified using the grades detailed in British standards 1449 (sheet, strip and plate) and 970 (bar). Austenitic steels are specified by the grades between 301 and 347 and are therefore known as the '300 series'. Subgrades referred to by the number after the 'S' indicates the maximum carbon level, i.e. 321S12 indicates a maximum carbon level of 0.08\% and 321S20 a maximum carbon
level of 0.12% for the 321 grade. Table 1.1 shows the composition of the austenitic stainless included in British standard 1446. The grades 301 to 310 contain increasing amounts of nickel and chromium. These improve corrosion resistance and the nickel improves the stability of the austenite with respect to transformation to martensite. Other grades have additions which make them more suitable for specific applications. Grade 316 has 2 to 3% addition of molybdenum which helps to protect the surface from pitting corrosion which occurs particularly in chloride solutions (salt water). Intergranular corrosion caused by depletion of chromium at grain boundaries can occur when chromium carbides are formed in the heat affected zone near a welded joint. This type of corrosion is often known as 'weld decay' could be prevented by annealing after welding. This is often not practical and alloying additions which form carbides in preference to the chromium are included in weldable stainless steels. In 321 the addition is titanium and in 347 niobium; these are added in proportions in excess of the stoichiometric ratio to combine with carbon. Grades 304 and 316 are produced in forms with carbon contents less than 0.03% and so can also be welded. Addition of sulphur of between 0.15 and 0.3% are used to produce a steel, grade 325, which is more easily machined. This is not included in table 1.1 as it is only specified in BS 970 and is therefore only available in bar form.

Many of the mechanical properties of austenitic stainless steels, particularly at high rates of strain, will be discussed later, but a brief summary will be given here. The stress against strain curve is smooth with no definite yield point or yield drop, as in mild steel. The yield stress is therefore usually quoted
<table>
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<tr>
<th>GRADE</th>
<th>EN STEEL REPLACED</th>
<th>C (MAX)</th>
<th>S_i</th>
<th>Mn</th>
<th>N_i</th>
<th>Cr</th>
<th>Mo</th>
<th>Others</th>
<th>S (MAX)</th>
<th>P (MAX)</th>
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<td></td>
<td>0.15</td>
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<td>0.5/2.0</td>
<td>6.0/8.0</td>
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<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
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<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>8.0/11.0</td>
<td>17.0/19.0</td>
<td></td>
<td></td>
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<td>0.045</td>
</tr>
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<td>0.5/2.0</td>
<td>8.0/11.0</td>
<td>17.0/19.0</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
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<td>0.03</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>9.0/12.0</td>
<td>17.5/19.0</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
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<td>0.2/1.0</td>
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<td>8.0/11.0</td>
<td>17.5/19.0</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
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<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>9.0/11.0</td>
<td>17.5/19.0</td>
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<td></td>
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<td>0.045</td>
</tr>
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<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>11.0/13.0</td>
<td>17.0/19.0</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>309 S24</td>
<td></td>
<td>0.15</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>13.0/16.0</td>
<td>22.0/25.0</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>310 S24</td>
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<td>0.15</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>19.0/22.0</td>
<td>23.0/26.0</td>
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<td></td>
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<td>0.045</td>
</tr>
<tr>
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<td>0.15</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>16.0/19.0</td>
<td>23.0/26.0</td>
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<td></td>
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<td>0.5/2.0</td>
<td>9.0/11.0</td>
<td>16.5/18.5</td>
<td>1.25/1.75</td>
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<td>0.03</td>
<td>0.045</td>
</tr>
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<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>11.0/14.0</td>
<td>16.5/18.5</td>
<td>2.25/3.00</td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>316 S16 58J</td>
<td></td>
<td>0.07</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>10.0/13.0</td>
<td>16.5/18.5</td>
<td>2.25/3.00</td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>317 S12</td>
<td></td>
<td>0.03</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>14.0/17.0</td>
<td>17.5/19.5</td>
<td>3.00/4.00</td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>317 S16</td>
<td></td>
<td>0.06</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>12.0/15.0</td>
<td>17.5/19.5</td>
<td>3.00/4.00</td>
<td></td>
<td>0.03</td>
<td>0.045</td>
</tr>
<tr>
<td>320 S17 58J</td>
<td></td>
<td>0.08</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>11.0/14.0</td>
<td>16.5/18.5</td>
<td>2.25/3.00</td>
<td></td>
<td>4xC / 4ópez</td>
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</tr>
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<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>9.0/12.0</td>
<td>17.0/19.0</td>
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<td>5xC / 0.7T_i</td>
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</tr>
<tr>
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<td>0.08</td>
<td>0.2/1.0</td>
<td>0.5/2.0</td>
<td>9.0/12.0</td>
<td>17.0/19.0</td>
<td></td>
<td></td>
<td>10xC / 1.0Nb</td>
<td>0.03</td>
</tr>
</tbody>
</table>

TABLE 1.1 Composition of Austenitic stainless steels for BS 1447.
as the 0.2% proof stress, or the stress required to produce a permanent ε (after unloading) of 0.2%. The work hardening rate (or plastic modulus) of softened material is greater than for most metals. This is particularly true for unstable alloys which transform to martensite on straining. Cast stainless steels generally have poor mechanical properties as it is difficult to produce a casting that is sufficiently sound. Wrought products are more generally used. Their fatigue strength can be increased by cold working, but the impact resistance is reduced. Figures 1.6 and 1.7 summarise the mechanical properties at elevated temperature, the strength of the steel being maintained up to 500-600°C. The ductility properties are unusual in that a decrease is observed up to 400°C and a working temperature of over 900°C has to be used to obtain increases in ductility for hot working. At low temperatures there is only a slight increase in yield point with decreasing temperature, but the ultimate tensile strength typically doubles on reduction to -200°C. The austenite is less stable at low temperatures and is more likely to decompose to martensite on straining. Ferrite content can increase by exposure to low temperature, an increase from 8 to 25% being typically observed after several hours at -200°C.

Many physical properties of austenitic stainless steels differ significantly from those of plain carbon steels, i.e. mild steel. The density at between 7750 and 8000 kg/m³ is similar to that of mild steel, but the electrical resistance at around 9.6 x 10⁻⁷ Ωm is 6 to 7 times that of mild steel. The thermal conductivity is also less than that of mild steel and the specific heat is in the region of 510 J/kg K⁻¹. The
FIGURE 1.6 Effect of Temperature on Ultimate Strength of 18/8/Ti Stainless Steel (Keating 1956)

FIGURE 1.7 Effect of Temperature on Ductility of 18/8/Ti Stainless Steel
thermal expansion is however slightly greater than that of mild steel at $1.73 \times 10^{-5} \text{C}^{-1}$. As the austenitic structured steels have a low magnetic permeability these steels are much less magnetic than mild steels. This however is increased by martensite formation or the presence of other phases due to differing composition or heat treatment.

Stainless steels find wide application mainly due to their corrosion resistance. This can be used for the ability for trim to maintain its finish, in cutlery or surgical instruments which have to be hygienic, or for situations where it is exposed to particularly corrosive environments. They are also useful for service at high temperatures and some forms can be used up to $1000^\circ\text{C}$ although $550^\circ\text{C}$ is the limit normally imposed for most austenitic grades. An example of the corrosion resistance is the fact that in a saline solution the fatigue strength of a 18/8 steel is reduced by only 5% whereas mild steel has no fatigue strength in the same conditions.

The corrosion resistance is imparted by a thin layer (several Å) surface layer of chromium or chromium oxide which adheres well to the surface and is self repairing. These steels have particularly good resistance to sulphuric acid, and this can be improved further by the addition of inhibitors (e.g. Galvene) in the corrosive liquor around the metal. Corrosion can occur in pores in the surface, resulting in pitting. Contact corrosion can occur between different types of stainless steel and particularly in contact with platinum, copper or lead. Stress can accelerate corrosion in some environments leading to stress corrosion cracking.
A limited literature is available on the metallurgy of stainless steel and much use has to be made of manufacturers' sales and technical publications. Most useful of these is the data book produced by International Nickel (1966) and catalogues from several stockists. The review paper by Pickering (1976) is a standard work in this field. The book by Keating (1956) is a useful introduction as is the chapter on austenitic steels in the recent book by Honeycombe (1981).
CHAPTER 2 HOPKINSON BAR TECHNIQUE

2.1 Theory of Technique

2.1.1 Introduction

As discussed in section 1.3 the split Hopkinson pressure bar as a method for materials testing is a modification by Kolsky of the technique for measuring pulse shapes developed by B. Hopkinson. In the form generally used for compression testing, it consists of two bars, incident and transmitter, with a cylindrical specimen placed between them. A stress pulse is propagated in the incident bar. This is often initiated by impact with a length of similar bar material but impact of a bullet or detonation of an explosive charge have been also widely used. To enable the pulses to be propagated with no distortion the amplitude is restricted to within the elastic limit of the bar material, and the length to greater than several (five) bar diameters. In the technique described by Kolsky (1949) capacitive displacement transducers were placed at A and C (see figure 2.1). Most workers now use strain gauges attached to the bars at points equi-distant from the sample (i.e. A and B) and record the incident pulse and the reflected and transmitted pulses created when a sample is deformed plastically. Some workers measure stress (by slices of quartz crystal) and strain (by optical techniques or strain gauges) directly on the sample.

2.1.2 Calculation of Sample Stress and Strain

Consideration of the motion of the bar faces at the sample leads to expressions for sample stress and strain from the
Figure 2.1 General arrangement of split Hopkinson pressure bar.
transmitted and reflected pulses.

Using elastic theory:

\[ \text{Force} = \sigma A = E_b A \varepsilon \]  

(2.1)

where \( E_b \) is elastic modulus of bar, and \( A \) cross sectional area.

Using elastic wave propagation theory:

\[
\sigma = \rho c_o \dot{u} \\
\therefore \dot{u} = \frac{\sigma}{\rho c_o} = \frac{\varepsilon E_b}{\rho E_b / \rho} = \varepsilon c_o
\]

(2.2)

\( u \) is particle displacement and \( \dot{u} \) particle velocity. If subscripts \( I, R \) and \( T \) refer to incident, reflected and transmitted pulses respectively, and subscripts \( 1 \) and \( 2 \) refer to the end faces of the incident and transmitter bar adjacent to the sample, then:

Forces on bar faces

\[
F_1 = E_b A (\varepsilon_I + \varepsilon_R) \\
F_2 = E_b A \varepsilon_T
\]

Velocity of bar faces

\[
\dot{u}_1 = c_o (\varepsilon_I - \varepsilon_R) \\
\dot{u}_2 = c_o \varepsilon_T
\]

Displacements of bar faces

\[
u_1 = c_o \int_0^t (\varepsilon_I - \varepsilon_R) dt' \\
u_2 = c_o \int_0^t \varepsilon_T dt'
\]

Therefore for sample

\[
\sigma_s = \frac{F_1 + F_2}{2A} = \frac{1}{2} E_b (\varepsilon_I + \varepsilon_R + \varepsilon_T) \\
\varepsilon_s = \frac{u_1 - u_2}{l_s} = \frac{c_o}{l_s} \int_0^t (\varepsilon_I - \varepsilon_R - \varepsilon_T) dt'
\]
Neglecting delay due to wave propagation in the sample:

\[ F_1 = F_2 \]

This gives:

\[ \varepsilon_T = \varepsilon_I + \varepsilon_R \]  

so:

\[ \sigma_s = E_b \varepsilon_T \]  

\[ \varepsilon_s = \frac{-2c_o}{l_s} \int_0^t \varepsilon_R \, dt' \]  

\[ \varepsilon_s = \frac{-2c_o}{l_s} \varepsilon_R \]  

For analysis the recorded reflected and transmitted pulses are shifted so that they start from the same origin, and so specimen stress, strain rate can be calculated and plotted against time. Corresponding points of specimen stress and strain against time are plotted to give the stress against strain curve. For the purposes of calculation the expression for sample strain is modified to:

\[ \varepsilon_s = \frac{-2c_o}{l_s} \int_0^t \varepsilon_R \Delta t \]  

Where \( \Delta t \) is the interval between measurements of \( \varepsilon_R \) from the recording of the reflected pulse. If it is sufficiently small the errors in this approximation to the integral are minimal. The derivation so far has assumed that the specimen will be of the same diameter as the bar. Most compression samples are of smaller diameter than the bar to allow for lateral expansion as they are strained. If this is the case the expression for specimen stress will be modified to

\[ \sigma_s = E_b \left( \frac{A}{A_s} \right) \varepsilon_T \]  

where \( A \) and \( A_s \) are the bar and specimen cross-sectional areas.
respectively.

2.1.3 Discussion

The validity of results obtained in the Hopkinson pressure bar has been investigated by many workers. Three factors have been identified as causing non-uniformity of sample stress and errors to results: friction, inertia, and stress wave propagation within the sample. The paper by Hunter and Davies (1963) discusses these three factors. They use an analysis by Siebel (1923) and obtain a criterion for neglect of frictional effects.

\[
\frac{2\mu a}{3l} \ll 1
\]

where \(\mu\) is the Coulomb coefficient, a sample radius and \(l\) sample length. Considering the value for \(\mu\) between 0.02 and 0.06 for a lubricated polished metal/metal interface

\[
\frac{a}{l} \ll 25 \tag{2.9}
\]

This condition is satisfied if sample length approximately equals sample radius \((a/l = 1)\). Bell's (1966) experiments appeared to discredit this assumption of stress uniformity, but in that case the samples were bonded to the bars and so \(\mu\) was effectively infinite, and the above criterion was not met. Considerations of wave propagation within the specimen usually state some criterion such as waiting for the stress to propagate four times through a sample before it can be considered to be uniform. For a stainless steel sample (in elastic region) 5mm long it would then take about 4\(\mu\)s for stress to reach equilibrium. The stress pulses applied to samples in the author's work normally have a rise time of about 10\(\mu\)s and a duration of 100\(\mu\)s. This would mean that the conditions proposed by most workers are satisfied and that the stress would be uniform throughout the sample after
the first few micro-seconds. Normally when pulses are analysed this will tend to lead to an under-estimation of the elastic modulus at the start of the loading and this part of the test will have to be disregarded.

Kolsky's samples (1949) were made with a large radius to length ratio so that axial inertia effects could be neglected and a correction was made for radial inertia effects.

\[ \sigma_s = \sigma_b - \frac{1}{8} \nu^2 s d^2 \rho_s \frac{d^2 \epsilon}{dt^2} \]  

(2.10)

Where \( \sigma_b \) is the sample stress measured from the transmitter bar, \( \sigma_s \) is the corrected sample stress, \( d \) is diameter and \( \rho \) density of sample. Davies and Hunter criticised this technique as the sample proportions would lead to large frictional errors, for which it would be difficult to calculate a correction factor. They used the criterion for sample dimension as above and calculated the effects of axial inertia.

\[ \sigma_s = \sigma_b + \rho_s \left( \frac{1}{6} - \nu^2 s d^2 \right) \frac{d^2 \epsilon}{dt^2} \]  

(2.11)

This correction is zero if:

\[ \frac{1}{6} = \nu^2 s \frac{d^2}{8} \]

\[ \frac{1}{d} = \sqrt{\nu^2 \frac{6}{8}} = \frac{\nu \sqrt{3}}{2} \]  

(2.12)

Davies and Hunter thus show that a sample or proportions given in 2.12 would need no correction for inertial effects and satisfy the criterion for neglect of frictional and wave propagation. Subsequent analyses of the Hopkinson bar include the one dimensional calculations by Jashman (1971) and the torsional work by Nicholas (1973). In particular the two-dimensional computer analysis by Bertholf and Karnes (1974) confirms that
for lubricated samples of the proportions derived by Davies
and Hunter the assumptions made of uniformity of stress and
neglect of inertia in the derivation of sample stress and
strain from reflected and transmitted pulses above are valid.

2.2 Description of Hopkinson Bar Apparatus

2.2.1 Introduction

An operational split Hopkinson pressure bar apparatus
existed at Loughborough before the author commenced Postgraduate
research. However, a second new system was built, with a
larger gas gun and longer optical bench enabling the new bar
configurations developed by the author to be assembled. The
design of the new system is mainly due to Dr. Parry and
Dr. Griffiths as it is derived from the previous system, but
incorporates suggestions made by the author.

The tensile tests described (see chapters 4 and 5) were
carried out mainly on the older system. But all the results
reported for compression tests were obtained using the new
system, the older being used for development of techniques.

The current overall arrangement is shown in figure 2.2
which is a schematic diagram showing the bar and gas gun along
with the piping for the vacuum system and a block diagram
of the electronics. Figure 2.3 illustrates the older Loughborough
system. The purpose of the gas gun is to accelerate the projectile
until it impacts the face of the incident bar within the gas
gun tube and creates a stress pulse of duration

\[ T = \frac{2lp}{C_o} \]  (2.13)

where lp is the projectile length and \( C_o \) is the velocity of
longitudinal waves in the bar. The amplitude of the pulse is
FIGURE 2.3 INITIAL LOUGHBOROUGH HOPKINSON BAR ARRANGEMENT
given by:

\[ \varepsilon_I = \frac{V}{2C_0} \]  \hspace{1cm} (2.14)

where \( V \) is the projectile velocity at impact and \( C_0 \) the velocity of longitudinal waves in the incident bar material. As the pulses produced are much more than five bar diameters in length the velocity is given by equation 1.8. Measurements of velocity by timing pulses and by a resonance method give a value of 5220 m/s for the 431 stainless steel bars used (section 4.4). The incident pulse produced by the projectile impact propagates along the incident bar and a reflected and transmitted pulse are produced as the sample is strained as described in 2.1. The momentum bar at the end of the transmitter bar flies off when the transmitted pulse is reflected as tensile pulse at the free end and returns to the transmitter bar. The momentum bar is stopped by the plasticine filled box and so most of the energy in the system is dissipated without causing any damage.

2.2.2 Gas Gun

Figure 2.4 is a photograph of the gas gun and vacuum valve system. The gas gun operates by evacuating the tube and then suddenly opening the end; atmospheric pressure then drives the projectile. Advantages of using a vacuum, rather than a high pressure system include safety, reliability, consistency and convenience. A description of the first version of the gas gun is contained in Griffiths and Parry (1978). The vacuum pump is a rotary type (Speedivac ES 50) and is placed on rubber matting on the floor under the table. It is connected to the valves by thick walled rubber tubing. There is an opening in the gas gun tube at either end each connected by thick walled rubber
FIGURE 2.4 Overall View of New Apparatus Showing Gas Gun at Right

FIGURE 2.5 25cm Long Projectile and Aperture Plate from New Gas Gun
tubing to a valve. This is to enable the gas gun to be pumped initially from the opening end, so that the projectile will remain in position, and have the full length of the tube in which to accelerate. This ensures a consistent amplitude of incident pulse, which is important when good control of the strain rate in the test is required. After a test the projectile is normally near the impact end of the gas gun and can be withdrawn by evacuating from the opening end and then letting air into the other. A vacuum gauge is included in the system. Tests have shown that the vacuum is not critical as long as it is below 1 Torr. The gas gun tube is made from 321 stainless steel, supplied with a polished bore. The inside diameter is 2\(\frac{1}{4}\)" and the length is 2.4m. The flanges are turned from 321 stainless steel. The inner ones are screwed directly onto the threads cut onto the outer surface of the tube ends. Outer flanges are attached to the inner ones with three nuts and cap head bolts. Where the bars enter the gas gun the gap is sealed by 'O' rings either side of the outer flange. These are held in position by brass discs screwed to the flange with 3 cap head bolts. These ensure a seal to enable a good vacuum and also allow some movement after impact. A plate attached to the end of a lever seals the open end of the gas gun by the air pressure holding it onto a large 'O' ring on the flange. The gas gun is fired manually by moving the lever and thus the plate. An aperture plate with various sized holes is fitted into the open end of the tube, the lever is arranged so that the tube cannot be sealed without this plate in position. This is a safety feature as the gas gun cannot be fired with an opening of the full 2\(\frac{1}{4}\)" diameter. At this aperture the resultant projectile velocity is more than has been required
for tests and could cause damage to the system. The aperture plate has holes of 2, 4, 6, 8, 12.5mm and two of 20mm diameter. These can be sealed with nylon plugs and so the diameter of air intake can be varied. This is used to control the impact velocity, fine control can be achieved by partially blocking holes with tape or by using combinations of holes together.

The impact velocity can be measured by micro-switches connected to a trigger circuit and to time-counters. The centre piece of the switch is a shaft turned from perspex and extends as the tip of a 1.5mm radius hemisphere into the bore of the gas gun. The switch piece is spring loaded and when the projectile reaches it, it rises and a circuit is broken. This causes a 5V signal to be generated which triggers the timer-counters. There are three switches positioned 10cm apart at the bar end of the gas gun, operating two timer counters. The first counter times the projectile over the first 10cm and the second over the last 10cm before impact.

2.2.3 Projectile

Figure 2.5 is a photograph of a 25cm projectile and the aperture disc. The main part of the projectile is a length of 431 stainless steel rod ½" in diameter, the same as the main bars. This is held centrally in a P.T.F.E. holder by means of 'O' rings and brass locating discs and so some movement is allowed on impact. The P.T.F.E. allows the projectile to slide freely down the tube, but is made to be a reasonable fit as air leak round the sides could decrease the acceleration. Sometimes the diameter of the projectile has to be decreased by cooling in a fridge to allow it to fit in the tube. Figure 2.6 is a graph
Figure 2.6 Projectile velocity against Gas Gun aperture for new gas gun.
of projectile final velocity, as measured by the switches and the timer counter, plotted against the logarithm of the aperture diameter of the open end of the tube. Results of series of shots with 25 and 55cm long projectile bars are plotted for comparison. The straight line graph on the log-linear scales indicates that the aperture is a good means of controlling the velocity, but it has to be doubled to give significant increments in velocity, hence the range of holes provided in the aperture plate. The maximum speed indicated (25cm projectile) with two 20mm holes of 34.5m/s would produce an incident stress pulse of \(7 \times 10^8 \text{N/m}^{-2}\) amplitude, close to the elastic limit of the bar material. For comparison the older gas gun has an inside diameter of 2" a length of 1.32m and with a 25cm projectile and full 2" aperture produces an impact velocity of 25m/s. Tables of the test shots with 25 and 55cm projectiles are presented in the next section where a comparison between measured projectile velocity and incident pulse amplitude is made.

2.2.4 Mechanical Supports

The table under the gas gun on which the valves are mounted and the timer-counters and trigger circuits are placed, is made from 'Speedifit'. This is a commercial system made from square tubular steel, ready painted black and with joiner pieces available from which tables and stands can be easily fabricated. The top is made from chipboard and is cut to fit under and in front of the gas gun. The gas gun is mounted on three clamps made from 1" thick aluminium alloy bolted to a length of 6" x 3" mild steel channel. This in turn is supported by 1" x 1" angle iron legs, independent of the table and with
cross angle braces and screwed to the laboratory floor.

The support for the bar stands is a separate length (3.5m) of 6” x 3” mild steel channel again with angle iron legs screwed to the floor. The fact that the gas gun and bars are on separate supports isolates the bars from any shock or vibration generated by the gas gun which might cause a false triggering of the recording equipment or disturb the alignment of the bars and sample. Two 2m lengths of optical bench are screwed to the mild steel channel to give a total length of 4m on which to locate bar stands. The bar supports (figure 2.7) are mounted on commercial optical bench stands which have a screw driven movement in two directions allowing variation in height of stand and across the axis of the bench. These allow precise alignment of the bars. The optical bench stands are designed to be moved along the optical bench and clamped in position to enable different bar lengths and configurations to be used. As the optical stands are only of light construction they are reinforced by addition of extra bolts and a clamp over the vertical slide. This prevents the slide from opening up due to the impact on the bars. In the older system the gas gun and optical bench are also mounted on mild steel channels, the gun being on a more solid table than the new and the optical bench on independent mild steel legs. There was only the capacity for a single 2m length of optical bench but the author added a 0.5m length to enable the tensile testing rig to be assembled. Many different types of bar/support have been tried and these include the use of 'O' rings and clamps similar to screw pipe fittings and three point supports with rollers at the contact with the bars. The
FIGURE 2.7  Adjustable Bar Stand as Designed for New System
supports designed for the current system (figure 2.7) include a nylon block with a 'V' in which the bar rests and a nylon block which goes across the 'V' and clamps the bar in position. This is held in place by two bolts and wing nuts which can be adjusted so that the bar is only gripped gently. These supports have the advantage that there is not too much restraint on the bars and the top piece can be removed so that the bars can be lifted off easily and without damage to the strain gauges and leads.

2.2.5 Bars

All the bars used by the author are of 431 martensitic stainless steel 1" diameter rod. This material is chosen for its high yield point, machinability and availability. The size is a compromise between a convenient sample size and the stress that is produced by impact with a similar rod in the gas gun. The bars are finished by careful turning on a lathe and then polishing.

The bars are held in close contact with the samples by means of a light force provided by three elastic bands wrapped around the bars and connected to one of the supports. This light pressure on the samples is too small to affect the results, but ensures a good contact as bars can drift away from the samples, sometimes due to vibration from the gas gun firing.

2.3 Pulse Measurement

2.3.1 Use of Strain Gauges

Measurement of stress pulses in Hopkinson pressure bars have included the use of capacitive gauges and optical techniques. A previously used technique at Loughborough (Griffiths and
Martin (1974)) involved the use of shutters mounted on the bars adjacent to the samples. These partially interrupted light beams and when moved changed the light intensity falling on photomultipliers. This system was found to be difficult to calibrate, inconvenient and susceptible to interference by bending waves (Griffiths, et al (1979)).

The technique used by the author and most other workers today is the use of resistive foil strain gauges mounted on the bars, in diametrically opposite pairs, so as to cancel out effects of bending and double the effect of longitudinal strain. The gauges used on the bars have a gauge length of 6mm and so the rise time or time for propagation of longitudinal wave in bars, is about 1us. This means that the pulses which have a rise time of about 10us can be recorded. The gauges have a nominal resistance $R_s$ of 120Ω and for a change in resistance of $dR_s$ the strain is given by

$$\varepsilon = \frac{1}{F} \frac{dR_s}{R_s} \quad (2.15)$$

Where $F$ is the gauge factor; this is 2.11 in the gauges used.

The gauges of the type used (Tokyo Sokki Kenkyso Co. Ltd. Type FLA-6-17) are designed to operate with a linear output with strain up to 1-2% but can be used in tension up to 5-6% where the backing, adhesive (cyramicrylate type CN-2) or resistive foil fail. Normally such strain gauges are used for static testing where a balanced Wheatstone bridge circuit is used to measure strain. For the dynamic situation a simple potential divider circuit (figure 2.8) can be used as the d.c. level on the output can be disregarded using capacitive coupling. The power supply used is a Farnel 200mA type ES 350. The resistors are 2.2kΩ, 10 Watt wire wound and are mounted in a die cast box with sockets for connection.
$dV_s$ is positive for compression with power supply as shown.

Figures 2.8 Strain Gauge Circuit.
to the strain gauge leads, power supply and output to an amplifier, recorder or C.R.O.

In the circuit shown:

\[ V_s = \frac{R_s}{R_b + R_s} E = \frac{1}{n + 1} E \]

where

\[ n = \frac{R_b}{R_s} \]

differentiating:

\[ \frac{dV_s}{dn} = \frac{-E}{(n + 1)^2} \]

and

\[ \frac{dn}{dR_s} = \frac{-R_b}{R_s^2} \]

\[ \frac{dV_s}{dR_s} = \frac{dV_s}{dn} \times \frac{dn}{dR_s} = \frac{-R_b}{R_s^2} \left[ \frac{-E}{(n + 1)^2} \right] \]

\[ dR_s = \frac{R_s^2 (n + 1)^2}{R_b E} dV_s \]

from 2.15

\[ \varepsilon = \frac{1}{F} \frac{dR_s}{R_s} \]

\[ = \frac{R_s^2 (n + 1)^2}{R_s R_b F E} dV_s \]

\[ = \frac{(n + 1)^2}{n F E} dV_s \] \hspace{1cm} (2.16)

Thus strain can be measured from change in voltage across the strain gauges, once gauge factor, applied voltage and ratio of resistances of ballast and gauge are known. The applied voltage and ratio of the resistances is measured before the shots using a digital voltmeter. The power supply polarity is
chosen to give positive signal for compression of bar gauges. The gauge factor specified when the gauges are supplied is used. One advantage of the ballast resistor circuit is its simplicity, but like an out of balance Wheatstone bridge is only linear for small strains. For each of the gauges in a pair a separate lead is used to connect it with the ballast circuit, the interconnection being made immediately above the box, to reduce noise and allow access to individual gauges.

2.3.2 Pulse Amplification and Recording

For connection of the output of the ballast circuit to a recorder or oscilloscope an amplifier is used to bring the signals up to a more convenient voltage level. The amplifier circuits are based on 531 integrated circuits and were designed and built by the Physics electronics workshop (figure 2.9). Three different nominal gains are available - 5, 10 and 20. These are sufficient to display the smaller signals obtained when testing soft materials and are useful for reducing noise and optimising the use of the transient recorder ranges. For all ranges the gain was independent of input level up to 100mV. Figure 2.10 shows the frequency response of the amplifiers, that of the 5x range is adequate, but care will be needed when using the 10x and 20x ranges as gain tends to decrease above 100kHz. In previous work in this laboratory the pulses were recorded by using a polaroid camera, with an open shutter, placed over the screen of an oscilloscope on which the signals were displayed. The oscilloscope was used in the 'single sweep' mode and triggered by an inertia switch at the start of the incident bar. A significant improvement results from the use of a transient
Figure 2.9 Strain gauge amplifier circuit

Figure 2.10 Frequency response of strain gauge amplifier
recorder (Datalabs 922 used) which automatically digitises the signals and also provides a more reliable trigger. The signal can be displayed on the oscilloscope as a continuous display, which can then be adjusted to the correct position and brightness for photography. Most importantly the data can be fed from the transient recorder into a computer for analysis.

2.3.3 Discussion of Strain Measurement Technique

Tables 2.1 and 2.2 show the results of calibration shots of the gas gun, as described in previous sections, with the 25 and 55cm projectile respectively. Included in the tables are the expected incident pulse amplitudes calculated from equation 2.14 and from the final projectile velocity measured by switches on the gas gun and the timer counter. The height of the incident pulse measured using the strain gauges on the incident bar and displayed using the amplifiers, transient recorder and C.R.O. is also included. These two sets of points show very good agreement for both projectile lengths and over the entire range of velocities used. This then confirms the validity of equation 2.16 used to calculate strain, and also calibration of the equipment used. Amplitude of pulses can thus be measured with confidence, the shape will now be discussed.

2.3.4 Measurement of Pulse Shape

Initial experiments were carried out with the strain gauges on the incident and transmitter bars being located 37cm from the specimen. This meant that when the outputs of the gauges were recorded on a two channel recorder
<table>
<thead>
<tr>
<th>GAS GUN APERTURE/mm</th>
<th>PROJECTILE VELOCITY/ms(^{-1})</th>
<th>MAXIMUM INCIDENT STRAIN CALCULATED FROM VELOCITY/%</th>
<th>MAXIMUM INCIDENT STRAIN FROM STRAIN GAUGE/%</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.109</td>
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</tr>
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</tr>
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<td>0.233</td>
</tr>
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<td>2x20</td>
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<td>0.307</td>
<td>0.313</td>
</tr>
</tbody>
</table>

Table 2.1 Calibration of 2½" gas gun using 25cm projectile.

<table>
<thead>
<tr>
<th>GAS GUN APERTURE/mm</th>
<th>PROJECTILE VELOCITY/ms(^{-1})</th>
<th>MAXIMUM INCIDENT STRAIN CALCULATED FROM VELOCITY/%</th>
<th>MAXIMUM INCIDENT STRAIN FROM STRAIN GAUGE/%</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>2x20</td>
<td>26.62</td>
<td>0.255</td>
<td>0.271</td>
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</tbody>
</table>

Table 2.2 Calibration of 2½" gas gun using 55cm projectile.
the reflected and transmitted pulses were recorded simultaneously so that the combination of stress and strain used to determine sample stress against strain could be made by direct cross plotting of points. The positions of the gauges are also determined by a need to separate the incident and reflected pulses on the trace from the incident bar. The distance of 37cm was initially chosen to satisfy this criterion.

It is normally assumed when carrying out experiments on the Hopkinson bar that the pulses are propagated in the bars without dispersion or attenuation. If this were true then the reflected and transmitted pulses would add up to equal the pulse incident on the specimen being tested. Work on carbon fibres produced traces (figure 2.11) which were inconsistent with perfect pulse propagation. The transmitted pulses were more rounded in shape than the incident pulses, even though the sample had not yielded. Shots with the second bar and sample not in position, should show the reflected pulse as a mirror image (i.e. in tension) of the incident pulse (see figure 2.12). The lower trace in figure 2.13 shows the reflected pulse again as a rounded version of the incident pulse. This apparent damping in the bar may be a property that cannot be removed, or it may be due to some fault in the system (e.g. bending waves, circuitry, magnetic effects, projectile or clamping) that can be rectified.

Other apparent faults in the pulses were: the absence of 'Pochhammer-Chree' oscillations (due to lateral strain in bars) from most of the traces (figure 2.14); the tendency for the trace not to return to the baseline after the incident
Vertical gain: 0.053% / cm
Time base: 50 μs / cm
Carbon Fibre Sample

Figure 2.11 Carbon fibre shot to show losses in pulses.

Figure 2.12 Idealised pulses showing perfect reflection.
Figure 2.13 Outputs of separate gauges showing bending waves.

Figure 2.14 Idealised pulse showing Pochhammer-Chree oscillations.
pulse (figure 2.15); and some small unexplained 'blips' on the traces (figure 2.16).

The source of these discrepancies had to be found, as they could affect the validity of analyses carried out using the system.

2.3.5 Bending Waves

The upper two traces in figure 2.13 show the separated signals from a pair of strain gauges placed on diametrically opposite sides of a bar. The bending waves can easily be seen as a signal of decreasing frequency (bending waves exhibit dispersion) superimposed on the longitudinal pulses. The length of the incident bar is such that the slower bending waves (velocity 3.4\text{mm/\mu s}, compared with longitudinal at 5.2\text{mm/\mu s}), do not reach the sample until the loading cycle has been completed. The lower traces show no sign of bending waves as they have been completely cancelled by using the technique of connecting the gauges in series. Such records show that bending waves can be eliminated from the recordings and are not responsible for the trace defects.

The two signals at the start of the upper two traces in figure 2.13 cannot be bending waves as they occur too soon in the record.

2.3.6 Projectile adjustment

A good axial impact between projectile and incident bar is normally characterised by presence of 'Pochhammer-Chree' oscillation on the top of the incident pulse, and absence of bending waves. Some effort has been made to improve the
Figure 2.15 Idealised trace showing slow return to baseline after pulse.

Figure 2.16 Idealised pulses showing unexplained 'blips', (in circles).
mounting of the projectile in its PTFE guide, as the faces of the projectile bar were found to be not perpendicular to the sides of the guide. This has led to a slight improvement in the quality of the impacts but has had no influence on the signals slow return to the baseline at the end of the incident pulse, or its apparent damping in the bars.

2.3.7 Effects from the Electrical Circuitry

The shape of the pulses may have been affected detrimentally by the nature of the detecting and recording circuitry used.

Figure 2.17 shows that the integrated amplifier described does not produce any significant distortion of the incident pulse. The lower trace is the gauge output fed directly into the transient recorder and the upper is the same signal after passing through the 5X amplifier. The transient recorder's gain is 5X less on the upper trace, so that the two traces are identical in height as well as in shape. The projectile velocity used was quite high, about 30ms\(^{-1}\). The Pochhammer oscillations are absent from both traces, and the return to the baseline is not immediate.

Two shots were performed using the open shutter camera and the single sweep on the oscilloscope, instead of the transient recorder. The two traces were of the same shape and show the same faults as when the transient recorder is used. These show that the transient recorder is not responsible for the problems experienced.

Some shots were carried out varying the value of the ballast resistors in the strain-gauge circuit and applied
Via 5X amplifier, recorder on 0.5V range.

Direct, recorder on 0.1V range.

Both timebase: 20μs/cm
Both Gains: 0.053%/cm

Figure 2.17 Pulses showing effect of amplifier.
49

voltage, and no difference was observable. Strain gauges will be discussed later and again do not seem to be the cause of the faults.

2.3.8 Clamping Effects

A further possible cause of the problems could be that the manner in which the bars are supported affected the shape of the pulses. Experiments in which the supports were removed produced no change in the overall shape of the pulses.

Overtight clamping did produce some further distortion of the pulses. This can be seen in figure 2.18 where there is a clamp after the gauges on the incident bar. The top trace shows a dip on the top of the incident pulse and its position corresponds to a reflected pulse from the clamping position. The lower trace in figure 2.18 shows the same thing except that the clamp has been moved further away from the gauges.

The upper trace in figure 2.19 shows the effect of over tightening the support at the gas gun. The clamp for the upper trace was tightened more than normal and a similar dip to those in figure 2.18 appears at the start of the incident pulse. For the lower trace the clamp was left very loose and now some Pochhammer-Chree oscillations can be seen.

Normally clamping is not a problem, as the clamps are only a light grip on the bars, but it is interesting to note that it could affect the traces if care is not taken.

2.3.9 Magnetic Effects

The small 'blips' at the beginning of the incident pulse
Gains: - 0.106%/cm
Timebase: - 50µs/cm

Figure 2.18 Pulses showing 'dips' due to clamping.

Gains: - 0.106%/cm
Timebase: - 50µs/cm

Figure 2.19 Pulses showing effect of overtight clamping at gas gun.
on the top two traces on figure 2.13 cannot be due to bending wave propagation down the bar, as they occur before the longitudinal incident pulse has arrived at the gauges. They are not normally observed on the combined traces usually recorded as they are of opposite sign and are cancelled. Such 'blips' however, have been observed on traces and they could have caused problems, if not properly cancelled.

They were shown not to be a strain effect by the fact that their sign is reversed if the leads to an individual gauge are reversed. As the bar material is magnetic it was thought that magnetic pickup could be the cause of these 'blips' and possibly be the cause of other problems.

The bar near to the gauges was rubbed with a permanent magnet, and a shot carried out. Figure 2.20 shows the resultant traces, the 'blips' being now much greater in size and number. The bar was then passed through a coil, through which 3 amps of 50Hz a.c. current was flowing. The coil was about 6.0cm long, and had 2100 turns. The velocity of the pass was about 0.5m/sec. Figure 2.21 shows the result of a shot after such treatment and the 'blips' have completely gone. It is thus apparent that the 'blips' were due to magnetic pickup at the gauges, and could be removed by de-magnetising the bar. However, the trace in figure 2.21 still shows the other faults under investigation even though the bars have been de-magnetised.

2.3.10 Effect of Different Bar Materials

To see if the bar material was the cause of the problems some strain gauges were attached to an 18/8 austenitic
Figure 2.20 Effect of magnetising bars with permanent magnet.

Figure 2.21 Effect of demagnetising bars used in Figure 2.20.
stainless steel bar and a shot carried out, with no second bar in place.

Figure 2.22 shows the resultant record. The upper two traces are the outputs from the individual gauges, and the lower is their sum. It can be seen that this material shows even worse damping (the pulses become rounded more rapidly) than the 431, probably because it has a lower yield point, and becomes non-linear at lower stress levels.

This experiment is not conclusive proof, but it points towards the fact that the properties of the bar may be the cause of the problems experienced.

2.3.11 Pulse Propagation in 2m Bar

A 2m length of the normal bar material (431) was available in the laboratory, and it was decided to attach strain gauges to it at the same positions (SG3 and SG4) as used normally with a two, 1m bar arrangement. This then eliminates any effects due to poor reflection or mismatch at the junction of the two bars. Figure 2.23 illustrates the positions of the gauges used. The pair of gauges (SG1 and SG2) 27cm from the start of the bar are at the position normally used in experiments several years ago in this laboratory. As only two channels were available at a time on the transient recorder, two shots had to be performed at each projectile velocity. The first (figures 2.24, 2.26, 2.28) shows the traces from the forward two positions (SG1 + SG2, Ch1 and SG3, Ch2) and the second (figures 2.25, 2.27, 2.29), from the others (SG3, Ch1 and SG4, Ch2).

The traces obtained clearly show that distortion is serious
Timebase: 50µs/cm

No 2nd bar or sample

Figure 2.22 Pulses in 18/8 stainless steel bar.

Figure 2.23 Position of strain gauges on 2 metre bar.
above $20\text{ms}^{-1}$ (about $400\text{MNm}^{-2}$) and is dependent on position along the bar. This latter point eliminates the possibility that the damping is due to the gauges or influence from external circuitry.

Pochhammer-Chree oscillations are evident on the lower speed shots, at the positions near the gas gun. They are either not produced or, more likely, they are more rapidly damped at the higher stress levels.

At the slowest projectile speed the return to the baseline is quite rapid, but gets worse as the speed increases. This particular effect does not seem to be dependent on position along the bar.

Figure 2.30 shows the long term decay of the pulses in the 2m bar at the three speeds used. These clearly show that the damping is dependent on amplitude, and possibly also frequency. They also show that the bending waves are dissipated very rapidly, probably due to damping and dispersion.

### 2.3.12 Conclusions of Work on Pulse Shape

Until a better bar material has been found, nothing can be done to prevent the damping at high stress levels. One major improvement is to move the gauges on the transmitter bar nearer to the specimen (to about 10cm instead of previous 37cm, to ensure plane waves at the gauges), so that the transmitted pulse recorded is less affected by damping and more representative of the stress cycle in the specimen. There is little benefit in moving the gauges on the incident bar, as the reflected pulse is normally at much lower stress levels (and hence suffers little damping). But the gauge
Bar Modulus: $2.12 \times 10^{11} \text{ Nm}^{-2}$

Timebase: 50us/cm

Velocity of impact: 15.9m/s

Figure 2.24 Pulses in 2 metre bar.

Bar Modulus: $2.12 \times 10^{11} \text{ Nm}^{-2}$

Timebase: 50us/cm

Velocity of impact: 16.1 m/s

Figure 2.25 Pulses in 2 metre bar.
Bar Modulus: $2.12 \times 10^{11} \text{ N m}^{-2}$

Timebase: 50μs/cm

Velocity of impact: 20.9 m/s

Figure 2.26 Pulses in 2 metre bar.

Bar Modulus: $2.12 \times 10^{11} \text{ N m}^{-2}$

Timebase: 50μs/cm

Velocity of impact: 22.4 m/s

Figure 2.27 Pulses in 2 metre bar.
SG1 + SG2 Gain: 0.053%/cm

SG3 Gain: 0.106%/cm

Bar Modulus: $2.12 \times 10^{11}$ Nm$^{-2}$

Timebase: 50μs/cm

Velocity of impact: 32.5 m/s

Figure 2.28 Pulses in 2 metre bar.

SG3 Gain: 0.106%/cm

Bar Modulus: $2.12 \times 10^{11}$ Nm$^{-2}$

Timebase: 50μs/cm

Velocity of impact: 33 m/s

Figure 2.29 Pulses in 2 metre bar.
Gain 0.106%/cm
Bar Modulus: $2.12 \times 10^{11}$ Nm$^{-2}$
Timebase: 250μs/cm
Velocity of impact: 16 m/s

Gain: 0.106%/cm
Bar Modulus: $2.12 \times 10^{11}$ Nm$^{-2}$
Timebase: 250μs/cm
Velocity of impact: 22 m/s

Gain: 0.106%/cm
Bar Modulus: $2.12 \times 10^{11}$ Nm$^{-2}$
Timebase: 250μs/cm
Velocity of impact: 33 m/s

Figure 2.30 Pulses in 2 metre bar.
position of 47 cm from sample allows a clear separation of the incident and reflected pulses on the records and enables the incident pulse to return to the baseline before the reflected pulse returns to the gauges.

The absence of Pochhammer-Chree oscillations on the records is not of importance, as they normally only appear on the incident pulse. To eliminate any effects due to magnetic pickup, it is advisable to de-magnetise the bars before use. This is most easily done just before new gauges are attached (i.e. about every 50 shots).

2.4 Sample Preparation

2.4.1 Introduction

When testing materials the careful selection of samples is important to ensure the validity of tests. Variations between materials of differing batches (same specification) and between differing points within a batch or even a single piece mean that comparison of tests can be difficult. Manufacturing processes (rolling or extruding) can mean that materials are anisotropic in mechanical properties and so loading direction is important. This is obviously more important when strongly anisotropic materials, e.g. carbon fibre and wood, are tested, but it is normal to at least test for directional properties. Problems encountered when testing samples from different locations will be described in chapter 5 when results are presented. Variations in results due to testing techniques or to sample properties mean that the number of samples to be tested has to be great enough to ensure a valid series of tests. Too few could lead to a totally false impression of behaviour
and too many could be needlessly expensive and time consuming.

2.4.2 Compression Sample Dimensions

As discussed above the analyses of the Hopkinson bar by previous workers, for compression testing have led to criteria for sample proportions and size. The bars used at Loughborough are 12.7mm in diameter and so an initial sample diameter of 10mm is normally used to ensure that the sample remains within the faces of the bars and does not spread over their edges. A length of about 5mm would satisfy most criteria proposed for the neglect of frictional and wave propagation effects. The proportions for the cancelling of axial and radial inertia proposed by Davies and Hunter (equation 2.12) leads to a length of 4.33mm. This is using a Poisson's ratio of 0.5, which means that the material is assumed incompressible, which is generally true for plastically deforming materials. All compression samples used by the author have a diameter of 10mm and length of 4.33mm, usually with a tolerance of 0.1mm on these nominal dimensions.

It is important that both flat faces of the samples are in good contact with the bar faces. Assuming that the bar faces are flat, polished, and perpendicular to the bar sides, and that the bars are in correct axial alignment with the sample, then the sample faces have also to be flat, of good finish and parallel. The quality of finish of the samples used has been limited by what can be easily and economically achieved.

2.4.3 Preparation Techniques

Samples were taken to the nominal dimensions by cutting in a lathe. The sides were then given a fine turned finish and
the faces cut as well as possible before final finishing. All samples were held in the lathe with collets to assure the faces are parallel and are also perpendicular to the sides.

Some samples of 321 stainless steel supplied by AWRE Foulness were finished by a firm of optical instrument makers to a very fine tolerance (better than 1µm on surface finish and on parallel faces). Unfortunately these samples were unsuitable for comparison with the tensile tests due to initial location in the source bar material. (This is discussed later in chapter 5). Figure 2.31 shows the results of a Talystep test on one of the samples. The Talystep is a device which consists of a diamond stylus which scans across a surface and by means of an amplifier and pen recorder can produce a record of surface features.

The Talystep charts presented in this section have a gain on the vertical axes of 5000 x, or 0.01mm variation of height of stylus for full scale deflection of 5cm. The gains on the horizontal axes are 50 x, the length of the trace of 10cm thus corresponds to the maximum scan length of 2mm. Each pair of traces presented contains one near the centre of the sample face, and one which goes over its edge. The traces in figure 2.31 show a very good surface finish and a variation of thickness of sample equivalent to about 0.002mm (2µm) across the 10mm faces. No drop off near the edge is shown. These very good quality samples produced good results with almost perfect 'matching' of the faces, but as they are expensive to produce and have to be prepared in large batches have not been available for any other tests.
Middle of sample face.

Near edge of sample face.

Figure 2.31 Talystep traces of face of initial compression sample supplied by Foulness.
Most of the sample tests have had to rely on good quality turning and been finished off by a very light rubbing on 200 grade wet and dry paper to finish. As the samples are hand held while this finishing is done the minimum is done to eliminate the circular turning marks. Care is taken not to finish by rubbing the sample to and fro, but to rotate the sample by 90° between single rubs with the sample pressed firmly onto the paper. The Talystep traces in figures 2.32 and 2.33 show such a sample after turning and after rubbing on the wet and dry. They show that the effect of the abrasion is to make the finish better and the surface generally more even. However, it does tend to produce a drop of approximately 0.005mm in the final 1mm around the edge of the faces. The wet and dry was used on all samples as it tended to improve and standardise the sample faces. A more convenient check on sample quality is provided by measured sample length, with a micrometer, at various points on the sample faces. A variation of less than 0.01mm was usually the tolerance used; samples with larger variation were difficult to improve by re-turning and were generally discarded or used as pulse shapers (see chapter 3).

2.4.4 Discussion of other Techniques

Other techniques for sample finishing are under consideration. One is the use of a commercial rig to hold the sample over a lapping iron with an abrasive slurry. It should be possible to set up the rig so that several good quality samples are produced at a time, the limits of accuracy probably being set by the adjustment of the rig and in the mounting of samples. The other is the use of a flat bed grinder, a suitable mild
Middle of sample face.

Figure 2.32 Talystep traces of compression sample face after turning and finishing on both wet and dry on lathe.
Middle of sample face.

Near edge of sample face.

Figure 2.33 Talystep traces of compression sample face after turning and finishing on 600 wet and dry.
steel rig would have to be designed to mount the stainless steel samples as these machines usually have a magnetic base for holding the work piece. Surface hardness checks on a trial sample finished with such a machine (using coolant and fine cuts) showed that the surface was less hard than a turned surface and similar to one after abrading with wet and dry paper. Initial fears that finishing by grinding would harden the surface and change material properties would thus appear to be unfounded. Quality of sample surface produced by grinding is probably midway between those produced by the optical instrument makers and by finishing with wet and dry paper.

2.4.5 Sample Lubrication

As discussed in section 2.1, the criterion for disregarding frictional effects is met if the radius to length ratio is about 1 and if the surfaces are lubricated. Figure 2.34 shows the effect on the stress and strain curve of compressive 316 samples, of changing the lubricant. The effect of using no lubricant is to delay yielding and so the sample have apparently a higher yield point. The P.T.F.E. spray used had some effect but the lowest and probably the truest values were obtained using a light silicone spray lubricant. It can be noted that in general the effect of friction is to increase the yield point, but not to affect the work hardening rate.

2.5 Computer Analysis
2.5.1 Introduction

For the analysis of the results, measurements have to be taken from short duration stress pulses (≈ 100μs). In previous
Figure 2.34 Effect of lubricant on sample face during dynamic compression test, 316 stainless steel.
work the pulses have mainly been recorded by using a polaroid camera with an open shutter placed over the screen of an oscilloscope, on which the signals were displayed. The oscilloscope was used in the 'single sweep' mode and triggered by an inertia switch at the start of the incident bar. Taking readings from the resultant photograph, doing the analysis (using programmable calculator), and plotting graphs takes about 4 hours.

A significant improvement on single-shot oscilloscope photography results from the use of a transient recorder which automatically digitises the signals, and also provides a more reliable trigger. The signal can then be displayed on the oscilloscope as a continuous display, which can then be adjusted to the correct position and brightness for photography. Most importantly the data can be fed from the transient recorder into a computer for the analysis. Ellwood (1979) describes the initial attempt to do this using punched paper tape as the transfer medium from the transient recorder to computer. This initially gave good results, and after a little preparation the analysis could be done as an overnight batch job and be collected the next day. Unfortunately, the paper tape punch machine proved to be very unreliable, and the delay in analysis was inconvenient.

As an alternative (to the punched tape system) a link directly from the transient recorder to the University's PRIME terminal computer system was investigated. The interface needed would have been a microprocessor board supplied and installed by the University computer unit, who would have also have helped with the necessary software.
However, it was decided to purchase a Commodore PET microcomputer (figure 2.35) and link this directly to the transient recorder. This has the advantage of high speed (~20 minutes for data transfer, analysis and graphs) and reliability. The cost of the computer is only about the same as the interface to the PRIME or a new punch. This installation does have the advantage of being independent of the central system and so can be operated at all times without the restriction of waiting for other users who could slow down the use of the PRIME at peak times.

This section describes the connection of the PET to the Hopkinson bar system, and the programme developed to carry out all the required functions.

The interfacing of the transient recorder and the PET computer was thought to be the most difficult part of the development of the system. Before the computer was purchased many inquiries were made, and an interface designed in the Electrical Engineering department at Loughborough was tried. The situation was complicated by the fact that the interface in the transient recorder was designed for a paper tape punch and a more suitable one would have been very expensive (~£700).

However, the manual for the PET indicated that the parallel user port of the PET could be programmed to behave like the paper tape punch and input the data. It was electrically compatible with the transient recorder output as both were TTL compatible. Of the 2048 data points available in each channel of the transient recorder, only 400 are inputed and
FIGURE 2.35 Computing System. From left to right: Floppy Disc Drive, Printer, PET Microcomputer, Transient Recorder.
used by the computer. This gives about 100 points 1 μs apart for each of the pulses, which is adequate for analysis and saves much time and space over the use of the entire traces. A 5 volt peak to peak wave (from the calibration output of the 556 oscilloscope) is injected into the word request line of the transient recorder after a data set has been transferred. This then allows the recorder to 'skip' through the 1648 remaining points, and return to the display mode without disturbing the stored data. The PET's parallel user port is thus directly connected to the data output of the transient recorder (figure 2.36). There is a switch and socket on the word request line to allow the injection of the 'skip' signal when required. A zener diode across the socket prevents input of too high a voltage.

The PET itself is the 32k professional model with 31743 bytes of memory available to the user and a typewriter keyboard. An external cassette recorder and plain paper printer were supplied with the computer. The recorder is used for the storage of data and programmes, and the printer provides a 'hard copy' output of results, tables and graphs.

The programme developed for use with the Hopkinson bar and PET computer is listed in Appendix 1. It is written in the language 'BASIC' and it was designed to incorporate all required functions in the one programme, so that the transfer of data, analysis and hard copy output can be performed for several shots whilst remaining in the 'Run' mode. This means that constants can be retained between runs (if required) and the complication and delay of feeding in new programme segments is avoided. The programme presents the
Figure 2.36. Interconnection of transient recorder and PET microcomputer.

Note
1. Arrows indicate direction of signal.
2. 2 pole, 2 way switch shown in load position. In other position the transient recorder is skipped to the end of its memory, back into display mode.
user with instructions and questions which are easily
carried out and provide flexibility. Most of the questions
are followed by checks and are repeated if the user's reply
is obviously in error. The entire programme was found to
fit in the memory of the 32k PET and so no attempt has been
made to optimise the coding, as it was found to work
reliably and without too much delay.

2.5.2 Interface between Transient Recorder and PET

The data output pins (excluding parity line) of the
transient recorder are connected directly to pins PA0 to PA6,
of the parallel user port on the PET. The word request is
connected to pin PA7, with a break for the switch and socket
to allow the injection of the skip signal. The digital
grounds of the two devices are interconnected. The start
of the interface segment is line 120: POKE 59459, 128.
This programmes the user port and makes pin PA7 an output and
pins PA0-6 inputs. There is then a loop with 800 steps,
each one collecting a data point, which is put alternatively
in the arrays C1 and C2. The pair of lines 'POKE 59471, 128'
and 'POKE 59471, 0' put a '1' and then a '0' on pin PA7.
As this is connected to the word request pin of the transient
recorder, a new symbol appears on its output pins. PEEK (59471)
reads the contents of PA0-6 as a base 10 number, the sum
of the binary number presented to the input. This sum represents
a symbol in the ASCII code. Of the 13 characters sent
from the recorder the non-numeric ones are all less than 33
and so can easily be discarded. The numerics appear as the
digit represented, plus 48. The data points appear as a string
of three digits, representing 100's, 10's, and 1's. These
are arranged to give the data point as a number between 000 and 255 which represents the full voltage range as preselected on the recorder. During the development of the interface, it was found that error conditions such as the recorder not being in the punch mode, gave a certain type of error in output. This is used by the programme to detect such conditions, cease input, and to advise the operator of the error.

2.5.3 Use of Cassette Recorder for Data Storage

When the list of data has been taken from the recorder, the user has the option of storing it on the cassette recorder. This can act as a buffer in case of an error or failure during analysis, but is mainly to allow analysis at a later stage. This is carried out by lines 600 to 640, by opening a file for the cassette and then printing to it. A similar section (1060 to 1100) is included at the start of the analysis section to allow the user to input a data set from the cassette recorder if desired.

2.5.4 Analysis Section

Before the equations for the analysis of result can be applied to the data it has to be processed to put it into the correct form. Lines 1202 to 1320 allow the user to input the relevant parameters about the shot, such as settings on the transient recorder and specimen dimensions. One of these is a 'calibration factor' which includes the effect of gauge and ballast resistance, gauge factor, amplifier gain and any other voltage loss or gains in the system. As the strain gauges are not equidistant to the sample, channel 2 is moved relative to channel 1 by an amount entered as the delay in
micro-seconds.

A digital filter is included as lines 1330 to 1360: this equates adjacent points if their difference is greater than 50, and helps to filter out some of the worst spikes in the data. The first 50 points from each channel are averaged, and the mean used as a baseline by subtracting it from all the points. As the first pulse expected on each channel should be positive, then this is used as a check on the polarity of each channel and if incorrect it is inverted. The first signal from the incident bar is expected before the first one from the transmission bar and so this can be used to check that the channels are not crossed. If they are, they are automatically swapped over. The calculation of sample strain involves the integration of the reflected pulse; the starting point of the calculations is thus important. There are two options available to the user. The simplest is to start the calculations at the beginning of the transmitted pulse using the baselines already calculated. The second is to start the calculations at the beginning of the reflected pulse, but correcting the reflected pulse's baseline using a straight line from 2.5μs before its start to 2.5μs after its end. This is often necessary when using the 25cm projectile, as after the incident pulse the strain recorded by the gauges on the incident bar takes a while to settle back to the original level. The need for this correction can be seen in the record of the shot P210 (figure 2.37), and its extent is always indicated in the table of parameters printed after each analysis. The lines 1660 to 1740 carry out the actual analysis by applying the formulae
Austenitic stainless steel compression sample,
25cm projectile, 4 x 16mm aperture
Vertical scale: 0.0525%/cm
Horizontal scale: 20μS/cm

Figure 2.37 Oscilloscope record from shot P210.
derived earlier (equations 2.7 and 2.8). They calculate strain from voltage, sample stress and sample strain.

The calculations are continued for a time determined by the projectile length, which is entered along with the other parameters. Sample stress and strain are thus calculated in the analysis. The user has the option of either or both of two final corrections. The first is a correction of the stress against strain curve, to make the initial elastic slope equal the 'correct value' (figure 2.38). This involves correcting the values of strain, leaving stress alone, and is useful for eliminating the effects of any mismatch which may have occurred. The limit of proportionality is found by inspection of the stress/strain curve which is printed if this option is selected. Up to this limit the corrected strain is:

\[ \varepsilon_{\text{corr}} = \frac{\sigma_s}{E} \]  
(2.17)

and after is:

\[ \varepsilon_{\text{corr}} = \varepsilon_s - (\varepsilon_L - \frac{\sigma_L}{E}) \]
(2.18)

The second correction is the calculation of true stress \( \sigma_T \) and strain \( \varepsilon_T \) from the engineering stress and strain already calculated. This has the effect of correcting for the change in cross sectional area and axial length as the sample is strained, and is carried out by:

\[ \sigma_T = \sigma_s (1 - \varepsilon_s) \]  
(2.19)

\[ \varepsilon_T = -\log_e (1 - \varepsilon_s) \]  
(2.20)

Johnson (1970) contains derivations of these formulae. If the first strain correction has already been carried out then \( \varepsilon_{\text{corr}} \) would be used instead of \( \varepsilon_s \). Equation 2.19 applies strictly for plastic strain (\( \nu = 0.5 \)). These equations are correct treating compression as positive.
FIGURE 2.38 Correction of sample strain
2.5.5 Graphs and Tables of Results

Graphs may be plotted at several stages in the analysis of results. At line 1750 the user may display the uncorrected results on the computer's screen in the form of graphs. These provide a good check on the quality of the analysis and results up to that stage. Graphs are printed, to enable the limit of proportionality to be found in the stress/strain curve for the elastic slope correction. The user may also at this stage take the opportunity to print a graph of uncorrected strain against time. Finally graphs of results may be printed after all the corrections have been made as a final record of the shot.

The routine from 5060 to 6460 calculates the shape of the graphs. If X and Y are 40 and 60 respectively then the graph fills the screen, if 80 and 120 then a double sized version for the printer results. The graph plotter routine starts by asking the user to select the parameters he requires plotting from sample stress, sample strain and time. The computer returns the range of values for the relevant parameters and asks for the full-scale values for the axes.

Most graph plotting routines for the PET use the rectangular symbol the size of the curser. The routine here doubles the resolution by using the quarter square symbols. If more than one point lies within a cursor point then alternative symbols are chosen to show this. The programme steps through the two arrays, instead of scanning the graph looking for points (this was an alternative tried by the author). The graph is constructed as a series of lines, stored as the array V(1). This makes the graph routine suitable for
screen or printer, as all that is required after the calculations is a listing of \( V \) along with the required axes.

When the graph is printed, the computer includes axes and labels to complete the graph. The numbers indicated on the axes are full-scale values. The printed graph has a full scale resolution of 80 by 120 points or about 1% of the full scale values, and so although they are quite good they are only really intended as rough indicators. An X-Y digital graph plotter which can be connected directly to the P.E.T. has recently become commercially available. This will enable graphs with very high resolutions to be plotted. One has been ordered for the Loughborough facility at the recommendation of the author.

After printing out the graphs the user may elect to print out a table of results. Unlike FORTRAN, in BASIC the format of the table has to be constructed when number of the form \( X.XXXE+Y \) are required. The calculations for this are on lines 2810 to 2836 and make use of the limited formatting capability of the printer. The table headings are automatically selected depending on what corrections have been made. The spacing of the points in the table in microseconds is selected by the user after the headings have been printed.

Finally, the computer may if requested print out a table of parameters. This includes values fed in by the user as a check and a permanent record. It also includes (if relevant) the correction values used when the reflected baseline was corrected, for comparison with the photograph of the oscilloscope from the shot.
2.5.6 Example Calculations

As an example of the type of results obtained using the computer the results of shot P210 are presented here. The analysis of this shot was also carried out using the method of taking readings from the enlarged trace by hand and calculating with a Texas T158 calculator. For the hand calculations a calibrated photograph was taken from the replay of the transient recorder, as it does not appear to distort signals and provides a good quality record. The Hopkinson bar used was the conventional two bar system. The new type amplifier on the 5X setting was used on channel one to increase the signal to noise ratio.

Details of the test are:-

Date: 14/4/80

Material: Austenitic stainless steel

Aperture on gas gun: 4X16mm

Projectile length: 25cm

Oscilloscope settings: Voltage gain: 10mV/cm

Time base: 20μs/cm

Transient recorder settings: Range Ch1: 0.5V

Range Ch2: 0.1V

Sweep: 2mS

Trigger: 5% pre-trigger on Ch1

Sample length: 4.33mm

Sample diameter: 9.99mm

Gauge supply voltage: 90.0V

During the computer calculations the reflected baseline was corrected and true stress/strain calculated. The elastic slope of the stress/strain graph was not corrected. A table of results is included in Appendix 2. For the hand calculations
a tracing of the polaroid photograph (enlarged by a factor of two) from shot P210 (figure 2.37) was taken.

The reflected baseline was corrected by taking readings relative to a line through the start and finish of the pulse. The calculator programme was extended to include the calculation of true stress/strain and the results are presented in Appendix 2. Graphs of true stress against true strain for the two analyses are shown as figure 2.39. Figure 2.40 shows the two graphs of true strain against time.

2.5.7 Discussion

The correction of reflected baseline is the first of the corrections available in the analysis. It is probably only required when the 25cm projectile has been used. With the 16cm one there is a larger gap between the incident and reflected pulses and a tendency to return to the base strain level more quickly. Shots using the 25cm projectile and no sample (figure 2.41) show the slow return to the baseline more clearly. This seems to be a genuine strain level and not an electrical effect. A linear correction would seem to be reasonable. Most shots after development of the programme had the constant bar gauges 47cm for the sample and so the correction required was only slight.

For shot P210 the actual correction used is given in the table of parameters in Appendix 2. Inspection of the record (figure 2.37) shows that the total correction of 6.7 (each cm = 25 increments) is reasonable. This is confirmed by the agreement in strain obtained from computer and hand calculations.
Figure 2.39 Result of analysis of shot P210

Figure 2.40 Result of analysis of shot P210
No Sample

25cm projectile, 16mm aperture

Vertical Scale: 0.0525%/cm

Horizontal Scale: 20μS/cm

Figure 2.41 Oscilloscope record showing need for corrected baseline.
The elastic strain correction involves the modification of the stress/strain curve so that the slope up to the limit of proportionality equals the expected value of Young's modulus. This is achieved by a correction in the strain levels. The reason for doing this correction is to effectively remove the 'blip' at the start of the reflected pulse which sometimes occurs in a shot. This indicates, when analysed, a much greater strain than is expected at low stress levels.

During the development of the computer programme a series of shots was carried out with deliberately defective specimens. One class of these specimens had a small 'pip' left on them to simulate a gap between bar and sample. Figure 2.43 shows the type of stress/strain curve obtained with such a sample. The initial strain (A-B), was proportional to the size of the pip which also decreased the elastic slope. Specimens with no pip, but with non-parallel faces did not have such an apparent large initial strain, but the elastic slope was decreased. The use of rubber bands to hold the bars and sample (normal samples) together gives a considerable improvement in the stress/strain curves. This would indicate that some early results were affected by gaps, between the bars and even good quality samples, (possibly due to vibrations).

Even though it is expected that this correction will be needed less with the extra restraint, the correction is retained as it is useful to produce a valid result if a slight gap does occur. This was shown by the fact that corrected stress/strain curves for the defective specimens were similar to the uncorrected ones for normal specimens held in place with bands. If errors do occur because of wave
Figure 2.43 Effect of sample 'defects' on stress/strain curve

Figure 2.44 Comparison of final sample strain from computer calculations and from direct measurement of sample
propagation they are probably insignificant compared with the effect of using imperfect specimens; figure 2.44 compares the final strain calculated by the computer and that measured by taking micrometer readings before and after a shot for about 50 tests. The good agreement is a vindication of the method used and in particular at low strains of the correction of elastic slope.

Equations 2.19 and 2.20 show how the calculation of true stress and strain is carried out. It is made to allow for the change in cross-sectional area as the material is strained. There is little doubt as to the validity of this correction as it is well established.

Figure 2.45 illustrates the need for this correction in the shot P210. The correction in stress at maximum strain is 9%, well outside the accuracy of the measurements and method. The corresponding correction in strain level is an increase of about 4.5%, also a worthwhile correction. This does illustrate the value of computer techniques, as it is little extra effort to include the few lines necessary for a calculation that would take a long time by hand.

The accuracy of any computer graph plotter is limited to the resolution of the lattice of points used. In this case for the printer version, the programme uses a 120 by 80 array, which gives an accuracy of about 1% of the full scale values. Figure 2.46 is an illustration of the accuracy that is achieved by the graph plotter. It shows a typical output with points, calculated from the table of results and the dimensions of the axes, drawn in. These show that the graphs
Figure 2.45 Comparison of true and engineering stress against time curves for shot P210

Figure 2.46 Example of computer graph of sample strain against time showing accuracy of plotting
produced on the printer are quite adequate even though the individual points are not as accurate as hand plotted ones from the tabulated values. This means that the graph plotter can produce a perfectly adequate graph in much less time than hand plotting.

Figure 2.40 shows that at maximum stress and strain, agreement between the hand calculation and the computer is about 2%. This shows that the computer was able to carry out the analysis in the correct manner. The difference is probably due to errors in reading voltage levels, and the starting of the calculations at slightly different points.

A form of automatic analysis that has been used by other workers is to use a CRO in X-Y mode, with the reflected pulses being fed to the x axis via an integrating amplifier and the transmitted pulse to the y axis. A record is made using an open shutter camera and the resultant trace can be calibrated directly in sample stress and strain. This technique has the advantage of simplicity, but is likely to be less accurate and reliable than the use of a digital recorder and computer. Strain against time cannot be plotted or strain rate measured without the use of a second CRO. Also, corrections and calculations of true stress and strain cannot be easily carried out using this technique, whereas a computer can easily be programmed to include such functions, and to present the final data in the required form.

The main source of error in the computer calculations is due to the digital increment used to indicate voltage. This
is 1/256 of the transient recorder voltage range selected before each test. If care is taken, then measurement of the pulses can be made to within 1% of the peak values. Errors due to the strain gauges and detection circuits are probably about 2%, giving an accuracy of about 3% for the sample stress and strain values. This is probably a slightly smaller error than is inherent in the analysis by hand, particularly as the computer is not prone to errors due to tiredness or boredom which could affect the manual technique. As stated in the introduction, the main reason for using a computer method for analysis of results is speed. The analysis of shot P210 by hand took about 4 hours to complete, including the drawing of the two graphs. Using the computer the same analysis could be carried out in about 20 minutes, producing a more complete and much neater output. This includes the transfer of data from the transient recorder to the PET, and then to the cassette recorder which acts as a buffer in case of power failure or a mistake.

Over 500 analyses have been carried out using this system since the programme was finally completed and debugged. This shows that the software is reliable and able to cope with the range of faults that can occur in the data. The problems with the paper tape system were the reliability of the punch machine, and the overnight delay while the data was being processed by the main frame computer. The new computer system is a significant improvement in both of these respects, and if anything does go wrong with the computer, parts are available locally and much easier to check and replace.
2.6 Static Tests

For comparison with the dynamic tests on samples of all materials tested, tests were carried out at much lower rates of strain. Such static tests are typical of most mechanical tests carried out on material samples and are used to provide basic material data. Static compressive tests were carried out on an Instron Test machine capable of a 5000kg maximum load, and fitted with a chart recorder to give a permanent record of load against cross head displacement. This machine is designed to run at various pre-set crosshead velocities. Using 0.5mm/min gives a sample strain rate of approximately $10^{-3}\, \text{sec}^{-2}$.

The machine was prepared for use by the technician by fitting the compressive plates, switching on for a warm up and calibrating the load cell using calibration weights. To protect the platen faces and to allow for fitting of an oven for high temperature tests a simple rig turned from 431 stainless steel was made. Figure 2.47 shows the arrangement for compressive testing. The samples used are all of the same dimensions as in the dynamic tests and the ends of the rig are finished in the same manner as the Hopkinson bar rod ends, so that direct comparison of tests is possible. The sample faces are lubricated with silicone spray, as frictional effects affect static tests in a similar manner to dynamic tests.

Due to the compliance of the rig used and to machine components, the crosshead movement plotted on the chart is greater than the displacement of the sample. Tests up to full load with no sample between the faces of the rig show
FIGURE 2.47 Static compression tests arrangement
that the correction required is proportional to load. Such a test produces a straight line trace which could be subtracted from that obtained when a sample is present. However this technique is susceptible to small changes that may occur between runs. What is normally done is to extrapolate the initial elastic region in every test and to draw a calibration line calculated using the displacement obtained using an assumed value of elastic modulus (figure 2.48). The sample displacement can then be read off the chart, relative to this calibration if the crosshead and paper speeds are known (usually 0.5mm/min and 100mm/min). As the displacement whilst the sample is elastic is only small this technique is relatively insensitive to changes in assumed modulus. Points of load and sample displacement are read off the chart every 6 seconds of testing time (1cm on chart). These are recorded on a duplicated chart on which other parameters such as sample type and dimensions are recorded. A simple programme was written for the PET micro-computer. Values of displacement and load are typed in and true stress and strain are calculated. Tables of results and graphs of stress against strain and stress or strain against time are plotted using the graph plotting routine developed for the dynamic analyses. In general these tests produce a lower yield point than in dynamic tests but the rate of work hardening is unaltered.

Most tests were carried out at room temperature, but tests, both dynamic and static were carried out at elevated temperatures (up to 600°C).
FIGURE 2.48 Derivation of sample deflection from test machine output

Machine compliance
Elastic response of sample
Sample deflection

Elastic extension $\equiv E = 1.8 \times 10^6$ Nm$^{-2}$

FIGURE 2.49 Arrangement used to heat samples in elevated temperature tests

- 240V a.c. Variac
- 60V 8A Transformer
- 0 - 10A Ammeter
- Ceramic tube
- 30 turns of 2/4 swg Ni-chrome wire

FIGURE 2.48 Derivation of sample deflection from test machine output

FIGURE 2.49 Arrangement used to heat samples in elevated temperature tests
2.7 Elevated Temperature Tests

To heat the specimens, a coil of about 30 turns of 24 swg Ni-chrome wire was constructed on a length of ceramic tube (approximately 75mm long, 15mm inside diameter, 4mm wall thickness) which fitted around the specimen (figure 2.49). The coil was lagged with 2" wide asbestos tape, which was wound to give a thickness of about 2". The power was supplied using a 2Amp variac and an 8Amp transformer which gives an output of 60 Volts for an input of 240 Volts. Current was measured using an AVO-8 meter on the 10Amp ac range.

Sample temperature was measured using a Nickel Chromium/Nickel Aluminium thermocouple spot welded to the sample and connected to a digital voltmeter with a 4½ digit display and resolution of 0.01mV. The sample temperature was measured by looking up the thermocouple voltage in a standard table and adding 20°C to the indicated temperature.

The temperature could be controlled by changing the current in the coil with the variac. This system is very versatile as it can be used with compression, tensile, static and dynamic tests. A current of 8Amps was sufficient for a sample temperature of 600°C to be attained in all configurations.

Tests were carried out with the coil around the centre of a continuous 2 metre bar, and it was shown that even at the highest temperatures used there was no significant effect on the propagation of pulses through the 431 bars (figure 2.50).

The strain gauges used in the high temperature tests were far enough away (37cm even on transmitter bar) from the coil not to suffer more than a few degrees rise in temperature, and so
Figure 2.50 Transmitted pulses after passing through heated region in 2 metre bar.

Vertical scale: 0.105%/cm

Horizontal scale: 50μS/cm
<table>
<thead>
<tr>
<th>TEMPERATURE/°C</th>
<th>ELASTIC MODULUS/10^6Nm(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.00</td>
</tr>
<tr>
<td>90</td>
<td>1.97</td>
</tr>
<tr>
<td>150</td>
<td>1.92</td>
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<tr>
<td>200</td>
<td>1.86</td>
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<td>260</td>
<td>1.87</td>
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<td>320</td>
<td>1.78</td>
</tr>
<tr>
<td>370</td>
<td>1.72</td>
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<tr>
<td>430</td>
<td>1.67</td>
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<td>480</td>
<td>1.63</td>
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<td>540</td>
<td>1.58</td>
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<td>590</td>
<td>1.54</td>
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<td>650</td>
<td>1.49</td>
</tr>
<tr>
<td>700</td>
<td>1.43</td>
</tr>
<tr>
<td>760</td>
<td>1.39</td>
</tr>
<tr>
<td>820</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 2.3 Elastic modulus of 321 stainless steel at elevated temperature from International Nickel (1966).
readings were not affected. Silicone lubricant was used even at the highest temperatures, but a substitute such as graphite paste may be more suitable if the high temperatures are maintained for long periods.

High temperature tests are analysed in the same manner ambient tests, but a lower value of assumed modulus has to be used. Values obtained for an International Nickel Limited (1966) data book were used for 321 stainless steel, see Table 3. These techniques can be used for static and dynamic, compression and tensile tests at elevated temperature.
CHAPTER 3 CONTROL OF STRAIN RATE BY PULSE SHAPING

3.1 Initial Investigations

3.1.1 Introduction

The strain rates measured on the deformable vessels during test explosions for the COVA programme were in the region 50 - 250 sec\(^{-1}\). Mechanical material data from tests conducted in this range were therefore required to enable comparison of computer calculations with experimental results.

Compressive Hopkinson bar tests are usually carried out at much higher rates (> 1,000 sec\(^{-1}\)), and strain rates are controlled by varying the amplitude of the incident pulse. This can prove successful for some materials at low strain rates. Initial tests on stainless steel using the flat topped pulse produced by the gas gun impact showed that control at the lower rates might not be practical by simply controlling projectile velocity. Figure 3.27 shows strain against time curves; the lowest curve (P138) has an average strain rate of about 100 sec\(^{-1}\), but the final rate of 70 sec\(^{-1}\) is preceded by an initial maximum rate of 370 sec\(^{-1}\). This situation is also repeated with the higher rates where the initial rate is as much as three times the average. The initially high strain rate is as much as three times the average. The initially high strain rate is undesirable as strain rate history effects could mask any actual strain rate dependence (particularly in materials prone to work hardening). There is a requirement for a means of control to maintain the strain rate constant.
If it is not exactly constant, it should perhaps increase slightly rather than decrease during the test.

3.1.2 Simulation Programme

To investigate the factors affecting strain rate, and perhaps devise techniques for effective control, a simple simulation of the Hopkinson bar was written for running on the University's PRIME computer terminal system.

A listing of the programme used in the initial investigation is listed in Appendix 3, and a flow diagram is presented as figure 3.1.

The programme, written in Fortran, makes use of some of the basic formulae derived in Chapter 2. It uses an iterative technique based on the assumption that the reflected and transmitted pulses add up to equal the incident.

For each real time point $T$, separated by an interval $\Delta T$ the sample stress is guessed and transmitted strain calculated, from 2.8:

$$
\varepsilon_T = \frac{A_s}{A} \frac{\sigma_s}{F_b}
$$

A bilinear stress against strain curve for the material being tested in the simulation is assumed (figure 3.2) and sample strain calculated from stress. The reflected strain is calculated, from equation 2.7:

$$
\varepsilon_R = \frac{1}{2c_o} \varepsilon_s \frac{1}{\Delta T}
$$

The incident strain is taken from a simplified incident pulse (figure 3.3). A test value can now be calculated:
Input incident pulse shape and material properties

First point $\varepsilon_I$

Initial guess $\sigma_S$

Calculation $\varepsilon_R$ and $\varepsilon_T$

Calculation Test

Increase guessed $\sigma_S$ by increment

Calculation $\varepsilon_R$ and $\varepsilon_T$

Calculation Test

Has test changed sign?

YES → decrease increment

NO →

Is test further from zero?

YES → change sign of increment

NO → use same increment again

Test = $\varepsilon_I - (\varepsilon_R + \varepsilon_T)$

Increment means multiply by: 1 + CREM

CREM tends to 0.00002 on final run at each $\varepsilon_I$ value.

When iteration is complete - programme goes to next $\varepsilon_I$ value (2uS spacing).

FIGURE 3.1 Flow diagram of ORACLE simulation programme
FIGURE 3.2 Bilinear stress against strain curve assumed in ORACLE simulation.

FIGURE 3.3 Flat topped incident pulse assumed in ORACLE simulation.
\[ \text{TEST} = \varepsilon_I - (\varepsilon_R + \varepsilon_T) \quad (3.3) \]

After the initial calculation the value of the guessed stress is incremented and the calculation of \( \varepsilon_R, \varepsilon_T \) and \( \text{TEST} \) repeated. The value of stress is incremented by multiplication with a factor which converges on 1.0 as the iteration proceeds.

\[ \text{STRESS} (I) = \text{STRESS} (I) \ast (1 + \text{CREM}) \quad (3.4) \]

CREM starts at a value of \( 20 \times 10^{-1} \) and decreases to \( 20 \times 10^{-6} \) on the sixth time around the loop. The new value of \( \text{TEST} \) is compared with the previous one. If it has increased, the sign of \( \text{CREM} \) is reversed, and the incrementation process continued. If the value of \( \text{TEST} \) has changed sign \( \text{CREM} \) is decreased before using again, as the value of \( \text{TEST} \) must be within one increment of zero.

The programme works along the pulses by taking values of \( \varepsilon_I \) at 2\( \mu \)sec intervals. At each \( \varepsilon_I \) point the iteration proceeds until \( \text{CREM} \) has been decremented six times, and \( \varepsilon_R, \varepsilon_T \) and sample stress and strain are computed before proceeding to the next.

The results were presented in the form of graphs produced on the terminal by use of a GINOGR AF sub-routine.

3.1.3 Comparison of Simulation and Actual Shot

For purposes of comparison a simulation was carried out using the material properties derived from an actual Hopkinson bar shot, to see if the programme produces realistic results. The sample used was made from stainless steel, of the type
to be used in later experiments. The parameters used were:

Material properties:

Elastic modulus  =  1.62 x 10^6 Nm^-2  
Plastic modulus  =  0.0314 x 10^6 Nm^-2  
Yield point     =  510 MNm^-2

The value of yield stress is obtained by extrapolating the elastic and plastic regions of the Stress/Strain curve, so that they meet at the point shown on figure 3.4. The elastic modulus used is lower than would normally be expected, but is used as that was the value obtained in the actual shot.

Incident pulse:

T1       =  15\mu s  
T2       =  70\mu s  
T3       =  90\mu s  
c_{I \text{ max}} =  0.27\%  

Sample dimensions:

\ell_s  =  0.00433 m  
d      =  0.01 m

Figures 3.5 to 3.7 illustrate the results from the shot and the simulation plotted on the same axes. The main results are:

<table>
<thead>
<tr>
<th>In sample</th>
<th>Actual results</th>
<th>ORACLE prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Stress/MNm^-2</td>
<td>762</td>
<td>810</td>
</tr>
<tr>
<td>Maximum Strain/%</td>
<td>9.22</td>
<td>9.88</td>
</tr>
<tr>
<td>Residual Strain/%</td>
<td>8.93</td>
<td>9.46</td>
</tr>
<tr>
<td>Plastic Strain Rate/sec^-1</td>
<td>1875</td>
<td>1900</td>
</tr>
</tbody>
</table>

The results presented show that the simulation can produce reasonably accurate results. The overall parameters such as maximum stress are predicted to within 10% in the example
Figure 3.4 Stress/strain curve obtained from dynamic compression test on an austenitic stainless steel sample

Figure 3.5 Comparison of strain rate cycle from simulation with that from the experimental test
Figure 3.6 Comparison of stress/time curve from simulation with that from the experimental test

Figure 3.7 Comparison of strain/time curve from simulation with that from the experimental test.
shown. This is certainly good enough for the work, as general trends and orders of magnitude are all that are required. The shape of the reflected pulse is not very accurately predicted, but the transmitted pulse is much better.

The comparison with the actual shot justifies the use of the simplifications in the programme. The incident pulse is assumed to be flat topped and

\[ \epsilon_I = \epsilon_R + \epsilon_T \] (3.5)

to hold throughout all the pulses. The material stress/strain curve is simplified to be bilinear, with a definite yield point. This is reasonable with stainless steels but would have to be reconsidered if other materials are to be used. Finally the formulae used for Hopkinson bar analysis are assumed to hold exactly, i.e. factors such as inertia, friction and wave propagation in the sample are ignored.

3.1.4 Discussion of Results

The first series of simulations (Table 3.1) was done to see how the properties of the material under test affect the rate of strain applied. The parameters used are basically modifications of the stainless steel properties used earlier. The yield point is varied in the first six rows, and in the next three rows the modulii are altered.

Table 3.2 shows the effects of altering the incident pulse shape. The results are presented in order of increasing pulse height, with the material properties staying constant, with the values used in the previous section.

In the results presented here '(?)' indicates some
<table>
<thead>
<tr>
<th>MATERIAL PROPERTIES</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus /10^{11} Nm^{-2}</td>
<td>Plastic Modulus /10^{11} Nm^{-2}</td>
</tr>
<tr>
<td>1.62</td>
<td>0.0314</td>
</tr>
<tr>
<td>1.62</td>
<td>0.0314</td>
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<td>1.62</td>
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<tr>
<td>100</td>
<td>0.001</td>
</tr>
<tr>
<td>1.62</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Incident pulse for all simulations above:

- T1 = 15\mu S
- T2 = 70\mu S
- T3 = 90\mu S

Maximum Strain = 0.27\% 
Maximum sample = 9300 MNm^{-2}

Stress
<table>
<thead>
<tr>
<th>Incident Pulse Shape</th>
<th>Results</th>
<th>Strain rate/sec&lt;sup&gt;-1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1/μs</td>
<td>T2/μs</td>
<td>T3/μs</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>115</td>
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<td>90</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>90</td>
</tr>
</tbody>
</table>

Material properties for all simulations above: Elastic Modulus = 1.62 x 10<sup>11</sup> Nm<sup>-2</sup>, Plastic Modulus = 0.0314 x 10<sup>11</sup> Nm<sup>-2</sup>  
Yield Point = 510 Nm<sup>-2</sup>
uncertainty in the result or non-convergence of the iteration, during part of the simulation. In the strain rate columns 'E' indicates rate of strain whilst elastic, and 'P' whilst plastic.

Many of the sample strain against time graphs plotted by the computer show a distinction between rate of strain whilst elastic and plastic. This will have to be considered when doing work on the strain rate sensitivity of materials. From the first six rows in table 3.1 it can be seen that the yield point of the material under test has a large effect on the rate of strain of the sample (figure 3.8). The values of the two modulii have much less influence on the strain rate. It is interesting to note that when testing materials the converse of these effects might be expected to hold, i.e. strain rate affects yield point but not modulii.

Figure 3.9 shows the effect of the pulse height on the sample rate of strain, plotted from data in table 3.2. It would seem that to obtain properties at low rates of strain, the pulse height must be such that the material just passes its yield point. The rise time (T₁) is the other important parameter influencing rate of strain as shown in figure 3.10. Its effect is mainly on the elastic rate of strain. Simulations with virtually triangular pulses i.e. with rise times of 50 or 100μs, indicate the possibility of very low rates of strain. The overall length of the incident pulse, has little effect on the rate of strain, but influences the total strain imposed on the specimen, the final strain being given by

$$\varepsilon_{\text{final}} = \dot{\varepsilon}_{\text{Ave}} T$$
Figure 3.8 Results obtained from a series of simulations obtained by varying value of assumed material yield point

for all points:
\[ T_1 = 15\mu s \]
\[ T_2 = 70\mu s \]
\[ T_3 = 90\mu s \]
Max incident strain = 0.277
Max incident sample stress = 9 x 10^6 Pa
Elastic modulus = 1.6 x 10^{11} Pa
Plastic modulus = 0.011 x 10^{11} Pa

Figure 3.9 Results obtained from a series of simulations obtained by varying amplitude of incident pulse

Key
○ plastic strain rate
△ elastic strain rate

For all points:
\[ T_1 = 15\mu s \]
\[ T_2 = 70\mu s \]
\[ T_3 = 90\mu s \]
Elastic modulus = 1.62 x 10^{11} Pa
Plastic modulus = 0.0374 x 10^{11} Pa
Yield point = 3100 m/s
For all points:
\[ \varepsilon_{\text{max}} = 0.16\% \]
\[ T_2 = 70\mu S \]
\[ T_3 = 90\mu S \]
Elastic modulus = \[1.62 \times 10^{11}\text{Nm}^{-2}\]
Plastic modulus = \[0.0314 \times 10^{11}\text{Nm}^{-2}\]
Yield point = \[510\text{MNm}^{-2}\]

FIGURE 3.10 ORACLE results showing effect of incident pulse rise time in sample strain rate.
where \( \varepsilon \) average is the average sample strain rate and \( T \) the duration of the straining (normally about 100\( \mu \)s with the 25cm projectile used in practice).

3.1.5 Calculation of Incident Pulse Shape

The basic formulae can be applied in the opposite direction by calculating the incident pulse needed for a required strain rate history (usually a constant strain rate), and representative material property (\( \sigma \) against \( \varepsilon \) curve). Sample strain is calculated at various time points separated by \( \Delta T \), from the strain rate history and the reflected strain calculated from equation 3.2. Sample stress is obtained from sample strain using the material properties, the transmitted strain being calculated from equation 3.1. The incident strain is then obtained from the addition of reflected and transmitted strain, the incident pulse shape being obtained from a collection of such points. Again one of the problems of such a technique is that material properties have to be guessed, which can be difficult before any dynamic tests have been performed. Examples of the incident pulses calculated using stress against strain curves obtained in experiments and a constant strain rate equal to the plastic strain rate, are presented for some preliminary tests as figure 3.11. The pulses are all basically trapezoidal in shape with the amplitude increasing and the rise time decreasing with the increasing strain rate. Unfortunately, for the higher rates, 375s and above, the rise time is faster (< 5\( \mu \)s) than normally obtained by the projectile impact. This is because in the calculations the strain rate was assumed to be constant even in the elastic region. In practise the rise time of pulses
Figure 3.11 Calculated incident pulse shape required for various constant sample strain rates

Figure 3.12 Shape of assumed trapezoidal incident pulse used in simulations
is about 10μs, and for higher strain rate tests the elastic strain rate is much lower than when plastic. The overall shape of these pulses is however typical of the transmitted pulses obtained when materials such as stainless steel are tested.

3.1.6 Simulation Using Trapezoidal Incident Pulses

A second version of the ORACLE computer programme was written using incident pulse as in figure 3.12. Table 3.3 contains the results of these calculations. The assumed material properties used throughout were similar to those of austenitic stainless steels with a yield point of 400MNm$^{-2}$ elastic modulus of $1.5 \times 10^{11}$Nm$^{-2}$ and plastic modulus of $0.2 \times 10^{11}$Nm$^{-2}$.

Strain rates between 45 and 265sec$^{-1}$ were calculated, this being the range obtained in COVA tests.

In some cases the elastic and plastic strain rates were similar indicating the desired constant strain rate.

3.1.7 Proposal of Pulse Shaping Technique

Low constant strain rates were produced in the simulations by applying different shaped incident pulses to the sample under test. It was proposed that a three bar Hopkinson bar system (figure 3.13) should be assembled with a dummy sample between the first and second bars. This sample would act as a pulse shaper by modifying the flat topped pulse from the projectile impact. The transmitted pulse from the pulse shaper would then be the incident pulse on the sample between the second and third bars. Strain rate can be controlled by choice of pulse shaper material and dimensions, and also by projectile velocity. Much
<table>
<thead>
<tr>
<th>INCIDENT PULSE SHAPE</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMAX 1/2, EMAX 2/2, Max Stress [MN/m²], Max Strain [%], Residual Elastic Strain [%], Plastic Strain rate/sec⁻¹</td>
</tr>
<tr>
<td>0.15 0.15 319 0.21 0 30</td>
<td>-</td>
</tr>
<tr>
<td>0.15 0.20 416 0.35 0.11 48 55</td>
<td>-</td>
</tr>
<tr>
<td>0.15 0.23 471 0.62 0.36 65 125</td>
<td>-</td>
</tr>
<tr>
<td>0.15 0.25 509 0.81 0.52 75 160</td>
<td>-</td>
</tr>
<tr>
<td>0.15 0.27 547 1.00 0.69 85 190</td>
<td>-</td>
</tr>
<tr>
<td>0.15 0.30 604 1.28 0.94 90 235</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.18 383 0.26 0 35</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.20 383 0.26 0 35</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.23 478 0.66 0.38 110 85</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.25 516 0.85 0.55 120 120</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.28 573 1.13 0.87 135 170</td>
<td>-</td>
</tr>
<tr>
<td>0.18 0.30 611 1.32 0.97 140 180</td>
<td>-</td>
</tr>
<tr>
<td>0.20 0.20 426 0.39 0.15 175 22</td>
<td>-</td>
</tr>
<tr>
<td>0.20 0.22 464 0.59 0.32 175 60</td>
<td>-</td>
</tr>
<tr>
<td>0.20 0.25 521 0.87 0.57 175 110</td>
<td>-</td>
</tr>
<tr>
<td>0.20 0.27 559 1.06 0.74 180 145</td>
<td>-</td>
</tr>
<tr>
<td>0.20 0.30 615 1.34 0.99 185 195</td>
<td>-</td>
</tr>
<tr>
<td>0.225 0.225 479 0.65 0.39 205 70</td>
<td>-</td>
</tr>
<tr>
<td>0.225 0.25 527 0.90 0.60 205 110</td>
<td>-</td>
</tr>
<tr>
<td>0.225 0.275 574 1.14 0.81 205 155</td>
<td>-</td>
</tr>
<tr>
<td>0.225 0.30 621 1.37 1.02 205 195</td>
<td>-</td>
</tr>
<tr>
<td>0.25 0.25 532 0.92 0.62 220 125</td>
<td>-</td>
</tr>
<tr>
<td>0.25 0.275 580 1.17 0.83 220 155</td>
<td>-</td>
</tr>
<tr>
<td>0.25 0.3 630 1.40 1.04 220 195</td>
<td>-</td>
</tr>
<tr>
<td>0.275 0.275 590 1.18 0.86 255 155</td>
<td>-</td>
</tr>
<tr>
<td>0.275 0.30 630 1.43 1.07 255 195</td>
<td>-</td>
</tr>
<tr>
<td>0.30 0.30 640 1.45 1.10 265 200</td>
<td>-</td>
</tr>
</tbody>
</table>

For all incident pulses: $T_1 = 15 \mu s$
$T_2 = 70 \mu s$
$T_3 = 90 \mu s$

All material properties: Elastic Modulus = $1.5 \times 10^8$[MN/m²]
Plastic Modulus = $0.2 \times 10^8$[MN/m²]
Yield Point = 400[MN/m²]

Table 3.3 ORACLE simulations of Hopkinson bar to show effects of trapezoidal incident pulses.
FIGURE 3.13 General arrangement for pulse shaper control of sample strain rate
care would be needed in the selection of this dummy sample, but constraints on the proportions need not apply and surface finish is not critical as the transmitted and reflected pulses produced from it will not be used for analysis.

A three bar system has been described by previous authors, Albertini and Montagnani (1977) and Rees (1970) use a pulse smoother to limit pulse rise time and eliminate high frequency oscillations from the oscilloscope trace. Duffy (1974) used a pulse smoother in torsional tests that also acted to attenuate axial waves.

The next section describes experiments designed to investigate the transmitted pulses obtained from samples of various materials and proportions.

3.2 Survey of Transmitted Pulses

3.2.1 Introduction

A survey of transmitted pulses produced from various materials was carried out, to see what pulses would be available for use in a three bar system for the production of low constant strain rates. Initial thoughts were that ramp-shaped pulses should be used and this is reflected in the investigation of annealed materials. Others were investigated with the purpose of producing small amplitude pulses that might be required in the tensile tests which use much smaller diameter samples.

The materials tested were mainly lower strength material chosen to try and obtain a ramp-shaped transmitted pulse. Others were chosen because of ease of machining or to give a reasonable range of pulse shapes and heights. A range of materials was
first tested using the 16cm projectile varying the velocity and the sample length. A few shots were done with the 25cm projectile for comparison. All shots were done at room temperature.

Some of the materials were annealed at a range of temperatures before testing to reduce the yield stress and to incorporate a large amount of work hardening during the test. The final series of shots was done using stainless steel samples of different diameters.

3.2.2 Technique

The conventional two-bar system was used for all of these shots. The pulses were detected by strain gauges attached to the bars in pairs to cancel any bending waves present. They were recorded using a two channel Datalab 922 transient recorder in the 'Pre-trig' mode. This mode uses the leading edge of the incident pulse as a trigger but enables information prior to the trigger to be captured. It is a completely reliable means of recording the signals. The signals were displayed on an oscilloscope and photographed using a Polaroid oscilloscope camera.

Two records are shown in figure 3.14 as examples of the traces obtained. The calibration in time and voltage, of each channel, was checked before each session of shots. No attempts were made to obtain stress/strain curves for any of these shots since only the transmitted pulses were important. The analysis was done by hand because the computer facility was under repair.

The samples were prepared by the author in an attempt to save time and were probably not as good a quality as would be
Pure Al sample
25cm projectile, velocity: 12.9 m/s

Vertical scale: 0.0525 %/div
Horizontal scale: 40μS/div

Brass sample
16cm projectile, velocity: 17.3 m/s

Vertical scale: 0.0525 %/div
Horizontal scale: 50μS/div

Graphs show incident and reflected pulses and transmitted pulses for Pure Al and Brass samples.
required for shots done for a definitive stress/strain analysis. The stock material available was 12.7mm diameter rod (the same as the pressure bars) and so all samples were of that diameter. The samples were cut to length and faced off in a lathe. They were finished by briefly rubbing the flat faces on a sheet of 600 wet and dry paper placed on a flat surface.

3.2.3 Results

The five materials used in the main part of the transmitted pulse investigation were:-

(i) Aluminium, 99.99\% pure

(ii) Lead, believed to be pure, obtained from the Physics X-ray laboratory

(iii) Aluminium alloy, BS1474/HE30TF.

Chemical composition (% by weight) from stockists catalogue:-

<table>
<thead>
<tr>
<th>Element</th>
<th>(%) by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.1</td>
</tr>
<tr>
<td>Mg</td>
<td>0.4 - 1.4</td>
</tr>
<tr>
<td>Si</td>
<td>0.5</td>
</tr>
<tr>
<td>Fe</td>
<td>0.5</td>
</tr>
<tr>
<td>Mn</td>
<td>0.4 - 1.0</td>
</tr>
<tr>
<td>Zn</td>
<td>0.1</td>
</tr>
<tr>
<td>Cr</td>
<td>0.3</td>
</tr>
<tr>
<td>Al</td>
<td>Rem.</td>
</tr>
</tbody>
</table>

(iv) Brass, BS 2874/CZ121M

Chemical composition (% by weight) from stockists catalogue:-

<table>
<thead>
<tr>
<th>Element</th>
<th>(%) by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>56.0 - 59.0</td>
</tr>
<tr>
<td>Zn</td>
<td>Rem.</td>
</tr>
<tr>
<td>Pb</td>
<td>2.0 - 4.5</td>
</tr>
</tbody>
</table>

(v) Copper, high conductivity alloy

Chemical composition (% by weight) from stockists catalogue:-
Cu 99.0
Pb 0.005
Bi 0.001

For composition of the stainless steel see the later results (section 3.3.2).

On all the diagrams of transmitted pulses (figure 3.15 to 3.23) the specimen length and height of the incident pulse are given. Scales are included to show the values of transmitted strain and time. All the shots are with the 16cm projectile unless stated. Figure 3.15 to 3.19 show the transmitted pulses obtained from the five materials in the non-annealed state. The top series of pulses indicates the variation with changing sample length, and the middle shows the effect of using a 25cm projectile. The lower series are all with ~6mm long samples with variable projectile speed and so incident pulse height.

Figure 3.20 to 3.22 display the transmitted pulses from aluminium alloy, brass and copper in the annealed state. Attempts to anneal pure aluminium and lead were not made as they are already very soft. As indicated on the diagrams each material was annealed at 200, 400 or 600°C for 1 hour and then impacted with three different heights of incident pulse. The relevant non-annealed results are also presented to enable comparisons. All the annealed specimens were ~6mm long, ~12.7mm diameter and tested with the 16cm projectile. Figure 3.23 shows the effect of changing diameter on the transmitted pulses from stainless steel specimens. All were non-annealed specimens, ~5mm long and impacted by the 25cm projectile.
### Variable Sample Length

<table>
<thead>
<tr>
<th>SHOT</th>
<th>SAMPLE LENGTH/mm</th>
<th>INCIDENT PULSE HEIGHT/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p29</td>
<td>3.93</td>
<td>0.16</td>
</tr>
<tr>
<td>p25</td>
<td>5.94</td>
<td>0.17</td>
</tr>
<tr>
<td>p30</td>
<td>9.25</td>
<td>0.17</td>
</tr>
<tr>
<td>p31</td>
<td>19.56</td>
<td>0.17</td>
</tr>
</tbody>
</table>

### Variable Projectile Length

<table>
<thead>
<tr>
<th>PROJECTILE LENGTH/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>p28  25</td>
</tr>
<tr>
<td>p24  16</td>
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### Variable Projectile Velocity

<table>
<thead>
<tr>
<th>PROJECTILE VELOCITY/m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>p26  26.8</td>
</tr>
<tr>
<td>p25  18.9</td>
</tr>
<tr>
<td>p24  12.6</td>
</tr>
<tr>
<td>p23  7.5</td>
</tr>
</tbody>
</table>

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 20µS/cm
Sample Diameter: 12.7mm
Sample length (unless stated): 6.0mm
Projectile length (unless stated): 16cm

FIGURE 3.15 Transmitted pulses from pure aluminium samples.
Variable Sample Length

<table>
<thead>
<tr>
<th>SHOT</th>
<th>SAMPLE LENGTH/mm</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p43</td>
<td>3.8</td>
<td>0.11</td>
</tr>
<tr>
<td>p42</td>
<td>10.8</td>
<td>0.10</td>
</tr>
<tr>
<td>p41</td>
<td>14.8</td>
<td>0.09</td>
</tr>
<tr>
<td>p36</td>
<td>6.51</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Variable Projectile Length

<table>
<thead>
<tr>
<th>PROJECTILE LENGTH/cm</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p39</td>
<td>25</td>
</tr>
<tr>
<td>p35</td>
<td>16</td>
</tr>
</tbody>
</table>

Variable Projectile Velocity

<table>
<thead>
<tr>
<th>PROJECTILE VELOCITY/m/s</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p37</td>
<td>18.7</td>
</tr>
<tr>
<td>p38</td>
<td>25.9</td>
</tr>
<tr>
<td>p36</td>
<td>11.5</td>
</tr>
<tr>
<td>p35</td>
<td>7.1</td>
</tr>
</tbody>
</table>

All Vertical Scales: 0.011 %/cm
Horizontal Scales: 20μS/cm
Sample Diameter: 13.5mm
Sample Length (unless stated): 6.3mm
Projectile Length (unless stated): 16cm

FIGURE 3.16 Transmitted pulses from lead samples.
Variable Sample Length

<table>
<thead>
<tr>
<th>SHOT</th>
<th>SAMPLE LENGTH/mm</th>
<th>INCIDENT PULSE $H_t$/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p57</td>
<td>3.71</td>
<td>0.145</td>
</tr>
<tr>
<td>p55</td>
<td>12.68</td>
<td>0.145</td>
</tr>
<tr>
<td>p49</td>
<td>5.98</td>
<td>0.14</td>
</tr>
<tr>
<td>p56</td>
<td>9.53</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Variable Projectile Length

<table>
<thead>
<tr>
<th>PROJECTILE LENGTH/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>p53</td>
</tr>
<tr>
<td>p49</td>
</tr>
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</table>

Variable Projectile Velocity

<table>
<thead>
<tr>
<th>PROJECTILE VELOCITY/m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>p50</td>
</tr>
<tr>
<td>p49</td>
</tr>
<tr>
<td>p48</td>
</tr>
<tr>
<td>p47</td>
</tr>
</tbody>
</table>

All Vertical Scales: 0.0251 $\%$/cm
Horizontal Scales: 20$\mu$S/cm
Sample Diameter: 12.7mm
Sample Length (unless stated): 6.0mm
Projectile Length (unless stated): 16cm

FIGURE 3.17 Transmitted pulses from aluminium alloy samples.
Variable Sample Lengths

<table>
<thead>
<tr>
<th>SHOT</th>
<th>SAMPLE LENGTH/mm</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p69</td>
<td>3.48</td>
<td>0.26</td>
</tr>
<tr>
<td>p64</td>
<td>5.85</td>
<td>0.24</td>
</tr>
<tr>
<td>p68</td>
<td>9.87</td>
<td>0.23</td>
</tr>
<tr>
<td>p67</td>
<td>13.65</td>
<td>0.20</td>
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Variable Projectile Length

<table>
<thead>
<tr>
<th>PROJECTILE LENGTH/cm</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p66 25</td>
<td>0.16</td>
</tr>
<tr>
<td>p63 16</td>
<td>0.16</td>
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</table>

Variable Projectile Velocity

<table>
<thead>
<tr>
<th>PROJECTILE VELOCITY/m/s</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p64 24.5</td>
<td>0.24</td>
</tr>
<tr>
<td>p63 17.3</td>
<td>0.16</td>
</tr>
<tr>
<td>p62 11.8</td>
<td>0.12</td>
</tr>
<tr>
<td>p60 7.4</td>
<td>0.07</td>
</tr>
</tbody>
</table>

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 25μS/cm
Sample Diameter: 12.7mm
Sample Lengths (unless stated): 6.0mm
Projectile Lengths (unless stated): 16cm

FIGURE 3.18 Transmitted pulses from brass samples.
Variable Sample Length

<table>
<thead>
<tr>
<th>SHOT</th>
<th>SAMPLE LENGTH/mm</th>
<th>INCIDENT PULSE Ht/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>p76</td>
<td>3.96</td>
<td>0.17</td>
</tr>
<tr>
<td>p72</td>
<td>6.03</td>
<td>0.17</td>
</tr>
<tr>
<td>p77</td>
<td>8.61</td>
<td>0.16</td>
</tr>
<tr>
<td>p78</td>
<td>13.61</td>
<td>0.17</td>
</tr>
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</table>

Variable Projectile Length

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>p72  16</td>
</tr>
</tbody>
</table>

Variable Projectile Velocity

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<th>PROJECTILE VELOCITY/m/s</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>p71  11.7</td>
</tr>
<tr>
<td>p70  6.9</td>
</tr>
</tbody>
</table>

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 25μS/cm
Sample Diameter: 11.1mm
Sample Lengths (unless stated): 6.0mm
Projectile Length (unless stated): 16cm

FIGURE 3.19 Transmitted pulses from copper samples.
3.2.4 Discussion

As expected, the softer materials (lead and pure aluminium) give transmitted pulses which were very low ramps while the others showed more complete transmission. For all materials the transmitted pulse increased in height as the incident pulse was increased in height or length. The percentage transmission, \(100 \left( \frac{C_{\text{Tmax}}}{C_{\text{Imax}}} \right)\), fell as the incident pulse height was increased. The two softer materials were more sensitive to this effect. Pure aluminium fell from 43% to 20% in the 4 shots shown at the bottom of figure 3.15, whereas the aluminium alloy only fell from 98% to 85% in the pulses in figure 3.17. In general the effect of increasing the length of the samples was to decrease the height of the transmitted pulse. Not all materials showed this effect clearly, but pure aluminium fell from 30 to 16% transmission when the sample length was increased from 3.93 to 19.56mm. This is probably due to a decrease in importance of friction between sample and bar, and inertial and wave propagation effects. It is clear that if a ramp shaped pulse is required then the sample should be as short as possible unless particularly low amplitude pulses are required.

In the five comparisons shown (figure 3.15 to 3.19) of the shape of the pulses produced by the 16mm and 25mm projectiles, it can be seen that the larger projectile causes a continuation of the transmitted pulse. It is then possible to predict the effect of substituting a 25cm projectile on all the other shots with the shorter one. It was thought that ramp-shaped pulses would be required for controlling the rate of strain with the pulse shaping technique. Lead and pure aluminium transmitted pulses are of the correct shape, but are too low to cause a
FIGURE 3.20 Transmitted pulses from annealed aluminium alloy samples.

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 25μS/cm
Sample Diameter: 12.7mm
Sample Length: 6.0mm
Projectile Length: 16cm

Amount by a shot number is incident pulse height
Norr-annealed

p97 (0.265%)
p96 (0.155%)
p95 (0.095%)
p87 (0.28%)
p86 (0.16%)
p85 (0.105%)
p107 (0.30%)
p106 (0.17%)
p105 (0.10%)

400°C for 1 hour

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 25μS/cm
Sample Diameter: 12.7mm
Sample Length: 6.0mm
Projectile Length: 16cm

Amount by a shot number is incident pulse height

FIGURE 3.21 Transmitted pulses from annealed brass samples.
Non-annealed

400°C for 1 hour

600°C for 1 hour

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 25μS/cm
Sample Diameter: 11.1 mm
Sample Length: 6.0 mm
Projectile Length: 16 cm

Amount by a shot number is incident pulse height

FIGURE 3.22 Transmitted pulses from annealed copper samples.
stainless steel sample to go plastic if used as incident pulses. Samples of the other three materials (brass, aluminium alloy and copper) were annealed in an oven at 200, 400 or 600°C for one hour each. The effect of incident pulses of different height can be seen in figure 3.20 to 3.22. There is little effect on brass of annealing, and ramp-shaped pulses were not produced. The aluminium alloy showed a gradual change in characteristics as the temperature was increased, and annealing at 600°C produced pulses which were nearly ramp-shaped. Attempts at annealing above this temperature caused one of the phases present in the alloy to melt. Annealing copper at above about 300°C softened the material sufficiently to give the best ramp-shape produced in this investigation. An annealing temperature of about 400°C is probably the best to limit the depth of oxidation on the surface.

Finally figure 3.23 shows the effect of varying the diameter of stainless steel specimen. All were about 5mm long, and the incident pulse was at about the same height for each. As expected from equation 3.1 the height of the elastic/plastic transition is reduced with the area of the sample. The yield load of the 6mm sample is slightly above 1/4 that of the 12mm sample, this is probably due to the strain rate sensitivity of the material.

Three main classes of pulses have now been shown to be available for use in the pulse shaping technique.

(i) Flat topped pulse - produced directly by the projectile, length controlled by projectile length, height by its velocity.

(ii) Trapezoidal pulse, produced as transmitted pulse from
Variable Sample Diameter

Sample Diameter/mm | Incident Pulse Amplitude/%
--- | ---
p148 12.01 | 0.17
p149 10.00 | 0.155
p150 8.03 | 0.17
p151 6.00 | 0.15

All Vertical Scales: 0.0251 %/cm
Horizontal Scales: 12.5µS/cm
Sample Length: 5.0 mm
Projectile Length: 25 cm

FIGURE 3.23 Transmitted pulses from stainless steel samples
most metals. Length controlled by projectile length and height by its velocity. Height also controlled by choice of material, heat treatment, sample diameter and length.

(iii) Ramp pulse—produced as transmitted pulse from softer metals, i.e. lead, pure aluminium and other metals after annealing. Length controlled by projectile length and height by its velocity. Height also controlled by choice of material, heat treatment, sample diameter and length.

3.3 Effect of Incident Pulse Shape on Strain Rate

3.3.1 Experimental Investigation

The conventional two-bar system was used for the application of flat topped pulses. The height of the pulse was controlled by changing the speed of the projectile in the gas gun. For the ramp and trapezoidal incident pulses the Hopkinson bar was modified to the three-bar arrangement shown in figure 3.13. The momentum bar had to be omitted as the optical bench the system was on at that time, was not long enough to include it. The ramp-shaped incident pulse was produced using a 5mm long, 12.7mm diameter copper sample annealed at 400°C for two hours. The trapezoidal pulses were provided by a series of 5mm long stainless steel samples of 6, 8, 10 and 12mm diameter and a constant projectile speed. The 25cm long projectile was used for all these shots to increase the length of incident pulse and so the duration and magnitude of the strain imposed during the test.

The stainless steel samples under test were turned from 12.7mm rod. The proportions were chosen using the criteria derived by Hunter and Davies. A Poisson's ratio
of 0.5 was used, which gave a length of 4.33mm for a diameter of 10.0mm. A diameter of 10mm was chosen, as the stress in a sample of smaller diameter than the bar is greater than the incident stress, enabling lower incident stress to be used. This has the advantage of smaller pulse distortion. It also ensures that the sample faces do not overlap the main bar faces during straining. The samples were finished by rubbing carefully on 600 wet and dry paper placed on a flat surface. They were then checked for length and parallelism. If they deviated from parallel by more than 0.01mm they were rejected. Great care was taken over the alignment of the three bars, as any mismatch of the surfaces could invalidate the results or spoil a particular shot.

3.3.2 Analysis and Results

The stainless steel used in the shots was obtained from the Physics workshop stock, and no record of its purchase and exact type could be found. It is however, an austenitic type steel, with chrome and nickel contents of about 18 and 9.5% respectively.

For the analysis, readings in mV off the reflected and transmitted pulses were scaled from the oscilloscope photographs at 5μs intervals. The values were taken relative to baselines drawn through the pulses which eliminated any background strain or voltage levels. As all the shots were well matched, reflected and transmitted pulses started co-incidently the analysing was started at the beginning of the transmitted pulse.

A simple programme was written to carry out the analysis on a Texas TI 58 calculator, as these tests were performed
before the PET was obtained. The pairs of mV values at each time point, 5μs separation, were fed into the calculator and sample stress and strain noted. When the analysis of a particular shot was complete a graph of sample stress against strain was plotted. The elastic slope was corrected using the same technique as discussed in section 2.5. Figures 3.24 to 3.35 show the results of the analyses. For each incident pulse type graphs of:

(i) stress against uncorrected strain
(ii) uncorrected strain against time
(iii) stress against corrected strain
(iv) corrected strain against time.

3.3.3 Discussion of Results

In the analyses the main source of error was in the scaling of the mV values from the photographs. The values of elastic modulus in the unloading part of the stress/strain curves were reasonably close to the book values, and agreement between shots was good. The overall error of stress, strain and time values is estimated at less than 5%. There were mismatches at some of the pulse shapers: this decreased the duration of the tests, but did not affect their validity.

The initial elastic part of the stress/strain graphs is of lower slope than expected. Wave propagation may be partly responsible for this, but the author believes that most of the error is due to slight misalignment of the bars or surface defects on the sample. The computer simulation carried out by Bertholf and Karnes (1974) verifies the validity of the SHPB technique. The shape of the incident pulse seems to have little effect on the validity of the results. Any inertial
Figure 3.24 Compression tests using flat topped incident pulses - stress against uncorrected strain

For sample dimensions and incident pulses see figure 3.24.

Figure 3.25 Compression tests using flat topped incident pulses - uncorrected strain against time

Sample strain / %

Sample dimensions and incident pulses see figure 3.24.
For sample dimensions and incident pulses see figure 3.24.

Figure 3.26 Compression tests using flat topped incident pulses - stress against corrected strain.

Figure 3.27 Compression tests using flat topped incident pulses - corrected strain against time.
errors are proportional to $\frac{d^2\epsilon}{dt^2}$ and this is reduced in the strain/time curves produced by pulse shaping (particularly for corrected strain/time).

In this type of test it is preferable for the steady plastic strain rate to be preceded by an equal or lower initial rate. This prevents any strain rate history effects (i.e. due to work hardening) affecting the validity of results.

Comparison of figures 3.27, 3.31 and 3.35 show the effect of the different pulse shapes in the sample strain as a function of time. As may be expected the samples subjected to a flat topped incident pulse had an initial high rate of strain followed by a decreasing rate. This meant that shots such p134 and p135 (3.27) which had a low rate of plastic strain had a much higher rate earlier in the cycle. Attempts to use lower flat topped incident pulses lead to the sample not yielding. At the higher rate of strain the flat topped pulse produced a reasonably constant rate.

The samples subjected to ramp-shaped incident pulses had a steadily increasing rate of strain during loading. The use of lower ramp incident pulses again led to the sample not yielding.

The trapezoidal shaped pulse seems to be a good compromise between the extremes of a flat topped or ramp shaped pulse. Figure 3.25 shows the strain/time curves obtained with this incident pulse shape and show the plastic strain rates are nearly constant for most of the loading part of the cycle. This type of pulse also seems to give a better range of control as the plastic strain rates varied between 120 and 980 sec$^{-1}$. 
Sample Pulse Shaper

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>PULSE SHAPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>l_o/\text{mm}</td>
<td>d_o/\text{mm}</td>
</tr>
<tr>
<td>p142</td>
<td>4.02</td>
</tr>
<tr>
<td>p143</td>
<td>4.10</td>
</tr>
</tbody>
</table>

Vertical Scale: 0.053 \text{X/cm}  
Horizontal Scale: 25\text{\mu S/cm}  
Projectile Length: 25cm  
Copper pulse shaper is annealed 2 hours at 400°C  
Stainless steel sample

Figure 3.28 Compression tests using ramp shaped incident pulses – stress against uncorrected strain

For sample dimensions and incident pulses see figure 3.28

Figure 3.29 Compression tests using ramp shaped incident pulses – uncorrected strain against time
Figure 3.30 Compression tests using ramp shaped incident pulses - stress against corrected strain

For sample dimensions and incident pulses see figure 3.28

Figure 3.31 Compression tests using ramp shaped incident pulses - corrected strain against time

For sample dimensions and incident pulses see figure 3.28
Figure 3.30 Compression tests using ramp shaped incident pulses - stress against corrected strain

Figure 3.31 Compression tests using ramp shaped incident pulses - corrected strain against time
Figure 3.32 Compression tests using trapezoidal incident pulses - stress against uncorrected strain

Figure 3.33 Compression tests using trapezoidal incident pulses - uncorrected strain against time
For sample dimensions and incident pulses see figure 3.32.

Figure 3.34 - Compression tests using trapezoidal incident pulses - stress against corrected strain

For sample dimensions and incident pulses see figure 3.32.

Figure 3.35 - Compression tests using trapezoidal incident pulses - corrected strain against time
Comparison of the stress/strain curves obtained for the different incident pulse shapes is difficult as the strain rate histories of the samples differs greatly, and the samples were made in two different batches.

3.3.4 Comparison of Pulse Shaped Shots with Simulation

It was decided to see how the ORACLE computer predictions compared with the actual results. The predictions contained in section 3.1 were not directly comparable to the results here, as the parameters used in the ORACLE programme are not the ones actually recorded, and so fresh computer runs had to be carried out. It was decided to re-write the ORACLE programme for use on the PET micro-computer. The new programme was therefore written in BASIC (called PETACLE) and opportunity was taken to incorporate a few improvements. The most important of these was to enter the material properties and incident pulses as a series of 10 points which would be distributed along the curves as desired to show any detail (i.e. elastic/plastic region) required. This system is more accurate but lacks the flexibility required in the investigation for which the original programme was used. The programme still follows the main flow diagram illustrated in figure 3.1 but at each time interval the increment is decreased less rapidly and more cycles are carried out.

Two of the flat-topped, one of the ramp, and two of the trapezoidal incident pulse shots were simulated, and the results can be seen in figures 3.36 and 3.38. These graphs show the experimental corrected strain against time, compared with the 'predicted' result obtained from the incident pulse and the relevant stress against corrected strain curve. The comparison
For the computer prediction incident pulses were taken from figure 3.24 and material properties from the stress against corrected strain curve, figure 3.28.

For the computer prediction incident pulses were taken from figure 3.28 and material properties from the stress against corrected strain curve, figure 3.30.

Figure 3.36 Comparison of test results using flat topped incident pulses and simulations

Figure 3.37 Comparison of test results using ramp shaped incident pulses and simulation
For the computer prediction incident pulses were taken from figure 3.32 and material properties from the stress against corrected strain figure 3.34.

Figure 3.38 Comparison of test results using trapezoidal incident pulses and simulations.
between the two sets of curves is good particularly with respect to strain rate and strain rate history. The agreement between stress levels is about as good as that between strains (i.e. within about 5%).

This new programme could be used as a tool to decide on which incident pulse to apply to a sample to obtain a required strain rate history. Such predictions could not be as accurate as the ones here, as the material properties would have to be estimated, but would be useful to prevent wasting carefully prepared and expensive specimens.

3.4 Pulse Shaping Technique

As it was found that the stainless steel pulse shapers provided the best means of control over strain rate for the stainless steel samples, it was thought possible that pulse shapers of the same material as the samples may in general be the best solution. As a constant strain rate is normally desired the ideal incident pulse would have the same shape as the material's stress against strain curve with a constant added for the reflected pulse. The use of a dummy sample of the same material gives a transmitted pulse which is automatically of the correct order of shape and size, as it is the stress against time curve for a test of approximately constant strain rate. The faces of the dummy sample are rarely lubricated and so frictional effects will increase its apparent yield point and so add to its transmitted pulse the constant amount required for the 'ideal' incident pulse. Thus a dummy sample of the same material and size as the sample could produce a moderate constant strain rate, 200 - 500 sec\(^{-1}\) in a test.
Variation of pulse shaper diameter and projectile velocity can both be used to control sample strain rate and in many cases one has to be adjusted with respect to the other to prevent an increasing or decreasing strain rate during the test. Increasing projectile velocity or decreasing pulse shaper diameter both tend to prevent a decreasing strain rate during the test. There are obviously minimum values for pulse shaper diameter and projectile velocity required for the test to produce yielding in the sample under test.

The best approach to this type of testing seems to be to start with a dummy sample of the same diameter as the actual sample, varying the projectile velocity to get a feel for the material properties. The strain rate can then be varied by changing the shaper diameter. The projectile velocity in general has to be decreased for smaller diameters and increased for larger diameters. A few test shots are generally required to find the conditions required for differing values of constant strain rate, but all can be analysed and provide valuable information on material behaviour. If such an experimental approach is not successful, particularly for brittle materials, use of the more theoretical techniques in 3.1 will have to be considered.

Specific conditions can then be repeated as required to reduce uncertainty due to the variation often found between different samples. As mentioned previously, at the higher strain rates (above 200 sec\(^{-1}\)) the elastic strain rate is lower than the plastic strain rate; this is because the rise times of less than 10\(\mu\)s cannot be achieved with the current system. If they could, problems in the interpretation of
tests could result from the effects of stress wave propagation in the samples. As most workers in the field of dynamic testing inevitably have this problem, average plastic strain rates are normally quoted, even thought they are not necessarily constant. Only order of magnitude strain rates are generally considered to be of importance, but later results will show that this is not necessarily the case and so maintenance of constant strain rates is important. The rapid variation in strain rate in the lower strain rate shots could lead to inertial effects, also masking strain rate effects.

To illustrate the applicability of the pulse shaping technique, and in particular the use of the same material as the shaper, tests on annealed pure aluminium and aluminium alloy were carried out (figures 3.39 to 3.42). They seemed to be good examples to choose as together with the stainless steel they represent the shape of stress against strain curves found for most materials. Constant (<20% variation) strain rates between 50 and 2800 sec\(^{-1}\) were achieved with aluminium alloy and between 100 and 2100 sec\(^{-1}\) for the pure aluminium. Plots of all the tests carried out on the two materials (figures 3.43 and 3.44) show the general strain rate sensitivity better than the few shots shown in figures 3.39 to 3.42 illustrating the need for a large number of tests to establish material properties. The lower yield point of the aluminium and the low rate of work hardening of the aluminium alloy both meant that pulse shapers were not required for the higher rates. But such good quality tests at the lower rates could have only been achieved using pulse
Figure 3.39 Results of dynamic compression tests on pure aluminium using pulse shaping techniques.

Figure 3.40 Results of dynamic compression tests on pure aluminium using pulse shaping techniques.
Figure 3.41 Results of dynamic compression tests on aluminium alloy using pulse shaping technique

Figure 3.42 Results of dynamic compression tests on aluminium alloy using pulse shaping techniques
Figure 3.43 Strain rate sensitivity of aluminium alloy

Figure 3.44 Strain rate sensitivity of pure aluminium
shaping.

Further tests on stainless steels have shown that with care even the variation in strain rates in the upper curves in figure 3.35 can be reduced as those early tests were carried out by varying pulse shaper diameter only. Figures 3.45 and 3.46 (Ellwood et al (1982)) both show two tests with similar average strain rates, one with and one without the use of a pulse shaper. Variations of a factor of 5 are common when materials such as stainless steel (with a high rate of work hardening) are tested even at high rates of strain (average 1900 sec\(^{-1}\) in curve A of figure 3.45) without pulse shaping. Pulse shaping is thus necessary to provide constant strain rates in Hopkinson bar tests when low rates are required (below 500 sec\(^{-1}\)) or when materials with a high rate of work hardening are tested in compression.
FIGURE 3.45 Stainless steel sample tested in compression.

Sample strain /% 

FIGURE 3.46 Stainless steel sample tested in compression.

Sample strain rate /sec$^{-1}$ 

- - - - - With no pulse shaping. Average strain rate 1900 sec$^{-1}$

- - - - - With pulse shaping. Average strain rate 1800 sec$^{-1}$

Time / µS
CHAPTER 4 TENSILE TECHNIQUE

4.1 Introduction

4.1.1 Background

The requirements of the COVA programme were mainly for dynamic material data obtained from samples tested in tension. One reason is that the models of the deformable vessels were made from thin stainless steel sheet 2mm thick at most. Such material is unsuitable for fabrication of compression test specimens, particularly of the size and shape normally used in Hopkinson bar tests. Another reason is that in the radial expansion of the vessels the material is deformed mainly in tension and so interpretation of dynamic tensile material tests is more likely to yield valuable results.

As no facility for dynamic tensile testing existed at Loughborough before the author commenced research work, such a system had to be built. An opportunity was thus taken to develop a novel modification of the conventional Hopkinson bar apparatus to enable tensile testing, which has some advantages over previous techniques used. Compression and tension samples of 321 stainless steel were provided by A.W.R.E. Foulness to enable a direct comparison of the two modes of deformation and to carry out a suitable series of tests to develop and verify the new technique.

4.1.2 Survey of Dynamic Tensile Techniques

This section describes briefly some of the techniques used by other workers for dynamic tensile testing. The first dynamic tests carried out were tensile tests. J. Hopkinson
(1876) showed that a mild steel wire could withstand twice its normal yield stress when a load was applied suddenly by means of a drop weight. No attempt could be made at this stage to determine stress against strain. When the first attempts were made to measure stress/strain they were generally for compression tests as these are easier to carry out. Experimental studies of elastic and elastic/plastic waves in solids were generally done for compressive waves, as they could be generated by impact with a projectile or detonation of an explosive charge. The significant modification of the basic Hopkinson bar by Kolsky for materials testing was thus made by using thin slices of material which could be sandwiched between two halves of a bar and then loaded in compression. The ease of applying compressive loads meant that all the early work and much current work is carried out in this mode; when certain precautions are carried out valuable data can be obtained.

Most tensile arrangements of the split Hopkinson pressure bar consist of a tubular incident bar surrounding the transmitter bar (Harding et al 1960). These are usually joined at the end of the tube distant from the impact, with the sample on the inner bar in the middle or near the joint. A compressive pulse generated by an impact on the tubular bar is reflected at the bar end as a tensile pulse which propagates along the inner bar and is incident on a sample in the same way as in a compression test. If the sample is midway along the bar the analysis of results can take place in a very similar way to the compressive system. If the sample is near the joint
then a calibration shot has to be carried out with no sample in place. Subtraction of the calibration pulse and the transmitted pulse with a sample will yield the reflected pulse and thus the strain. This has the disadvantage that it relies on a good consistency between shots, but only one channel has to be recorded at a time and this will simplify the electronics required. An alternative sometimes used is to measure strain directly from a strain gauge attached to the sample, but this is limited to low values of strain (< 10%). Major disadvantages of this type of system are the difficulty in passing leads from strain gauges out of the outer tube, and the limiting effect of the end coupling between tube and rod on the rise time of the incident pulses. This technique is, however, very simple and so once established is reliable and large values of strain rate and final strain can be achieved.

The kinetic energy of a rotating fly wheel can be used to impart a tensile load on a sample, the earliest known such tests being by Guillery (1906) where strain rates up to 200 sec\(^{-1}\) were achieved. A more modern version is described by Kawata (1979) and strain rates up to 2600 sec\(^{-1}\) are reported. They also describe a similar device using a swinging pendulum to apply the load, the sample being connected to an output bar fitted with strain gauges. The analysis is then similar to the tensile Hopkinson bar as above.

Isozaki and Oba (1979) report a compact device for dynamic tensile testing, there being no long bars, but the load is applied directly from the detonation of an explosive charge. The stress is measured by a load cell and the displacement
by an etched copper grid under contact brushes and recorded using a simple detector circuit and oscilloscope.

Albertini and Montagnani (1979) report on three means of applying tensile loads to otherwise conventional split Hopkinson bar systems with a tensile specimen screwed into the two halves of the bar. Strain gauges are mounted equidistant from the sample on both bars. The first is the use of explosive charges placed on a fixed mass. When detonated they act on a smaller mass attached to the input bar to load it in tension. The second makes use of a prestressed input bar, the stress being suddenly released by means of the fracture of a brittle bridge attached to the gripping jaws. In the third the apparatus is contained within a shock tube; the experiment is initiated by rupture of a diaphragm. The wave of compressed gas travels down the tube and acts on a plug at the end of the input bar to generate tensile loads in the bar. In their experiments stress is measured by means of a strain gauge on the transmitter bar. Strain is measured by obtaining reflected pulses from input bar, strain gauge on sample, displacement transducers, or the use of a high speed image converter camera (possible only on the first two methods).

The next section describes the tensile apparatus devised by the author. Details of a virtually identical technique were published by Nicholas (1981) after the development and experiments by the present author were complete. A critical discussion of all aspects of the technique will be made later, together with a comparison between the author's system and that of Nicholas.
4.2 The New Tensile System

4.2.1 Basic Principles and Apparatus

One of the criteria considered when devising this modification of the conventional compressive Hopkinson bar for tensile testing was the need for a simple conversion to be made between modes of deformation from compression to tension to enable the use of the existing gas gun system for compressive testing. A system based on a tubular impact bar and inner transmitter bar was considered and would probably have been tried if the new design described next had not proven eminently satisfactory.

The gas gun used with the compression system is used to produce a flat topped compressive pulse in the Hopkinson bars. This new tensile technique makes use of the fact that when a pulse is reflected from a free end it retains its shape but is reversed in sign. This means that the existing system is potentially a convenient and reliable source of flat topped tensile pulses.

The new system is shown in figure 4.1, it is very similar to the compressive rig described in a previous chapter. The bars are of the same material and diameter (431 stainless steel, \( \frac{1}{2} \)" diameter), but the ends are drilled and tapped to fit the specimens. The most important new component is the collar which fits around the specimen and protects it from the incident compressive pulse. The collar is made from a length of \( \frac{1}{2} \)" diameter 431 bar, 16mm long, inside diameter 6mm. With these dimensions the cross sectional area of the collar is 78% of the bars (same material), and so it undergoes only a little more strain than the main bars. The collar and sample are connected in parallel, and
Figure 4.1 Dynamic tensile testing arrangement.

Figure 4.2 Lagrangian showing timing of pulses in dynamic tensile test technique.
so when stressed they are subjected to the same strain. Hence, if the strain in the bars is limited then the sample can be protected from any permanent deformation which could adversely affect the results. This consideration leads to a maximum possible strain rate for this system. When the reflected compression wave is incident on the sample as a tensile pulse, the collar becomes free and therefore is no hindrance to the tensile deformation.

The sample has a much smaller cross sectional area than the bars, and it can be subjected to very great stresses. The technique has the potential for testing very high strength materials due to the stress amplification effect of the small area, and the transmission of the load by the large thread area. The small cross sectional area also means that most of the incident tensile pulse is reflected when sample goes plastic, and this enables constant strain rate tests to be carried out with flat topped pulses at comparatively low dynamic strain rates (50 to 500sec\(^{-1}\)). The main disadvantage of this is that the transmitted pulses are small and can be difficult to record accurately.

Figure 4.2 is a lagrangian diagram while figure 4.3 illustrates the pulses ideally expected at the two strain gauge positions. The initial compressive pulse from the projectile impact, \(\epsilon_{c}\), is transmitted through the collar into the 2nd bar. Unfortunately, this transmission is in practice, imperfect and there is a pulse reflected from the collar back into the 1st bar (not shown in figure 4.3). By arranging that the 1st bar is longer than the 2nd bar, the reflection of this
FIGURE 4.3 Pulses ideally expected in dynamic tensile technique.

FIGURE 4.4 Effect of bending waves on transmitted pulse.

FIGURE 4.5 Effect of 'stress drop' on transmitted pulse.
reflected pulse from the gas gun end will return to SG1 after the transmitted tensile pulse through the sample, and the recording will not be spoilt. By placing SG2 at the centre of the 2nd bar the pulses $\varepsilon_c$, $\varepsilon_i$ and $\varepsilon_r$ in it can be separated sufficiently for the analysis to be carried out.

Figures 4.4 and 4.5 illustrate two problems which can affect the transmitted pulse. Bending waves are not always perfectly cancelled by the strain gauge pairs used, and at the high amplification needed for a good record of the transmitted pulse can cause an apparent oscillation in the stress level (figure 4.4). Most of the bending waves originate at the impact between the projectile and the 1st bar. By using a small (0.5m) extra initial bar in the system, most of the bending waves can be prevented from appearing on the strain gauge records. Figure 4.5 shows the drop in strain level that occurred in most of the early tensile shots immediately after the yield point. As no yield drop had ever been reported in this type of stainless steel, some source of interference was sought. Subtraction of a set of incident and reflected pulses gave a transmitted pulse that still exhibited this stress drop, and so this drop must have originated at the sample. It was found that the drop could be eliminated by packing the threads of the sample with PTFE sealing tape, epoxy resin adhesive, or plasticine. The source of this drop was thus deduced to be in the threads on the sample, probably localised failure as the load was applied.

Sample strain rate was controlled by varying the projectile velocity. For the lower rates of strain (50 to 250sec$^{-1}$) the
appropriate low velocities could not be reliably obtained. Lower amplitude pulses could have been obtained by using a pulse shaping dummy compressive sample, but they were obtained using projectile rods of softer materials (Al alloy and pure Al) than the normal 431 stainless steel. These could be used repeatedly and saved a lot of extra machining and setting up.

### 4.2.2 Effective Gauge Length

The gradually tapered shoulders of the tensile samples (see drawing in Appendix 4) experience some strain when the sample is loaded. To calculate the strain in the 3mm diameter parallel region an effective gauge length longer than its 5mm length needs to be used.

The effective gauge length was firstly determined for static tests. The final strain was found by measuring the change in separation of scratch marks made in the parallel region of the sample. The final engineering strain ($\varepsilon_{sf}$) could then be calculated and the total sample deformation ($\Delta l$) obtained from the test machines chart record (see section 4.3). These are combined to give:

$$1_{\text{eff}} = \frac{\Delta l}{\varepsilon_{sf}}$$

The gauge length can then be used to give the strain in the parallel region if the overall displacement is known. Figure 4.6 shows a plot of measured effective gauge lengths against final strain. This indicates a virtually constant $1_{\text{eff}}$ of 8.3mm. The scatter is in part due to differences between samples and also to errors in measurement. The
Effective gauge length/mm

FIGURE 4.6 Calculated effective gauge length from a series of static tensile tests plotted against final sample strain.
overall trend is for the effective gauge length to decrease with increasing final strain. This trend is confirmed in the analysis by Malmburg (1977) but as it is only slight the gauge length is considered to be constant over the 10% strain measured in tests. Figures 4.7 and 4.8 show how the value of 8.3mm fits in with the sample shape and the final strain profile for a particular test.

The value of 8.3mm was confirmed for dynamic tests by attaching strain gauges to the first few samples tested (see figure 4.9). One benefit of this was to observe the effect of the initial compressive pulse on the specimen. Even at the highest projectile velocities used the strain in the sample did not exceed 0.15% and in all cases was fully recovered.

4.2.3 Discussion

For the purpose of analysis the pulses were recorded on a transient recorder and transferred to a Commodore PET microcomputer. The programme described earlier (chapter 2) was used with only a few slight modifications. The main difference was that the 3rd pulse appearing on channel 2 was required for analysis. This involved the transfer of a larger section of data (650 points per channel instead of 400) and rewriting the programme to select the correct pulse. The baseline of the reflected pulse was corrected for any sloping baseline as in previous work. The stress is calculated using the diameter of the central parallel region of the sample, it is thus measured at the same position as strain. When the stress against strain curves were obtained from the pulses, the elastic modulus was in many cases in
FIGURE 4.7 Initial tensile test sample profile.

FIGURE 4.8 Distribution of decrease in diameter of tensile sample after test.
Shot carried out using 25cm projectile at 15 m/s

Strain gauge:
- Overall length = 5.0 mm
- Overall width = 2.0 mm
- Gauge length = 1.0 mm
- Gauge width = 1.0 mm
- Gauge Factor = 2.01

Detection circuit: Ballast resistance = 2.2 kΩ
Applied voltage = 39.62 V

Recording made using open shutter Polaroid camera mounted on Tektronix 556 C.R.O. single sweep mode. Strain gauge mounted on parallel section at centre of specimen.

Recording:
- Ch1 gain 0.50%/div
- Ch2 gain 2.5%/div
- Timebase 100μs/div

During incident compressive pulse, \( \varepsilon_S \) max = 0.15% (fully recovered)
During test, sample \( \varepsilon_p = 1400 \text{ sec}^{-1} \)

FIGURE 4.9 Signal from strain gauge mounted on sample YWYTI during dynamic tensile test.
good agreement with the expected value. If this was not the case the elastic slopes were corrected as described earlier.

The oscillations in the stress levels still occurred with some shots at the higher strain rates (> 500sec\(^{-1}\)), even with the modifications mentioned above. To obtain some information from these shots a line was drawn by hand through the oscillations on the stress against strain curve. This results in a reduction in accuracy, but when many shots are taken into account the trends in material behaviour can still be observed.

Effects on the measurements due to wave propagation within the samples, and inertia \(\left(\frac{d^2e}{dt^2} \approx 0\right)\) in plastic flow) are not believed to be important, as the gauge length of 8.3mm has a propagation time of less than 2\(\mu\)s and the bulk of the specimen is much less than in compression samples. Comparison with compression tests and further analyses may help to confirm this.

The sample design (Appendix 4) is derived from that used by Albertini and Montagnani on tests carried out under contract for A.W.R.E. Foulness (unpublished results available to author, Albertini and Montagnani (1979)). All the tensile samples were provided for the author, by Foulness, as they were interested in the stress-strain characteristics of type 321 stainless steel in relation to their Nuclear Reactor Safety programmes. The virtually identical design of sample is useful as it allows direct comparison of results; this would have been even more informative if samples fabricated from thin sheets as well as bar could also have been tested.
Figure 4.10 shows three typical oscilloscope traces showing incident, reflected and transmitted pulses. Figures 4.11 and 4.12 are the resultant stress against strain and strain against time curves. The curves in 4.11 are uncorrected and unsmoothed and show some of the difficulties encountered in interpretation and particularly the need for a large number of tests before the trends with respect to strain rate can be established. The curve for the static test RWO1 is also shown for comparison with the dynamic tests. Figure 4.12 shows the constant strain rate obtained in tensile tests with no need for pulse shaping. This is because only a low load needed to strain the narrow sample and most of the flat topped incident pulse is reflected.

In this tensile technique the errors in measurement are similar to those in the compressive tests. An overall accuracy of 5% in stress and strain values can be achieved at moderate strain rates (100 - 500 sec\(^{-1}\)); where oscillations have to be smoothed out then the error in the stress values is about 10%.

Up to 600\(^{\circ}\)C there seems to be little difficulty in high temperature testing. Above this, higher temperature alloys will be needed for the rigs, and the effects of temperature on the pulse propagation may need to be considered for the analysis. The measurement of temperature can be easily and accurately (< 2% error) carried out using a thermocouple welded on to the sample. A small groove has to be cut in the collar to allow the thermocouple to be attached to the
Shot: VWYT1
Sample: 321 Stainless steel L
Projectile: 23cm Al Alloy
Temperature: 200C
Upper true gain: 0.0055%/div
Lower true gain: 0.024%/div
Time base: 50μS/div
Ave. plastic strain rate: 110sec

Shot: GWOT1
Sample: 321 stainless steel L
Projectile: 25cm 431 stainless steel
Temperature: 20°C
Upper true gain: 0.0055%/div
Lower true gain: 0.048%/div
Time base: 50μS/div
Ave. plastic strain rate: 740sec

Shot: VWYT1 (see fig. 4.9)
Sample: 321 stainless steel L
Projectile: 25cm 431 stainless steel
Temperature: 20°C
Upper true gain: 0.0055%/div
Lower true gain: 0.12%/div
Time base: 50μS/div
Ave. plastic strain rate: 1380sec

FIGURE 4.10 Three Oscilloscope traces from dynamic tensile tests.
Figure 4.11 Results of 4 tensile tests on 321 stainless steel

Figure 4.12 Strain against time for 3 dynamic tensile tests on 321 stainless steel
sample. The heater used is that described in chapter 2.

The main problems with this technique were associated with interference with the transmitted tensile pulse. This was made more apparent by the small diameter of the sample producing only small transmitted pulses. The first source of interference encountered was due to the reflection, at the gas-gun, of the incident compressive pulse reflected back from the collar reaching the strain-gauge (SG1) at the same time as the transmitted tensile pulse. This is inevitable if the two main bars are the same length, and the gauges the same distance from the sample. As indicated previously arranging that the first bar is longer than the second this reflected pulse arrives at the gauge after the end of the transmitted pulse. As the projectile speed increased then the amplitude of the bending waves tended to increase. Careful positioning of the gauges, care with the projectile alignment, and a short initial bar before the first main bar all helped to minimise this problem. An even longer first main bar, more care over gauge attachment (making sure that they are exactly opposite) and possibly the use of 3 or 4 gauges at each position would all help to ease this problem in future tests. The stress drop discussed earlier was the worst of the problems to affect the transmitted pulse. At moderate strain rates this could be eliminated by packing the threads of the sample with PTFE sealing tape or epoxy resin. At higher rates (> 500 sec\(^{-1}\)) then the incidence of stress drop increased as the strain rate increased. If high speed tests are to be carried out in future then some alternative material for packing the threads or completely different means of
holding the specimen is required.

Control of strain rate at lower rates of strain (100 to 500sec\(^{-1}\)) is much easier in the tensile tests as most of the incident tensile pulse is reflected, this reasonably flat-topped reflected pulse indicating a fairly constant rate of strain. This is one advantage of the tensile technique over the compressive, where a pulse shaping technique had to be developed for the incident pulse to obtain low constant strain rates. The use of the softer materials (Al and Al alloy) as the projectile was a convenient and re-usable means of producing lower incident pulses, but would be of little use for compressive testing except for very soft materials. As in the compressive tests the final strain is limited to the product of the average strain rate and the incident pulse duration (approximately 100\(\mu s\) using 25cm long projectile).

One distinct advantage of the tensile technique is the potential for testing high strength materials. In the compressive tests the sample stress is limited by the yield point of the bar material. In the tensile tests the stress is limited by the load that can be transmitted by the sample attachment to the bar.

The major disadvantage is that not all materials are suitable for machining into threaded tensile specimens (i.e. minerals, ceramics), and very low strength materials would produce even smaller transmitted pulses. Even for metals the production of tensile specimens is more difficult and costly than for compression.

The strain rate attainable with the collar system is
limited to a maximum of about 1500 sec\(^{-1}\) by the size of incident compression pulse that can be transmitted by the collar without causing any permanent deformation in the sample. This is not a serious limitation as above about 1500 sec\(^{-1}\) problems such as wave propagation in the sample and inertial effects could also limit the validity of the tests. With compression tests the samples have a much shorter length and their proportions are calculated to eliminate inertial effects. This means that higher strain rates can be reached without affecting the validity of results.

Comparison with the more conventional tensile technique of a tubular incident bar around an inner solid transmitter bar leads to several advantages and disadvantages of this system. Its drawbacks include the limit imposed on the amplitude of the incident pulse due to the possibility of permanent deformation of the sample by the initial compressive pulse on passing through the sample and collar. Another is that the limit on the length of pulses used is more severely limited by the bars, the 2.5m system used can only really be used with a maximum of 100 μs long pulses. The major advantage and reasons for its use were the ease of conversion between compression and tension, simplicity of construction and ease of access for strain gauge leads and furnace around the sample. One disadvantage of the conventional system is the limit imposed on the rise time of the incident pulse (> 20 μs) by the joint between outer tube and inner bar. This point is also true of most other tensile systems constructed and was the major advantage listed by Nicholas (1981) for the development of his apparatus. The apparatus described by Nicholas is identical
to that developed by the author. Main differences are the calculation of strain from a calibration only at static rates and no mention is made of the problems of a stress drop after yielding, possibly achieved by better fitting of screw threads in sample and bars.

4.3 Static Tensile Tests

For the static tests the samples were loaded in an Instron 1026 test machine (figure 4.13). This machine has a cross-head which can be driven at a constant rate, and has a pen recorder built into it which provides a graph of load against extension. The samples were mounted in a simple adaptor made to fit the universal joint supplied, and the base of the machine. The extension rate was fixed at 0.5mm per minute. For the first few tests, strain gauges were attached to the samples and their output recorded on a y-t pen recorder. These indicated a constant plastic strain rate of 0.00165sec\(^{-1}\) from which an equivalent gauge length of 8.3mm was calculated. This was confirmed in the subsequent static tests (including those at high temperatures) by measuring the distance between two marks on the parallel part of the specimen before and after loading.

Because of the compliance of the adaptor and other components, the elastic slope of the load extension curve has to be corrected using tabulated static values (figure 4.14) at the temperatures used. The calculation of true stress and strain had also to be carried out; this was done using a simple programme on the PET microcomputer, which produced a graphical output similar in form to the dynamic tests.
FIGURE 4.13 Static tensile testing arrangement.
Crosshead speed = 0.5 mm/min  
Load cell = 500 kg f.s.d. 

Paper speed = 100 mm/min 

FIGURE 4.14 Sample extension from test machine chart.
4.4 Tests on 431 Stainless Steel

4.4.1 Background

The material used for all the Hopkinson bars used by the author was 431 martensitic stainless steel. This was chosen mainly because of its high yield point. Tests have had to be carried out to characterise this material, particularly in terms of elastic modulus, yield stress and velocity \( C_0 \) of elastic longitudinal stress waves.

The dynamic results presented at the end of this section also serve to illustrate the application of the tensile technique to a high strength material.

4.4.2 Pulse Velocity

The first of these tests was to measure the velocity of elastic longitudinal stress pulses in a \( \frac{1}{4} \)" diameter 431 rod of the same type as used for the Hopkinson pressure bars. A 1 metre length was inserted into the gas gun and the output of only one strain gauge recorded on the transient recorder. The other channel of the recorder being used to record 100\( \mu \)s timing pulses produced by a Racal time-counter. Figure 4.15 shows the arrangement used in this test and figure 4.16 the oscilloscope trace recorded. The transient recorder was used on the 2\( \mu \)s sweep, the same sweep as used in the material property tests. The points stored in its memory were passed into the PET microcomputer which had been programmed to print out a list of the data points. The leading edge of the timing pulses were at 100\( \mu \)s intervals and equivalent points on 3 pulses were separated by 300 data points. The data points were therefore recorded at an interval of \( (1 + \)
FIGURE 4.15  Arrangement for measurement of pulse velocity bars.

FIGURE 4.16  Oscilloscope trace showing pulses in 1 metre bar and 100μS timing pulses.
0.003)\mu s. The time for a pulse to reflect off the
the bar ends twice and return to the strain gauge was
recorded as it made the measurement insensitive to gauge
position. The distance travelled was therefore (2 ±
0.002)m and the time interval for points at the same point
on the pulses was (384 ± 1)\mu s. The velocity of the
pulse was then calculated to be (5208 ± 20)ms⁻¹.

4.4.3 Resonance Experiment

A resonance technique was also used to determine the
longitudinal wave velocity in the bar (figure 4.17). The
rod was excited by means of an electro-magnetic transducer
acting magnetically on a small disc of radio-metal bonded
to the ends of the rod. The radio-metal disc could be
omitted as 431 is a magnetic material. The rod ends are
thus excited without contact with the transducer and can be
regarded as free. The rod resonates when both ends vibrate
with maximum amplitude, the vibration being detected by
means of a similar transducer to the exciter. Resonance
occurs when

\[ L = \frac{n\lambda}{2} \]

where \( n \) is an integer indicating the mode of the vibration,
\( L \) is the rod length and \( \lambda \) the wavelength of the oscillation.
The resonant frequencies are thus given by

\[ f_{\text{res}} = \frac{C_0}{\lambda} = \frac{nC_0}{2L} \]

After careful adjustment of the signal generator, taking
an average of 10 attempts, the frequency of the first mode
of oscillation (\( n = 1 \)) was found to be 2.636 ± 0.003 kHz.
Higher modes could not be accurately measured as the
FIGURE 4.17 Arrangement for resonance experiment.

FIGURE 4.18 Resonance modes in bar.
<table>
<thead>
<tr>
<th>VELOCITY $c_0/\text{ms}^{-1}$</th>
<th>DENSITY $\rho/\text{gcm}^{-3}$</th>
<th>ELASTIC MODULUS $/10^11\text{Nm}^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values for pulse propagation</td>
<td>5208 ± 20</td>
<td>2.10 ± 0.02</td>
</tr>
<tr>
<td>Values from resonance experiment</td>
<td>5219 ± 8  7.755 ± 0.015</td>
<td>2.11 ± 0.01</td>
</tr>
<tr>
<td>Values for tensile tests</td>
<td>2.06 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Values used in calculation of dynamic stress and strain</td>
<td>5220  N/A</td>
<td>2.11</td>
</tr>
</tbody>
</table>

**TABLE 4.1** Summary of properties of 431 stainless steel obtained in various experiments and used in subsequent calculations for Hopkinson bar tests.
amplitude was not great enough to trigger the timer-counter. This was for a rod length of 0.990 ± 0.005m, and application of equation 4.3 yields a value for $C_0$ of 5219 ± 8ms$^{-1}$. The density of the bar was found by weighing and measuring the volume giving a value of $7755 ± 15$kgm$^{-3}$. Values of elastic modulus could then be calculated from the values of average velocity and density since $C_0 = \sqrt{E/\rho}$. Table 4.1 summarises results obtained and gives the values of velocity and modulus previously used for Hopkinson bar analyses. All results presented in this work used a value of 5220ms$^{-1}$ for velocity and $2.11 \times 10^{11}$Nm$^{-2}$ for modulus.

4.4.4 Static Tensile Tests

Some tensile test samples, similar in shape to the 321 samples were manufactured from a length of 6mm diameter 431 stainless steel. As the shape was slightly different and the quality of finish not so good a constant value of 8.3mm could not be assumed for the gauge length. For all these samples a strain gauge was thus attached in the central parallel region. Figure 4.19 shows the circuit used for the static tensile tests. An out of balance Wheatstone bridge circuit was used for the static tests as it could be balanced to give zero output for no strain, (unlike the ballast resistor circuit) and was therefore more suitable for 'd.c.' measurements. Calibration of the circuit by putting standard resistors in series with the strain gauge and measuring the output (figure 4.20) showed that for small strains the output is linear. Such a circuit is generally non-linear, but it can be regarded as linear for small changes in resistance value.
Figure 4.19 Strain gauge circuit used for static tensile tests.

Figure 4.20 Calibration of strain gauge circuit used for static tensile tests.
The strain was recorded by plotting the output of the detector circuit on a y-t pen recorder. The load is recorded on the pen-recorder on the Instron test machine. Two loading/unloading cycles were performed on each of the two samples tested. The stress against strain curves obtained for one of these are presented in figures 4.21 and 4.22. They both show non-linear loading on the first cycle, but a straight line for the unloading and the second cycle. The average value of slope for the first sample was $1.97 \times 10^{11} \text{Nm}^{-2}$ and for the second was $2.06 \times 10^{11} \text{Nm}^{-2}$. Assuming an error of about 5% on these values, they are both consistent with those obtained in the pulse propagation and resonance experiments. The second loading in figure 4.20 shows that the material can behave with linear response with stresses above $7 \times 10^8 \text{Nm}^{-2}$. This value can only be obtained by work hardening as on initial loading the material became non-linear at only half this value.

4.4.5 Dynamic Tensile Tests

Some dynamic tensile tests were carried out on the 431 sample using the techniques detailed in 4.2. The major differences were the fact that sample strain gauge outputs had to be obtained for all tests analysed and the use of plasticine to pack the sample threads. The use of the plasticine was very successful and it is unfortunate that the 321 samples had all been tested before this change was tried. As three channels were recorded, these tests relied on the use of a strain gauge and amplifier to trigger an oscilloscope in the single sweep mode. The traces were
Figure L.21 First tensile loading/unloading cycle on l31 sample

Figure L.22 Second tensile loading/unloading cycle on l31 sample
then recorded using a polaroid camera with an open shutter. Figure 4.23 shows the traces obtained for two loading cycles on a single sample and 4.24 the stress against strain curves. The first cycle applies a much higher strain than is usual in the stress pulses, but with the second cycle shows that the material is capable of being work-hardened to behave linearly with stresses above $10 \times 10^8 \text{Nm}^{-2}$. This material differs from the austenitic steels in that the work hardening only continues up to about 2.5% strain. Values of elastic modulus from these tests vary greatly, but the average value of $2.06 \times 10^{11} \text{Nm}^{-2}$ shows that the values are consistent with those obtained previously. The lower values of modulus obtained in these tensile tests could be due to the fact that the 431 is from a different source and in a slightly different form than the Hopkinson bar material, but they are consistent with the more precise measurements from the other techniques.

The dynamic tensile tests on 431 stainless steel demonstrate the use of the tensile technique for testing very high strength materials which could not have been tested easily in compression. Repeat tests on some of the samples showed onset of necking; this occurred in the centre of the parallel region and is consistent with equilibrium loading of the sample.

The static tests put the yield point, (limit of linear behaviour) of the 431 at over $7 \times 10^8 \text{Nm}^{-2}$, and the dynamic tests show that this can be extended to over $10 \times 10^8 \text{Nm}^{-2}$ by sufficient work hardening. These tests show the need
Transmitted pulse gain = 0.024 %/div

incident & reflected pulses gain = 0.047%/div

Tensile test on 431 sample bar gauge signals

Sample gauge gain = 2.32%/div

Sample gauge gain = 0.47%/div

Tensile test on 431 sample sample gauge signals

Transmitted pulse gain = 0.024%/div

Sample gauge gain = 0.47%/div

2nd bar gauge signal gain = 0.024%/div

Timebase = 100μS/div

Second tensile test on 431 sample (same one as above) bar and sample gauge signals

FIGURE 4.23 Oscilloscope traces from dynamic tensile tests on 431 stainless steel samples.
FIGURE 4.24 Two stress/strain cycles for tensile test on 431.
for the application of several high velocity impacts on the bars before they are used as part of a split Hopkinson bar system used at high stress levels. The impacts are usually applied before de-magnetisation and attachment of strain gauges. The value of elastic modulus of the 431 bars is used in the determination of the sample stress and was found to be $2.11 \times 10^{11} \text{Nm}^{-2}$ by several methods; this value is consistent with the values obtained in tensile tests on samples of similar material. The value of $C_0$ used in the analysis of reflected pulses for the determination of sample strain was found to be $5220 \text{ms}^{-1}$; this was obtained by means of pulse propagation and resonance experiments.
CHAPTER 5 RESULTS OF TESTS ON Austenitic Stainless Steels

5.1 Tensile and Compression Tests on 321 Bar Material

5.1.1 Introduction

This series of tests was proposed by A.W.R.E. Foulness who supplied materials and ready finished samples. The object was to have data from a more detailed study of 321 available, and to establish the validity of techniques carried out at Loughborough. The main feature of this series of samples is that they are all taken from material from the same melt, more than enough for all samples being ordered initially. The material came in the form of six 3" x 1" section bars, each approximately 3m long. The grade received was 321S12, from BS970. After the bars had been rolled to size they had all been annealed and descaled before supply to the stockists. The initial appearance of the steel was thus a rough matt grey finish. Samples were taken from five of these lengths, each one being designated a colour code. Appendix 4 contains the documents supplied by Foulness to the contractors who prepared the samples. They show how every sample is colour coded to indicate bar position within a bar and direction of major axis with respect to initial rolling direction. The samples with their axis parallel to the rolling direction are designated 'L' type (white), and those with their axis perpendicular to rolling direction 'Q' type (black). Equal numbers of L and Q type samples were included in the 120 compressive and 120 tensile samples prepared. All material offcuts were saved and had a numerical code etched on the surface indicating bar and position. Most of the techniques used in manufacture are
indicated in appendix 3. All samples were cut from the bar material in the form of square blocks by use of a bandsaw and turned to shape on a lathe. Care was taken in all cases to use coolant and sharp tools to minimise the effect of machining on the sample properties. The sides of the tensile and compressive samples were thus a fine turned finish. The threads on the tensile samples were cut on a lathe rather than using a die to prevent twisting the sample and thus causing work hardening. The specification on the drawing for the compressive samples (appendix 4) for the surface finish and for the parallelism of the faces is better than could be achieved on a lathe. The contractors used by Foulness had in fact to sub-contract the final finishing of the compression sample faces to another firm (a manufacturer of optical instruments) and the quality obtained was then much better than the specification.

5.1.2 Tensile Tests at Room Temperature

The tensile samples were received first and so the tensile tests were completed before compressive tests on these samples were started. The techniques used were as detailed in Chapter 4, with all the dynamic tests using the modification of the split Hopkinson pressure bar developed by the author. All the tests at room temperature were performed with the threads of the samples filled with P.T.F.E. sealing tape. This material could not be used at elevated temperatures and so the threads were not filled. As the samples had a lower yield stress at elevated temperatures, problems with stress drop were not as important as at room temperature, and so the omission of a thread filler material was not too detrimental to the results.
obtained. As the cross-sectional area of the tensile samples is only small (approx. one tenth of the compression samples) only low amplitude incident pulses were required to produce yield in the samples, and flat topped pulses were adequate to ensure constant strain rate. The lower range of speeds (approx. 4ms\(^{-1}\)) available on the original 2\(^{\prime}\) diameter gas gun was used with low density projectiles to produce smaller amplitude pulses than could be reliably obtained with the slowest speeds and the 431 projectile. These projectiles were made from a 18cm length of pure aluminium and a 23cm length of aluminium alloy and unlike pulse shapers were re-usable. Static tests were performed in the Instron machine and all high temperature tests used the heating coil described in Chapter 3.

Only those shots successfully completed and analysed are shown on the graphs (figures 5.1 to 5.10 for tensile tests). Several tests, particularly at high strain rates, suffered from interference due to the bending waves; others could not be analysed due to other faults in the system. Plastic strain rate is shown for each shot analysed and stress at strain levels between 0.5 and 10\% are plotted. These points are taken directly from the true stress against true strain results produced by the computer.

For the tests at 20\(^\circ\)C the stress at various strain levels is plotted against plastic strain rate, figure 5.1 being the results for L type samples and 5.2 for 'Q' type samples. These graphs indicate the strain rate sensitivity of the material. The data for stress at strain equals 0.5\% are the most complete as these include the curves from the lowest (about 100sec\(^{-1}\)) dynamic strain rate tests. This strain level is also useful as it is
in all the cases shown that the strain immediately after yield point, and so the stress at this level, is a good measure of yield point. As there was no abrupt yield with the stainless steels tested, the limit of proportionality was difficult to measure reliably. The 0.2% proof stress was also difficult to measure as it could depend on small changes in the shape of the elastic/plastic region of the stress against strain curve. The stress at 0.5% strain is in this case very close to the 0.2% proof stress as the offset before yield is about 0.2% to 0.3%. The curves in figures 5.1 and 5.2 at strain equals 0.5% therefore show the variation in the material's yield point with increasing plastic strain rate. The L and Q type samples show very similar behaviour, with a large increase (approx. 25%) in yield point between the static tests and those at low dynamic rates (100 - 200sec\(^{-1}\)).

Above strain rates of 200sec\(^{-1}\) the increase in yield point with strain rate is less rapid. By taking points from the best fit curves through the points in figures 5.1 and 5.2, plots of stress against strain for any strain rates (in the range shown) can be plotted. Figure 5.3 shows the static curves and curves at rates of 200, 500 and 1500 sec\(^{-1}\) for both 'L' and 'Q' type samples. The main feature of these curves again is the increasing yield point with increasing strain rate. They also show a close agreement between 'L' and 'Q' type samples. The difference at 1500sec\(^{-1}\) being due to a single high result from a 'Q' type sample. The errors at this high strain rate are about 10% in stress, due to oscillations on the transmitted pulse, which had to be smoothed to obtain the points plotted.
Figure 5.1 Tension 321 bar, 20\(^\circ\)C, L type

Figure 5.2 Tension 321 bar, 20\(^\circ\)C, Q type
FIGURE 5.3 Tensile 321 bar, 200°C, L & Q type.
The stress against strain curves in figure 5.3 have to be treated with some caution. They are obtained from best fit lines smoothed through data obtained from smoothed stress against strain curves obtained from the computer, and so they are twice removed from the original data. The alternative method is to take a group of tests at a given nominal strain rate and to plot averaged stress against strain curves attributed to an average strain rate. As the degree of smoothing required for tensile tests increases with strain rate, this procedure is illustrated for a group of tests carried out on 'L' type tensile samples at a high average strain rate of 1510 sec\(^{-1}\) (figure 5.3a). The assumed average line is not taken through the arithmetic mean of the curves illustrated but is smoothed to indicate the most likely real material behaviour, estimated to have an error of ± 10\% in stress level.

Figure 5.3b compares the averaged curve obtained in figure 5.3a with similar ones obtained from groups of tensile tests with average strain rates of 490, 200 and 0.0016 sec\(^{-1}\). The elastic slope has been corrected, to enable comparison to be made with figure 5.3. The degree of smoothing required for the curves at below 500 sec\(^{-1}\) was negligible. They have an estimated error of ± 5\% in stress level, mainly due to sample to sample variation. The curves in figure 5.3b show very similar trends to those in figure 5.3, but are likely to be more reliable as they are more directly obtained from the initial stress against strain curves. However, curves obtained from the technique used for figure 5.3 are presented for the tensile data to enable comparison with the compression data.

The estimated error for the average curve at 1510 sec\(^{-1}\) of 10\% is greater than the approximately 5\% difference in yield stress between the tests at 490 and 1510 sec\(^{-1}\). A trend of increasing yield
Sample Stress (at $\varepsilon_r = 0.5\%$)/MN/m$^2$

Figure 5.3a Tensile 321 bar, $20^\circ C$, L type, experimental curves at strain rate $= 1500$ sec$^{-1}$.

Sample Stress (at $\varepsilon_r = 0.5\%$)/MN/m$^2$

Figure 5.3b Tensile 321 bar, $20^\circ C$, L type, averaged curves.
stress with strain rate in this region could therefore not be unambiguously reported from the tensile tests on 'L' type 321 bar. The extent of the trend has a large degree of error, as illustrated by the fact that the difference in stress at these two levels for the results in figure 5.2 is approximately double that for those in figure 5.1.

The trends at lower strain rates, less than approximately 800 sec\(^{-1}\), are more significant with respect to the errors in stress level of 5\%, due to the much lower degree of smoothing required. The curves in figure 4.11 illustrate the increase in reliability of the test with decreasing strain rate, and also the need for interpretation of trends from a large amount of averaged data if the error associated with the tests is great.

The curves for the lower dynamic rates........
do not cover as wide a range of strain as those at higher rates due to the fixed pulse length limiting the strain obtained in the test. Extrapolation of these curves parallel to the higher strain rate curves would probably give a good indication of the material properties in these regions if required. A final point to be noted from figure 5.3 is that the work hardening rates for the dynamic curves is marginally greater than those when samples are tested statically.

5.1.3 Tensile Tests at Elevated Temperature

The data obtained from the elevated temperature tests are shown in figures 5.4 to 5.10. There are less data available for each temperature than at room temperature as only half of all the batch of tensile samples were tested at elevated temperature. Figures 5.4 to 5.7 show plots of stress at various strain levels against plastic strain rates for temperatures of 150, 300, 450 and 600°C respectively. Points for both 'L' and 'Q' samples are shown on these curves to show any trends more clearly. These graphs show clearly that the increase in yield point between static tests and rates of about 200sec\(^{-1}\) is reduced at a testing temperature of 150°C and is not present at 300°C and above. The steady rise in yield point with strain rate above 200sec\(^{-1}\) appears to remain, but the curves at 450°C and 600°C show an abrupt rise above 1000sec\(^{-1}\). This again is due to high results from a few samples in a region where oscillations on the reflected pulse reduced accuracy. Further tests to check on this trend were not possible due to the limited supply of tensile samples and comparison with similar compression tests will have to be made. A good way of displaying the high temperature data is to plot stress at 0.5% strain.
Figure 5.4 Tension 321 bar, 150°C, L and Q type

Figure 5.5 Tension 321 bar, 300°C, L and Q type
Figure 5.6 Tension 321 bar, 450°C, L and Q type

Figure 5.7 Tension 321 bar, 600°C, L and Q type
against temperature at differing strain rates. By taking points of the lines of best fit in figures 5.4 to 5.7 this can be achieved. Figure 5.8 demonstrates the effect of decreasing yield point with increasing temperature. There being a large drop between room temperature to 150°C and a more gradual fall up to 600°C. The merging of the 500 and 200sec\(^{-1}\) curves with the static curve shows the decreasing strain rate sensitivity with temperature. The increase in yield point between 500 and 1500sec\(^{-1}\) seems to remain constant with changes in temperature. Figures 5.9 and 5.10 show stress against strain curves for temperatures of 20, 150 and 600°C, for static testing and for dynamic testing at 1000sec\(^{-1}\) respectively. They show that the material has an increased temperature sensitivity with increasing strain rate. Both show a slight tendency for decreasing work hardening with increasing temperature.

5.1.4 Investigation with Initial Compression Samples

As discussed earlier the compressive samples were made from the same 3" x 1" bar of 321 stainless steel as the tensile samples. They were from locations nearer the ends of the bars than the tensile samples. The finish of the sample faces was of an optical quality and the samples were made flat and parallel to within a few μm. This is probably better than is required for the SHPB method, the quality of matching then being limited by the quality of the bar end faces. Initial tests with these samples shows an excellent matching of the sample and bar faces. This is shown by the traces in figure 5.11 which indicate reflected pulses with no evidence of mismatch due to misalignments.

Some preliminary compression tests had been carried out
FIGURE 5.8 Tensile: 321 bar, 'L & Q type, all at $\varepsilon_s = 0.5\%$
Figure 5.9 Tension 321 bar, L and Q type, all static

Figure 5.10 Tension 321 bar, L and Q type, all at $\dot{\varepsilon}_s = 1000$ sec$^{-1}$
All the above were using the 25cm projectile in the new gas gun and Hopkinson bar rig (details at later date).

All vertical gains 0.118%/div. (Bar modulus = 2.11 x 10^9 Nm^-2)
All horizontal gains 50μS/div.

Figure 5.11 Oscilloscope traces showing good pulse matching obtained when using initial 321 compression samples supplied by Foulness.
on samples prepared by the author from the 321 bar material. These showed good agreement in terms of yield stress and strain rate sensitivity with the tensile tests. It was then very disturbing to find that the results of tests from the Foulness compression samples showed very different results. The yield points were generally lower than for the tensile tests and there was no evidence of strain rate sensitivity (figure 5.12).

Lower yield stress and lack of strain rate sensitivity were reported by Albertini and Montagnani (1979) as being typical of annealed austenitic stainless steel. This led to a consideration of the manufacturing processes, in particular the difference between that for tensile and compressive samples, to see if there had been any heating effects to cause the discrepancy. Enquiries were made to the contractors who prepared the samples and the author received assurances that the temperature of the material did not exceed 150°C during manufacture. Tests on samples pre-heated to temperatures of up to 400°C were carried out with no noticeable change in the mechanical properties. Such temperatures were sufficient to impart a gold coloured tint to the surface of the material; no such discolouration could be found on any samples or offcuts.

To investigate the cause of the discrepancy further a preliminary metallurgical investigation was carried out on the samples, the original material, and a few other cases. All faces under examination were cut using a hacksaw (under coolant) and filed flat. The samples were mounted in 30mm bakelite mounts which involved heating to 150°C and abraded using successively finer grades of wet and dry paper down
FIGURE 5.12 321 bar, 20°C, L & Q type, all at $e_s = 0.5\%$
to 1200 grade. The faces were then polished using 6 and then 1 micron diamond paste on polishing wheels. They were then etched using marbles solution as described in section 6.1 in the next chapter. All photographs shown were taken using a polaroid camera mounted on a Vickers microscope at 100X magnification.

The number one, or red bar of 321 was chosen for investigation, and figure 5.13 shows micrographs taken from the initial offcut at the end of the bar, material similar to that tested in the preliminary tests on the author's own samples. Faces across the rolling direction ('Q') and parallel to it ('L') are shown. Both show fairly large grains of about 0.1 and 0.2mm across. These are just visible to the naked eye after the sample has been polished and etched.

Figure 5.14 shows the micrographs obtained for an 'L' type sample from the red bar (RWGC1). Both the 'L' and 'Q' faces show large grains in the centre, similar to the offcut material and much smaller ones (0.03 to 0.05mm) nearer the edges. The sketch in the figure 5.14 shows one possible orientation, but as the sample is circular the fine grain regions could just as easily be parallel to the top and bottom faces of the bar. Figure 5.15 includes micrographs from a 'Q' type sample made from the red bar (RBBC1). Both 'L' and 'Q' faces show smaller grains across their width, similar to those at the edges of the 'L' type sample.

A tensile sample (from the yellow bar) was sectioned, polished and etched and it was shown to consist of the larger grains. The evidence obtained thus far was consistent with
FIGURE 5.13: Micrographs from initial effect of Number 1 321 bar.
Fine grain structure at edges
Course grain structure at centre

Q face near centre

Q face near edge

FIGURE 5.14 Micrograph from L type compression sample prepared by Foulness from Number 1 321 bar.
FIGURE 5.15: Micrograph from Q type compression sample prepared by Foulness from Number 1 321 bar.
some effect introduced during manufacture, and in particular
with an effect caused by the bandsawing of the blanks from
the 3" x 1" bar. The orientation of the sample in figure 5.14
and the fact that any heat affected zone would be removed when
tensile samples are turned seems to support this.

To investigate this possibility the author performed a
trial cut with a bandsaw. The material used was an offcut
from the 321 bar known to contain large grains. The conditions
used were those recommended for stainless steel, i.e., a 15
teeth per inch blade and a speed of 70 feet per minute. A
cutting speed of only 1mm/min could be achieved, possibly
due to a blunt blade. Using a thermo-couple attached to the
bar, a temperature rise of only 75°C was recorded 5mm away
from the saw-cut and this was without any coolant. To observe
any effects of the sawing on the micro-structure a section
was taken through the material adjacent to the cut face and
polished and etched. The resultant micrograph, (figure 5.16)
shows the saw-cut on the left-hand side. The large grained
structure of the material is unaltered to within 0.05mm of the
saw-cut and is probably unaffected to even nearer. As at
least 1mm of material is removed between any band-saw cut and
a sample, it is apparent that the fine-grained structure was
not caused by the sawing.

A metallurgical examination of the off-cut material was
carried out when further off-cuts were supplied by Foulness.
The benefits of retaining and numbering all of the off-cut
pieces were then seen. The grain structure of the off-cuts
was identical to the adjacent samples. In the case of the
'1' type sample (see figure 5.14) the regions of fine
FIGURE 5.16 Micrograph taken adjacent to bandsaw cut in offcut of Number 1 321 bar.
grain were in the upper and lower surfaces of the bar. The 12cm off-cut adjacent to the 'L' type samples of the red bar was particularly interesting as it showed a large grain structure at the end near the initial off-cut, a transition region in the centre near to the sample examined and fine grains across its width at the end nearest to the 'Q' type samples. There was thus a factor of four change in grain size in this short length. This region was possibly the site of a joint in the bars when manufactured, or a region where there was a sudden temperature change. This transition between large and small grains has been observed in three of the five bars used for sample manufacture. It has been found to occur in the region of the 'L' type compression samples in bar 1 (red) and bar 5 (violet). Its location has not been found in bar 4 (orange).

Static tests on some of the compression samples were carried out and the results are summarised in table 5.1. The average yield point of the 'L' type samples at 255MNm\(^{-2}\) is significantly lower than for the initial off-cuts at 301MNm\(^{-2}\). The average value for the 'Q' type samples at 286MNm\(^{-2}\) shows good agreement with both 'L' and 'Q' type tensile tests. As the 'Q' type compression samples are taken from the bars adjacent to the tensile samples this agreement shows that they could possibly be useful for comparison with tensile results. The lower yield point value for the 'L' type and the changes in grain size both mean that any mechanical tests on these samples will not be particularly useful for comparison with tensile tests.
Sample stress values at $\varepsilon = 0.5\%/$MNm$^{-2}$

<table>
<thead>
<tr>
<th>bar no.</th>
<th>Foulness prep. L type comp.</th>
<th>Foulness prep. Q type comp.</th>
<th>Own prep. initial off-cut</th>
<th>Average for bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270</td>
<td>300</td>
<td>315</td>
<td>295</td>
</tr>
<tr>
<td>2</td>
<td>245</td>
<td>285</td>
<td>300</td>
<td>276</td>
</tr>
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<td>3</td>
<td>240</td>
<td>270</td>
<td>300</td>
<td>270</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>270</td>
<td>285</td>
<td>268</td>
</tr>
<tr>
<td>5</td>
<td>270</td>
<td>305</td>
<td>305</td>
<td>293</td>
</tr>
</tbody>
</table>

Average for sample type

| Average for sample type | 255 | 286 | 301 |

**TABLE 5.1** Results for static compression tests on 321 samples taken from differing region of bars.
5.1.5 Tests on Final Compression Samples

After discussion with Foulness it was decided that they should supply a second set of 120 compression samples, manufactured in their own workshop. These new samples were to be made from the off-cuts left from the manufacture of the tensile samples. These were the same size as all other compression samples at 10.00mm diameter and 4.33mm length. To reduce manufacturing time the tolerance on the faces being parallel was changed to + 0.01mm and the length to + 0.1mm. They were supplied with a fine turned finish and were further finished by the author using 200 wet and dry paper to remove the turning marks. The quality so obtained was thus similar to the samples produced entirely by the author (see section 2.4).

Pulse shaping was used for all these tests to maintain a reasonably constant strain rate. Figures 5.17 and 5.18 are the sample stress at constant strain levels, against plastic strain rate for 'L' and 'Q' type samples. Considering the stress at 0.5% strain as a measure of yield point, there is a fairly rapid increase with strain rates up to 400sec\(^{-1}\) for both 'L' and 'Q' type. Above 400sec\(^{-1}\) the strain rate sensitivity is reduced. Figure 5.19 shows stress against strain curves at constant strain rates, obtained by interpolation of points on figures 5.17 and 5.18.
Figure 5.17 Compression 321 bar, 20°C, L type

Figure 5.18 Compression 321 bar, 20°C, Q type
FIGURE 5.19 Compression 321 bar, 20°C, L & Q type.
Figure 5.19b shows stress against strain curves obtained by averaging groups of tests conducted at similar strain rates. Figure 5.19a illustrates one of the groups used, with an average strain rate of 1860 sec\(^{-1}\). The average line is taken through the arithmetic mean of the curves plotted, no smoothing being required. The trends that can be obtained from examination of figures 5.19 and 5.19b have a much greater confidence level than with the tensile curves (figure 5.3 and 5.3b).

Control of strain rate at exact values is difficult with compression tests. It is more convenient to use the technique of producing stress against strain curves from best fit lines drawn through stress against strain rate plots at given strain levels. This technique allows the stress against strain curves for different series of tests to be drawn at equivalent strain rates to enable comparisons. It also means that tests at intermediate strain rates can also be taken into account and thus increase confidence in the trends obtained from the averaged stress against strain curves. As little smoothing is required for the stress against strain curves obtained from individual compression tests, the two plotting techniques are equivalent.

Figure 5.19 shows that for compression tests on 'Q' type samples flow stress levels are about 300M\(\text{N/m}^2\) higher than for 'L' type samples. The work hardening rate is the same for both 'L' and 'Q' types and is little changed by strain rate.
Figure 5.19a  Compression 321 bar, 20°C, L type, experimental curves at strain rate ≈ 1850 sec⁻¹.

Figure 5.19b  Compression 321 bar, 20°C, L type, averaged curves.
The static compression tests at elevated temperatures were performed using silicone spray lubricant between the sample and testing rig faces. Initial dynamic compression tests at elevated temperatures were performed without lubricant as it was thought that at high temperatures the spray would not be effective. Half way through the series of tests it was found that the silicone spray was still effective as it caused a marked reduction in yield points, even up to 600°C. This meant that many samples were wasted by not testing with lubricant, and only those tested using the silicone spray are shown in graphs.

Figures 5.20 to 5.23 show the stress at constant strain levels against strain rate for temperatures of 150, 300, 450 and 600°C for both 'L' and 'Q' type samples. Each sample type (L or Q) and temperature had only three samples each and so only the curves at strain equals 0.5% were drawn. With so few points it is difficult to observe trends, but the curves of stress at 0.5% against temperature for various strain rates (figure 5.24) serve to combine all the available data onto a single set of axes. These curves show a large drop in yield point between 20 and 150°C and a more gradual fall between 150 and 600°C. The static and 500sec\(^{-1}\) curves tend to merge above 300°C. The 1500sec\(^{-1}\) curve stays an approximately constant distance above the 500sec\(^{-1}\) curve.

Curves of stress against strain at various temperatures at quasi static rates (figure 5.25) and 1000sec\(^{-1}\) (figure 5.26) are plotted for the compression samples. These again serve to combine the data to enable trends to be observed.
Figure 5.20 Compression 321 bar, 150°C, L and Q type

Figure 5.21 Compression 321 bar, 300°C, L and Q type
Figure 5.22 Compression 321 bar, 450°C, L and Q type

Figure 5.23 Compression 321 bar, 600°C, L and Q type
FIGURE 5.24 Compression 321 bar, L & Q type, all at $\varepsilon_s = 0.5\%$.
Figure 5.25  Compression 321 bar, L and Q type, all static

Figure 5.26  Compression 321 bar, L and Q type, all $\dot{\varepsilon}_s = 1000$ sec$^{-1}$
They show that for the compression tests the work hardening rate is little changed by temperature and the 'Q' type samples show higher stress levels than the 'L' type. They also show that at a strain rate of $1000\text{sec}^{-1}$ the temperature sensitivity is approximately double that at quasi static rates.

5.1.6 Discussion of Tension and Compression Results

Calculations of elastic modulus using the results from the split Hopkinson pressure bar can be difficult due to the short gauge length used for all the samples making the accurate measurement of small amounts of strain difficult. The initial region of the loading cycle is difficult to interpret due to sample wave propagation effects and to mismatches due to the accommodation of sample surface and thickness irregularities. However, the unloading part of the cycle can be used to determine the elastic modulus. The tensile unloading tends to be much longer at about 70\text{$\mu$s} instead of the 20\text{$\mu$s} for compression and can be subject to interference. Values of elastic modulus for various temperatures of 321 stainless steel were shown in the table 2.3, taken from a data book on stainless steel. Measurement of slopes from graphs obtained from the computer yielded results in the range $1.0 - 3.0 \times 10^{11}\text{Nm}^{-2}$ at 20°C. These are of the correct order (expected value $1.9 \times 10^{11}\text{Nm}^{-2}$) but the scatter does make it difficult to use the data to observe trends. Values for the modulus obtained in elevated temperature tests tend to be rather lower, in the range $0.75$ to $1.5 \times 10^{11}\text{Nm}^{-2}$ confirming the expected result that the modulus decreases for increasing temperature. As the main purpose of these dynamic
tests is to measure yield point and work hardening rate, not much effort has been directed at measurement of elastic modulus. Tests in which the strain is measured by strain gauges attached to the sample, or by an optical method could prove to be more successful. Such tests may not be of much value, however, as the elastic modulus is not thought to vary much with strain rate and the rough values obtained tend to confirm this. Resonance tests to obtain Young's modulus (described for 431 in chapter 4) have been applied to ¹" diameter rods of autenitic stainless steels (including 321) and results will be included in the next section.

The intention of performing tensile and compressive tests of comparable material was to see how a material behaves in the two modes and also to examine the techniques used. Comparison of the sample stress at strain of 0.5% against plastic strain rate at 20°C on figures 5.1, 5.2, 5.17 and 5.18 show very similar curves for each case. The initial rise in yield point is more gradual for the compressive case and the strain rate sensitivity decreases above 400sec⁻¹ instead of at about 200sec⁻¹ for the tensile case. The increase in yield point beyond this change is also more gradual for the compressive case. Even with these differences the general shape of the curves are similar and the stress levels agree well. The tensile results show a slight tendency for the 'Q' type samples to have higher yield point than the 'L' type. As commented previously there is a significant difference between the two types for the compressive samples.
A plot of initial strain rate (averaged up to sample strain = 0.5%) against stress at 0.5% strain was made for the 'L' and 'Q' type compressive tests and the 'L' type tensile results (figure 5.27). The compressive 'Q' type results are generally higher than the 'L' type. But in this type of plot the tensile 'L' type results show the same trend as the compressive 'Q' type. Trends shown in this type of graph may be misleading due to influence of inertial and wave propagation effects in the first few micro-seconds of a test.

Comparison of the stress against strain curves in figures 5.3 and 5.19 show that the work hardening rates for dynamic tensile and compressive tests are similar. The work-hardening rate for the static tensile tests is significantly lower than for the static compressive tests, and as no error could be found in the calculations (particularly in calculation of true stress and strain) this effect is assumed to be real.

The elevated temperature behaviour is similar for both tension and compression but the upturn which occurs in the stress against strain curves for tensile tests at 450 and 600°C is not present in the compressive curves. It could be that this upturn is not a real effect, as it is only indicated by a few samples and more confidence is placed on the compressive tests at strain rates above 1000 sec\(^{-1}\) due to the oscillation effects on the transmitted pulses in the tensile technique. The general results of an increase in temperature sensitivity at high strain rates and a decrease in strain rate sensitivity at high temperatures is well demonstrated for both tension and
FIGURE 5.27 Sample Stress at $\varepsilon_s = 0.5\% / \text{MNm}^{-2}$

321 bar, 20°C, stress at $\varepsilon_s = 0.5\%$, against initial strain rate.
5.2 Compression Tests on 304, 316, 321 and 325 1" Rod Material

For comparison with the series of tests performed on 321 bar material, it was decided to carry out a series of tests on 304, 316, 325 austenitic stainless steels and also 321 from another source.

The most convenient form for obtaining material for compression tests was as round rods. These are normally finished with a bright ground surface, so the 1" diameter material was ordered to allow the surface to be removed when the 10.0mm diameter samples are fabricated. Test certificates for the material ordered for these tests are included in Appendix 5. Only 'L' type samples were made from 1" diameter rod as fabrication of 'Q' type samples would be difficult and probably would have prevented the testing of all four grades. Again tests were only carried out at room temperature to allow time for the testing of all four grades.

Approximately 20 samples from each grade were tested, two or three in the Instron test machine and the remainder in the split Hopkinson pressure bar at strain rates up to 2000sec⁻¹.

The graphs in figure 5.28 to figure 5.35 plot the data obtained from these tests. Plots of stress at the strain levels between 0.5 and 10% are shown in figures 5.28, 5.30, 5.32 and 5.34. Stress against strain curves are plotted in figures 5.29, 5.31, 5.33 and 5.35. These
Figure 5.28 Compression 304 rod, 20°C

Figure 5.29 Compression 304 rod, 20°C
Figure 5.30 Compression 316 rod, 20°C

Figure 5.31 Compression 316 rod, 20°C
Figure 5.32 Compression 321 rod, 20°C

Figure 5.33 Compression 321 rod, 20°C
Figure 5.34 Compression 325 rod, 20°C

Figure 5.35 Compression 325 rod, 20°C
latter curves are drawn from the former set by using the best fit from these stress against strain rate graphs at particular strain rates of 200, 500 and 1500 sec$^{-1}$.

Considering the stress at 0.5% strain as a measure of yield point, the strain rate sensitivity in all grades is similar to that observed for the 321 bar material. The yield point increases rapidly up to about 400 sec$^{-1}$ and then the strain rate sensitivity is rather less for higher rates. The scatter between individual tests again is quite high particularly at the lower dynamic strain rates.

The variation in yield point is greatest for the 304 stainless steel, varying between 450 MNm$^{-2}$ for static rates and 640 MNm$^{-2}$ at 1500 sec$^{-1}$. The total variation is also great for the weakest grade 316, ranging between 330 MNm$^{-2}$ at static rates to 490 MNm$^{-2}$ at 1500 sec$^{-1}$. Although the overall range for 316 is large the range for the dynamic tests is the smallest for all the grades tested as the yield point at 200 sec$^{-1}$ is 450 MNm$^{-2}$.

The 321 rod material is the strongest form of austenitic stainless steel tested varying between 580 MNm$^{-2}$ and 725 MNm$^{-2}$. This grade is unusual in that the yield point seems to remain virtually constant above 400 sec$^{-1}$. This effect cannot be investigated to higher rates as 1200 sec$^{-1}$ was the limit for this very strong material using the current apparatus with type 431 pressure bars.

The 325 is a moderate strength material with the lowest
FIGURE 5.36 Stainless steel 1" rod, compressed. 20°C, Stress at ε_s = 0.5% against initial strain rate.

Sample Stress at ε_s = 0.5%/MNm^{-2}
overall strain rate sensitivity of the types tested. The yield point at static rates and $200\text{sec}^{-1}$ is $460\text{MNm}^{-2}$ and at $1500\text{sec}^{-1}$ $565\text{MNm}^{-2}$.

The lack of strain rate sensitivity between static rates and $200\text{sec}^{-1}$ for the 325 and above $400\text{sec}^{-1}$ for the 321 are interesting as they show that the strain rate sensitivity for other materials is not merely an artefact of the measurement technique, but is dependent on actual differing dynamic material properties.

A plot of the stress at 0.5% strain, against strain rates up to 0.5% is made for all four grades in figure 5.36. These plots show a large amount of scatter, particularly for 321 for which the correlation is very poor. The correlation between the two parameters plotted is much better for 304 stainless steel, the second strongest grade, the slope being almost twice that for the 321 bar material (compression L type) in figure 5.27. The correlation from 316 and 325 is less good than for the 304, the slope being greater for 325 and less for the 316.

The work hardening rate does not change with strain rate for the various grades, even with the slightly different shapes between the grades, the 304 and 321 having very high work hardening rate at the lower strains, and then a gradually decreasing rate above 1% strain. The work hardening rate above 2% strain is less than for the 321 bar material tested previously. The decreasing work hardening rates with strain is indicative of a material subjected to previous work hardening, probably in the manufacture of the $\frac{1}{4}$" diameter
rods. The 316 and 325 show a nearly linear work-hardening rate above 2% strain, the 325 being nearly as steep as the 321 bar material and the 316 being about half that rate.

A resonance test as described in section 4.4, was carried out using a length of each of the four grades of \(\frac{1}{4}\)" diameter austenitic stainless steel. The lengths used were approximately 1 metre and discs of radio metal had to be attached to the ends as this type of material is non-magnetic. The results of these tests are summarised in Table 5.2. The values of elastic modulus calculated were all similar being about \(1.9 \times 10^{11} \text{Nm}^{-2}\). The highest values were for the 325 at \(1.96 \times 10^{11} \text{Nm}^{-2}\) and the lowest for 321 at \(1.88 \times 10^{11} \text{Nm}^{-2}\). These are all close to the accepted book values for stainless steels at room temperature.

5.3 Compression Tests on Annealed 321

The effects of annealing on the strain rate sensitivity of 321 austenitic stainless steel was investigated. The 321 from the bar material supplied by Foulness and the 321 \(\frac{1}{4}\)" diameter rod material were used. It was considered that they would be representative of the types of material tested earlier. It was thought possible that the large difference in strength of the two forms of 321 could be investigated by this experiment.

The samples used were all 10.0mm diameter, 4.33mm long, turned in a lathe, but not finished on the wet and dry until after the heat treatment, due to oxidation of the surface. The samples were the simplest forms to prepare of the two types.
<table>
<thead>
<tr>
<th>GRADE</th>
<th>304</th>
<th>316</th>
<th>321</th>
<th>325</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density/kgm$^{-3}$</td>
<td>7925</td>
<td>7991</td>
<td>7893</td>
<td>7883</td>
</tr>
<tr>
<td>Rod length/m</td>
<td>0.728</td>
<td>0.817</td>
<td>0.757</td>
<td>1.032</td>
</tr>
<tr>
<td>Resonant frequency n = 1/kHz</td>
<td>3.384</td>
<td>3.004</td>
<td>3.218</td>
<td>2.416</td>
</tr>
<tr>
<td>Resonant frequency n = 2/kHz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.837</td>
</tr>
<tr>
<td>Elastic modulus /10$^6$Nm$^{-2}$</td>
<td>1.92</td>
<td>1.92</td>
<td>1.88</td>
<td>1.96</td>
</tr>
</tbody>
</table>

TABLE 5.2 Results of resonance experiment on $\frac{1}{4}$" diameter austenitic stainless steel rod.
The ones for the 321 rod were all 'L' type. 'Q' type samples were taken from off-cut IA27 from the Number 1, or red bar. At each annealing temperature, all the samples required were treated at the same time to remove any inconsistencies due to differences in time and temperatures at each point. Extra samples were included in each heat treatment cycle to allow for mistakes in testing and for metallurgical examination at a later date.

The furnace used was a Metals Research cylindrical type with an electric controller, with a Platinum/Platinum Rhodium thermocouple sensor. The temperature required was set on the controller and the oven allowed to stabilise before placing the samples in it. Water cooling of the outer surface of the furnace had to be connected to ensure that the inner tube would be at the required temperature for most of its length and to prevent damage to the outer casing and other parts of the furnace. The samples were placed in a ceramic crucible lowered into the furnace by a length of nichrome wire. The top of the inner tube had to be blocked with a piece of firebrick, to prevent convective losses lowering the air temperature. The temperature of the inner tube was checked with a separate thermocouple and it was confirmed that it agreed with the set temperature on the controller.

The heat treatment consisted of lowering the samples into the pre-heated oven, heating for one hour, and then removing the crucible and allowing it to cool in air. Temperatures of 380, 600, 800 and 1200°C were used initially, and then after initial tests had been performed, temperatures of 700, 900 and
1100°C were used to explore more completely the regions of interest.

All static tests were performed on the 5000kg Instron test machine used earlier. The dynamic tests were carried out on the split Hopkinson pressure bar at strain rates in the region of 1000 - 1500 sec\(^{-1}\). Pulse shaping was not used, as this investigation was more of a comparison of 'static' and 'dynamic' properties at the differing annealing temperatures. Variations in projectile velocities were used to try and keep the average strain rate constant. Earlier tests have shown that particularly above 400 sec\(^{-1}\) the strain rate sensitivity of the 321 is low (zero for the 321 rod) and so all the tests were performed in this region.

The results of each shot were calculated in the form of stress values at various strain points between 0.5 and 10% strain. Stress against strain curves are plotted for each test in figures 5.37 to 5.40. Figures 5.37 and 5.38 are the static and dynamic curves for the 1A27 bar off-cuts. They show that the yield point (stress at strain = 0.5%) decreases as the annealing temperature is increased above 700°C. For the static tests it decreases from 310 MNm\(^{-2}\) to 190 MNm\(^{-2}\) for the samples annealed at 1200°C. The dynamic yield points range from 380 MNm\(^{-2}\) to 295 MNm\(^{-2}\). This means that the difference between dynamic and static tests is greater for the annealed samples, particularly if the ratio of the two values is taken as a measure of the strain rate sensitivity since this varies between 1.23 and 1.55. The work hardening rate is similar for the static and dynamic
Figure 5.37 Compression 321 bar, 20°C, Q type, all static, annealed

Figure 5.38 Compression 321 bar, 20°C, Q type, all dynamic, annealed
Figure 5.39 Compression 321 rod, 20°C, all static, annealed

Figure 5.40 Compression 321 rod, 20°C, all dynamic, annealed
tests and is not changed with the heat treatment.

Figures 5.39 and 5.40 are the curves for the static and dynamic tests on the 321 1" rod material. They show a wide variation in yield point. The work hardening is increased by the annealing to rates slightly higher than the bar off-cut values. Before annealing the yield point is about 750MNm$^{-2}$ for dynamic tests and 575MNm$^{-2}$ for the static tests.

Figure 5.41 is a plot of stress at 0.5% strain against annealing temperature and shows the trends for all four curves. The curves for the 1" diameter rod show a large drop in yield point above 600°C. Above 900°C the yield point still decreases with annealing temperature to 1200°C, but rather less rapidly and at the same rate as the bar off-cut material. The yield point after annealing above 1000°C is only slightly greater for the 1" diameter rod than for the bar off-cut with similar treatment and less than the bar off-cut with no heat treatment. The difference in yield point between static and dynamic tests is less for the annealed than for the non-annealed rod material, the ratio of the two values however is slightly increased by the heat treatment.

The similarity of the yield point, variation of yield point with temperature, work hardening rate and strain rate sensitivity for both types of 321 above annealing temperatures of 1000°C shows that the two materials are basically very similar. The rod material was probably work hardened in manufacture, possibly in the grinding of the surface. These tests do show that tests of particular grades of steel can be compared for annealed materials, but wide variations
Sample Stress at $c = 0.5\% / \text{MNm}^{-2}$

**FIGURE 5.41** Compression test temperature 20°C.
can be observed for as-received materials from different sources. The variation between different bars and position for the original Foulness samples show that comparison can even be difficult for samples from the same melt. The scatter on tests on the samples for the four grades of $\frac{1}{4}$" diameter rod also show this point.

5.4 Repeat Compression Tests on 321 Bar Material

To investigate the effects of strain rate history on mechanical properties many investigators have performed repeat tests on samples at differing strain rates (see Duffy (1979) for review). Such tests are possibly more valid in the form of incremental strain rate machines, which can apply an increase in strain rate without the unloading in between. The author decided that a brief investigation of this type for 321 could prove interesting, but as an incremental machine would take a lot of time to develop, repeat tests on a selected series of samples were performed.

If only two strain rates are considered, 'static' and 'dynamic' then there are four combinations of tests to be performed: static/static, static/dynamic, dynamic/dynamic and dynamic/static. Two samples were tested for each of these cases, one 'L' type and one 'Q' type, and the resultant pairs of stress against strain curves for the eight samples are presented as figures 5.42 to 5.49. The samples chosen are all from the 321 bar material as repeat static tests on the rod material would not have been possible on
Figure 5.42 Compression 321 bar, 20°C, two static tests, Q type sample.

Figure 5.43 Compression 321 bar, 20°C, two static tests, L type sample.
Figure 5.44 Compression 321 bar, 20°C, static and dynamic tests Q type sample.

Figure 5.45 Compression 321 bar, 20°C, static and dynamic tests L type sample.
Figure 5.46 Compression 321 bar, 20°C, two dynamic tests, Q type sample.

Figure 5.47 Compression 321 bar, 20°C, two dynamic tests, L type sample.
Figure 5.48 Compression 321 bar, 20°C, dynamic and static tests Q type sample.

Figure 5.49 Compression 321 bar, 20°C, dynamic and static tests L type sample.
the 5000kg machine, and even so the dynamic/static tests had to be with samples initially strained to only 2%, and the static/static tests with samples initially strained to only 5%, because of the load limitations of the test machine.

The tests at similar strain rates (static/static, figure 5.42 and 5.43, and dynamic/dynamic figure 5.46 and 5.47), show yield points just below the final stress of the initial test. Beyond about 1% in the repeat test the stress level is similar to what would have been observed if the initial test had been continued to higher strains (dashed line).

The static/dynamic tests show the material starts to yield at about the level of the final stress in the initial test, and above 1% strain the stress level in the repeat test is above the extrapolation of the initial test. The difference in stress levels between an extrapolation of the first curve and the second for both samples is approximately 50MNm⁻², rather less than the 75MNm⁻² expected between flow stress in tests at similar rates for the 'Q' type material sample in figure 5.44. A difference of 100MNm⁻² would have been expected between initial tests at similar rates for the 'L' type sample in figure 5.45.

The repeat static tests in the dynamic/static case show lower yield points than the final stress in the initial test. The stress above 1% strain in the repeat tests are about 50MNm⁻² lower than the extrapolation of the initial tests. This difference is greater than the 30MNm⁻² obtained previously for initial tests at similar rates for the 'Q' type sample in figure 5.48 and less than the expected
difference for the 'L' type sample in figure 5.49.

These tests show that repeat tests could possibly be used to continue tests at a constant rate. The discrepancies in the static/dynamic and dynamic/static tests show that the strain rate history effects can affect apparent strain rate sensitivity measured by repeated tests on samples. As strain rate history can influence the result of a second loading it is an important parameter to consider when mechanical tests are performed, particularly when a representative sample is being chosen for a particular situation.

5.5 Comparison of Results with Previous Workers

Despite the fact that 321 stainless steel is widely used for many applications, dynamic material data is almost absent from the literature. Fatigue tests are reported by Yamaguchi et al (1978) but these would be of limited use to anyone wanting to analyse an impact situation. One of the reasons for the instigation of the author's project was the sparseness of dynamic properties of the 321 material chosen for the COVA tests.

Nicholas (1981) includes three points of stress at 10% strain plotted against the logarithm of strain rate, obtained from his own tensile tests. The only other 321 results available for comparison with the author's work are some unpublished graphs produced by Albertini and Montagnani (1979) on tensile samples supplied by AWRE Foulness. These are plotted on figure 5.50 along with the
Sample stress at ε = 0.5%/MNm$^{-2}$

**FIGURE 5.50** Comparison of 321 tensile results with those obtained by Albertini and Montagnani using similar samples.
author's own tensile results. These results show scatter similar to the author's results, and they also show a very similar trend and strain rate sensitivity up to 400sec\(^{-1}\) which is the upper limit of Albertini and Montagnani's technique. The 321 samples were supplied to Albertini and Montagnani by Foulness and taken from thin (1 - 2mm) sheet and not the 3" x ½" bars used for the author's samples. The slightly higher results obtained by Albertini and Montagnani could thus be expected from the difference in the source material used.

Of the austenitic stainless steels 304 is the one most readily reported for its dynamic properties, recent papers by Isozaki and Oba (1977), Stechen (1973), Hansen (1966), Albertini and Montagnani (1974 and 1977) and Nicholas (1981). Dynamic properties of 316 have been presented by Isozaki and Oba (1979) and Albertini and Montagnani (1979). Uchida et al (1979) report on 301, and Albertini and Montagnani (1974) on 347.

Many workers display strain rate properties as yield point or stress at a given strain level against the logarithm of strain rate. Figures 5.51 to 5.53 are compilations in this form of some of the author's own results along with those from a few other workers for 304, 316 and 321 respectively. Figure 5.54 is a plot of the author's own results for 325 for comparison with other grades. No other results for 325
Figure 5.51 Comparison of results obtained from dynamic tests on 304 stainless steel

Figure 5.52 Comparison of results obtained from dynamic tests on 316 stainless steel
Figure 5.53 Comparison of results obtained from dynamic tests on 321 stainless steel

Figure 5.54 Results obtained from dynamic tests on 325 stainless steel
could be found. Many materials when plotted on a graph of this form show a low strain rate sensitivity between the static rates (approximately $10^{-3}\ \text{sec}^{-1}$), and the low dynamic rates ($10 - 100\ \text{sec}^{-1}$) and thereafter a nearly linear response with respect to the logarithm of strain rate. Many of the curves plotted in figures 5.51 to 5.54 show this type of behaviour.

The results by Nicholas for 304 (figure 5.51) agree fairly well with the author's own results for stress at 10\% strain. The author's results show higher stress levels, but the increase with strain rate is very similar. The author's own results for 304 at 1\% strain show much higher stress values than the results by Hauser (1966) and Albertini and Montagnani. Again the results show a similar amount of strain rate sensitivity, although the rate of increase at about $10^3\ \text{sec}^{-1}$ is greater than the other results.

The Albertini and Montagnani results for 316 (figure 5.52) show a linear and fairly steep increase in stress with the logarithm of strain rate. The two results by Isozaki and Oba show a much lower strain rate sensitivity similar to that in the author's own results which again show a trend of an increased sensitivity above $10^2\ \text{sec}^{-1}$.

The 321 results of Nicholas (figure 5.53) show the same trends and strain rate sensitivity as those by the author, and the stress levels are in between those for the 321 1\" diameter rod samples and the 321 samples supplied by Foulness.

The author's results for 325 stainless steel (figure 5.54) show no strain rate sensitivity between static rate and 200sec$^{-1}$. Above 200sec$^{-1}$ the response is linear with respect to the
logarithm of strain rate. The results obtained by the author on testing the four grades from \( \frac{1}{4} \)" diameter rod material in most cases show higher stress values than the results from other workers. This is probably due to the high degree of work hardening already present in the material as received, as observed by the tests on annealing the 321 rod material. This emphasises the great difficulty inherent in the comparison of mechanical properties by different authors, as few actually quote material source, form of supplied stock or amount (if any) of heat treatment before testing.

As was shown in section 5.3 comparison of similar materials from different sources is easier if the material is fully stress relieved by a specified heat treatment. This is sufficient for the comparison of techniques, but the object of most material tests is to determine the properties of a material in a particular situation, which is not necessarily annealed. For dynamic tests to be of value the material being tested must be fully specified, even so the use of such results directly can be incorrect, but if the trends of strain rate sensitivity are known a material could be characterised by a static test and comparison with results on a similar material.

Direct comparison of all the aspects of various tests with the results from other workers is not possible, particularly for the high temperature dynamic and annealed material tests on 321. However, various points from other workers help to verify the validity of the results obtained. Albertini and Montagnani (1979) results for 316 at
550°C show that the strain rate sensitivity up to 405s^{-1} is no longer present at this temperature. This is consistent with the elevated temperature results on 321 bar material obtained by the author. However, the results on welded 316 material by Albertini and Montagnani show a reduction in the sensitivity which is not observed with the annealed results on 321 obtained by the author. The trend for stress at 0.5% strain against annealing temperature for 321 rod material is similar to the curves of 0.2% proof stress of 321 and 304 stainless steels against re-heating temperature in Pickering (1976). The end of the large decrease in strength and start of more gradual reduction occurring in the author's work around 900°C and in Pickering at around 950°C.

The general trend for 321 bar observed of decreasing strength with increasing temperature with fairly rapid drop between room temperature and 150°C followed by a more gradual decrease up to 600°C is consistent with the results obtained by Isozaki and Oba in dynamic tests from 316 stainless steel. It shows good agreement with the trend in static data presented for 321 bar, Simmons and Echo (1965), in an American society for Testing and Materials report. Comparison of actual values of yield point are again not really possible due to the fact that these data were obtained for annealed 321 from a different source.

Many papers have been published describing strain rate history effects from repeat or incremental strain rate tests. The results obtained by the author of a smaller difference (in flow stress)
than expected for the tests at different strain rates is consistent with these other workers (mainly for other materials). This means that strain rate history effects are important for austenitic stainless steels and need to be included in any really complete description of its dynamic properties.
CHAPTER 6 METALLOGRAPHIC EXAMINATION

6.1 Introduction

The photography of metal surfaces specially prepared to reveal the grain structure is a very useful technique for the investigation of mechanical behaviour. Such an investigation was carried out to investigate differences in yield point found in early dynamic tests. (Section 5.1). A selection of micrographs are presented in this section, partly for reference and partly to enable discussion of the different forms of material used in mechanical tests.

Unlike the earlier micrographs the samples for this section were all polished by a commercial consultant (Charnwood Consultants Limited), using standard techniques similar to those used previously by the author.

Cut pieces required for mounting and polishing were supplied to the consultants with the faces to be polished marked. The pieces were mounted in conducting plastic blocks, each block 30mm in diameter and with up to four pieces in each mount. The identification of each piece within a block was made possible by filing away the corners to produce different shapes. Each of the fifteen blocks was numbered and so all 58 faces to be examined could be identified. Representative samples of the 321 bar material and of the 304, 316, 321 and 325 ¼" diameter rod material were taken. Annealed samples before and after straining, together with samples strained in tension and compression, at room temperature and 600°C, were also selected. For each sample type, where possible, a sample parallel
to the rolling direction (L face) and perpendicular to
the rolling direction (Q face) were taken.

6.2 Sample Preparation

The sample blocks were abraded on successively finer
grades of wet and dry paper down to 1200 grade. The
polishing was finished on a rotating polisher, with a
cloth face coated with 1 micron diamond paste. The
polishing normally continues until the marks from the
previous finishing can no longer be discerned. In the
case of the 321 the surface contained titanium deoxidation
particles which have poor cohesion to an austenite matrix.
As the polishing continues these particles, being much
harder than the surrounding matrix, stand proud. A
point can thus be reached where the particles can become
detached and scratch the surface. When this starts to
happen the quality of finish starts to decrease as polishing
continues, or at least does not improve. This fact was
pointed out by the consultant who ceased polishing at what
he considered to be the optimum point. Thus many of
the micrographs have scratch lines across their surface,
but these would not be removed by conventional techniques.

The polished faces have to be etched to enable grain
structure of the metal to be observed. The etching produces
this by etching different parts of the surface (e.g. grain
boundaries) at differing rates. The etchant used for all
samples is known as Marble's solution and is one of the few
capable of affecting stainless steel. Electro-etching
techniques are quite common but were not used due to lack
of time and experience, but they are useful as more control of the etching can be achieved. The proportions for Marble's solution were taken from the A.S.M. Handbook, Volume 8, as this standard work is the basis for most metallurgical work. The solution was made by dissolving 20 grammes of copper sulphate crystals in 100ml de-ionised water and adding 100ml of concentrated hydrochloric acid. The resultant green solution was stored in a glass bottle with a ground glass stopper and labelled (with a warning that it contained concentrated acid).

The polished metal surfaces were degreased using ethyl alcohol and dried under a hot air gun. The Marble's solution was applied to the surface using a cotton wool ball (held in metal tongs). After about 15 seconds the metal surface had etched to a dull grey finish with the naked eye and it was then rinsed under water and cleaned with alcohol again to remove all traces of the etchant.

6.3 Observation Technique

The specimens were all observed using a binocular Vickers microscope set up to view reflected light from the surface. The micrographs shown were taken using a Polaroid camera back mounted on the microscope. Calibration of the prints is achieved by photographing an object of known size. A 0.5mm feeler gauge was photographed using 100X magnification and the image on the resultant print was $5.4 \pm 0.1\text{cm}$ wide. The magnification of the Polaroid print is thus $1.08 \pm 0.02$ times the nominal figure on the microscope, for the purpose of
measuring grain size etc. The magnification of most of the prints presented is 400X, (432 + 8 actual), as this was the most convenient level for viewing grains. All of the 58 micrographs taken will not be presented here to save space and because many are similar in appearance. Only a representative selection and those required to illustrate specific points will be included.

6.4 Observation of Stainless Steels

Figure 6.1 shows L and Q faces of the 431 martensitic stainless steel used for the Hopkinson bars. The broad dark lines in the L face are evidence of some anisotropy but the grains are similar in both faces. The grains are all very fine (2 to 8μm) and irregular in shape, typical of a high strength single phase material.

Figure 6.2 illustrates L and Q faces of the 321 bar material taken from bar 1 in the region of the L type tensile and compressive samples. The L face show quite definite striations (due to slag) which are visible even to the naked eye. Less well defined lines are also evident on the Q face and these are aligned with the wide faces of the 3 x ½" bars. This difference in the two types of striations may explain why the wider compressive samples have differing yield points for L and Q types but the tensile samples appear to be similar. The grains are irregular in shape but do not differ between the two faces. Their size ranges from 10 to 30μm across. Within each grain parallel bands (slip planes) can also be seen, the orientation varying randomly between grains. The micrographs for the other bars
FIGURE 6.1 431 Martensitic stainless steel from ½" diameter rod.

FIGURE 6.2 321 Austenitic stainless steel from 3" x ½" bar number 1.
and from slices taken from the region of the Q type samples show similar grain sizes and bands. Many of the micrographs for the 321 bars also show small dots (approximately 2μm across) scattered about the surface and these are probably carbide particles.

Figures 6.3 to 6.6 show the L and Q faces from the ⁴⁄₅" diameter rod of 304, 316, 321 and 325 austenitic stainless steel dynamically tested for comparison with the 321 bar material. The 304 is the most similar to the 321 bar with grains of similar size (10 to 30μm) and bands within each grain. The striations parallel with the rolling direction are not as obvious in the 304 as in the 321 bar, but there would probably be some degree of anisotropy in the material qualities if Q type samples were tested.

The 316 ⁴⁄₅" diameter rod material has a larger grain size (30 - 100μm) and the larger scale bands are not visible on the micrographs but can still be seen on the sample face with the naked eye. These parallel lines within each grain can be more clearly seen in the 316 grains and probably correspond to slip planes within each grain.

The micrographs of the 321 and 325 stainless steel rods are not of such good quality as the bands parallel to the rolling direction are very strongly evident. From what can be discerned the grain sizes of these two types are small, particularly for the 321 where grains between 2 and 10μm can be seen. This may be some explanation of the large difference in strength between this material
FIGURE 6.3 304 Austenitic stainless steel from \( \frac{1}{2} \)" diameter rod.

FIGURE 6.4 316 Austenitic stainless steel from \( \frac{1}{2} \)" diameter rod.
FIGURE 6.5 321 Austenitic stainless steel from 1/2" diameter rod.

FIGURE 6.6 325 Austenitic stainless steel from 1/2" diameter rod.
and 321 bar material.

The prints of the 321 bar and rod after annealing one hour at 1000°C are not very different from the as-received material. This could be expected for the pre-softened bar material, but differences are difficult to see in the poorer quality samples of the 321 rod material. After one hour at 1200°C both types were significantly different, figures 6.7 and 6.8. The bands within the grains could not be seen and those parallel with the rolling direction were less evident. The grains of the 321 1" diameter rod were much larger than the original and irregular grains with sizes between 10 and 60μm were observed. The grains of the 321 bar material were also slightly enlarged and grains up to 60μm across could be seen. As many grains could not be easily seen accurate measures of grain size could not be made and so a test of the validity of the inverse square root law of grain size affecting strength (Hall-Petch equation) could not be made. It could be noted, however, that in most cases the strength decreased as the grain size increased.

Micrographs of the samples after testing (figure 6.9 and 6.10) did not reveal much difference to the pre-strained material. This is in some respect due to the quality of many of the micrographs but mainly to the low level of strain achieved in the tests (up to 10%). The most significant difference in the disorder and decrease in grain size is the 321 after 10% strain (figure 6.10).
FIGURE 6.7 321 3" x ½" bar material after 1 hour at 1200°C.

FIGURE 6.8 321 ½" diameter rod material after 1 hour at 1200°C.
FIGURE 6.9 321 3" x ½" bar material after straining to 10%.

FIGURE 6.10 321 ⅝" diameter rod material after straining to 10%.
6.5 Discussion

The samples prepared by Charnwood Consultants Limited, were of reasonable quality, limited by the problem with the hard particles. The use of more controlled etching techniques could have improved the quality of the final micrographs, but due to some of the factors discussed not much more information could have been obtained with the samples prepared. The main importance of this part of the work was to confirm the similarity of the various regions selected for the cutting of the tensile and the second batch of compressive samples.

The use of further techniques to prepare samples could provide more information. Distribution of different phases could be detected by the use of particular etchants or by the use of electron beam analysis techniques (reference Slattery et al 1979). However, as the strains involved are low the transformation of the austenite to martensite is not likely to be great. Dislocation density can be determined experimentally (Gilman 1969) by the use of etchants and optical or electron microscopy. These techniques could be useful as part of a further study into the mechanism of plastic flow and strain rate sensitivity in autenistic stainless steel. One of the biggest problems with such studies would be the requirement for examining the representative samples before and after straining, as these stainless steels are fairly irregular and many tests would have to be performed to obtain statistically significant results.
CHAPTER 7 CONSTITUTIVE EQUATIONS AND PLASTIC FLOW

7.1 Constitutive Equations

Constitutive equations which describe the flow of materials as a function of stress, strain rate and temperature,

\[ \sigma = f(\varepsilon, \dot{\varepsilon}, T) \]

are, like dynamic test results themselves, derived for two principal reasons. Firstly as an engineering tool to describe the material for use in the analysis of structures under loading conditions, particularly in dynamic situations. Secondly to use them to investigate the mechanisms of plastic flow and, in particular, strain rate sensitivity and strain rate history effects. In parallel with these two reasons are the two general approaches to the derivation of constitutive equations.

The first approach is macroscopic as it considers the material as a continuum, and the analysis is in terms of yield criteria or functions, or as an empirical fit with practical results. Lindholm (1974), Johnson (1972), Campbell (1973) contain reviews of this approach. One of the earliest attempts which can fit well for some materials in particular ranges is by Ludwik (1909) who proposed

\[ \sigma = \sigma_1 + \sigma_0 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \]

where \( \sigma_1, \sigma_0 \) and \( \dot{\varepsilon}_0 \) are constants. This is in effect

\[ \sigma \propto \ln \dot{\varepsilon} \]

which at room temperature describes the dynamic behaviour of the austenitic stainless steel tested (see figures 5.51 - 5.54) reasonably well, but does not extend to
include the static results obtained.

Equations of the form
\[ \sigma \propto \varepsilon^n \quad 6.4 \]
or
\[ \log_{10} \sigma \propto n \log_{10} \varepsilon \quad 6.5 \]
were used by Alder and Phillips (1954) to describe experimental results on copper, aluminium and steel. Figure 7.1 is a log-log plot of some of the author's experimental results. It can be seen that a single exponent is insufficient to describe the overall behaviour of the stainless steels, although again a reasonable fit could be obtained for the elevated strain rate tests. A polynomial fit with the results could be found and this could be the simplest approach if the results at room temperature were required in functional form, as curve fitting programmes are available in the libraries of most main-frame computers. Equations which include dependence of temperature have been proposed by several workers but they usually include a \( \ln \varepsilon \) dependence on strain rate, which can only be made to fit the stainless steel data over limited ranges. The equation used by Bell (1968)
\[ \sigma = (2/3)^{r/3} \mu(0) B_0 \left(1 - T/T_m\right) \varepsilon^{1/3} \quad 6.6 \]
does not include any strain rate dependence at all. Where \( \mu(0) \) is a shear modulus and \( B_0 \) and \( r \) are constants. But as elastic/plastic wave propagation studies (as in Bell's work) are intrinsically insensitive to strain rate it is possible such an equation would result.

A form that is often used was introduced in the one
Sample stress at $\varepsilon_s = 0.5\%$ /MNm$^{-2}$

FIGURE 7.1 Plot of author's results of compression tests at 20°C.
dimensional form by Malvern (1965)

\[ \dot{\varepsilon} = \frac{\dot{\sigma}}{E} + F(\sigma - \sigma_0(\varepsilon)) \] 6.7

where \( \sigma_0(\varepsilon) \) is the static stress as a function of strain, \( \varepsilon \).

This overstress is useful to describe high strain rate results but is difficult to incorporate all rates (including creep) into a single function.

### 7.2 Dislocation Theory

Much recent work has concentrated on deriving functions in terms of plastic flow. Plastic flow in crystalline materials is generally accepted to occur through the motion of dislocations, or lattice faults. This approach explains why the yield point of such materials is several orders of magnitude lower than that calculated assuming a perfect lattice and consideration of inter-atomic binding forces. Johnson and Gilman (1959) combine Orowan's equation for plastic flow with a factor for elastic deformation.

\[ \dot{\varepsilon} = \frac{1}{M} \delta + \phi b \rho v \] 6.8

where \( M \) is the elastic modulus, \( \phi \) an orientation factor and \( b \) the Burger's vector (deformation associated with each individual dislocation). The density of mobile dislocations is represented by \( \rho \) and \( v \) is their average velocity.

Several relations for variations of \( v \) with applied stress have been proposed.

\[ v \propto \sigma^n \] 6.9

Equation 6.9 being equivalent in form to 6.4 is an empirical equation based on direct observation of dislocation motion using etch pit techniques. Equation 6.10 is based on model proposed by Gilman (1965) based on interactions of
dislocations with point lattice defects, and is equivalent to equation 6.3 -

$$v \propto \exp\left(-\frac{D}{\sigma}\right)$$ \hspace{1cm} 6.10

Thermal activation theory is generally used to determine dislocation velocity in terms of applied stress. In the models used, the dislocations are impeded by a regular array of barriers (theory reviewed and effect of barrier shape discussed, Davidson and Lindholm (1974)). Thermal activation of the dislocation together with the applied stress both combine to overcome the barriers, and so the theory serves to combine dislocation velocity, stress and temperature. The dislocation velocity is given by:

$$v \propto \exp\left(-\frac{U_a}{kT}\right)$$ \hspace{1cm} 6.11

where $U_a$ is the stress dependent activation energy and $k$ Boltzmann's constant. From equation 6.8 and using factors given in Hull (1975) the Arrhenius equation is:

$$\dot{\tau}_p = \phi a_0 v \exp\left(-\frac{U_a}{kT}\right)$$ \hspace{1cm} 6.12

$A$ is the average area swept out by a moving dislocation, and $v$ is the frequency with which the dislocation attempts to overcome the barrier (upper limit, the Debye frequency $\approx 5 \times 10^{12}$ sec$^{-1}$).

If the distance between activation sites is given by $l$, and $d$ is the distance moved by a dislocation in moving through the barrier, then activation volume $V$ is given by:

$$V = b ld$$ \hspace{1cm} 6.13

† Hull, D., 1975, "Introduction to Dislocations", (Pergamon Press).
The activation volume is a useful factor to relate applied stress with the resultant energy $U_s$ of a moving dislocation, where

$$U_s = \alpha V \sigma$$

(6.14)

and $\alpha$ is a constant dependent on barrier shape. This is equal to unity for a rectangular barrier, which will be assumed for the following treatment.

The total energy $U$ required to overcome a barrier is given by the total of the thermally activated energy and the applied stress energy:

$$U = U_a + V \sigma$$

(6.15)

The barriers are short range obstacles of energy $U_b$ superimposed on a long range resistance (of energy $U_L$) to motion of the dislocations. This resistance is usually attributed to long range elastic interactions between dislocations. The total energy required to overcome the barrier could therefore also be expressed as:

$$U = U_b + U_L$$

(6.16)

$$= U_b + V\sigma_L$$

(6.17)

$\sigma_L$ is a lower limiting stress below which the thermal activation is ineffective, due to the long range nature of the resistance. Combining 6.15 and 6.17 gives the activation energy of the barriers as:

$$U_a = U_b + V(\sigma_L - \sigma)$$

(6.18)

substituting 6.18 in 6.12 gives:

$$\dot{\epsilon}_p = \frac{\phi b A \sigma \exp \left[ -\frac{(U_b + V(\sigma_L - \sigma))}{kT} \right]}{kT}$$

(6.19)
This can be re-arranged to give stress in terms of strain rate and temperature:

\[ \sigma = \sigma_L + \frac{U_b - kT \ln \left( \frac{\Omega b \alpha \nu}{\dot{\varepsilon}_p} \right)}{\dot{\varepsilon}} \]  

(6.20)

There is a critical temperature \( T_0 \) given by:

\[ U_b = kT_0 \ln \left( \frac{\Omega b \alpha \nu}{\dot{\varepsilon}_p} \right) \]

i.e.

\[ T_0 = \frac{U_b}{k \ln \left( \frac{\Omega b \alpha \nu}{\dot{\varepsilon}_p} \right)} \]  

(6.21)

For temperatures greater than \( T_0 \) equation 6.20 no longer holds, as the energy required to overcome the short range barriers is totally supplied by the thermal activation. The flow is then no longer strain rate or temperature dependent and is governed by the long range interactions. In this case,

\[ \sigma = \sigma_L \]  

(6.22)

Therefore the flow stress is given by the lower limiting stress level.

At very high strain rates other mechanisms of plastic flow tend to dominate. The motion of dislocations approaches the velocity of stress waves in the material; microscopic strain rates become very great indeed. Their motion is impeded by phonon scattering and damping and a linear relationship between stress and strain rate is more likely.

\[ \nu \propto (\sigma - \sigma_B) \]  

(6.23)

Where \( \sigma_B \) is a limiting stress above which this effect applies.
7.3 Analysis of 321 data

A comprehensive set of data has been obtained for 321 stainless steel bar material over a wide range of temperature and strain rates, under compressive and tensile loading conditions. Equation 6.20 predicts a linear dependence of stress against log strain rate on the basis of thermal activation theory. Figure 7.2 and 7.3 show stress (at $\varepsilon_s = 0.5\%$) plotted against log strain rate for tensile and compressive loading of 321 bar ('L' and 'Q' type results averaged). These curves indicate that a single linear dependence of stress against log strain rate does not seem to fit over all the range of strain rates. There appears to be two distinct regions, one for $\dot{\varepsilon} > 100\text{sec}^{-1}$ and another for $10^{-3} < \dot{\varepsilon} < 10^2\text{sec}^{-1}$. However, for this low strain rate region there are insufficient experimental points to determine whether there is any linear dependence of stress against log strain rate.

If the pre-exponential factors in equation 6.12 are combined to a single strain rate factor $\dot{\varepsilon}_o$, the equation becomes

$$\dot{\varepsilon}_p = \dot{\varepsilon}_o \exp \left( -\frac{U_a}{kT} \right) \quad 6.24$$

Re-arranging gives

$$\ln \left( \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_o} \right) = -\frac{U_a}{kT} \quad 6.25$$

If $-\frac{U_a}{kT} = 0$

then $\dot{\varepsilon}_p = \dot{\varepsilon}_o$

The strain rate $\dot{\varepsilon}_p$ is a limiting strain rate reached at infinite temperature. To obtain a value of $\dot{\varepsilon}_o$, $\ln \dot{\varepsilon}_p$ was plotted against $1/kT$ at
Figure 7.2  Tension 321 bar results, average of L and Q types.

Figure 7.3  Compression 321 bar results, average of L and Q types.
several constant stress levels \( U_a \) kept constant). The data for the tensile tests (figure 7.4) show no clear convergence at \( 1/kT = 0 \), but an estimate of \( \dot{\varepsilon}_0 = 5 \times 10^5 \text{sec}^{-1} \) using the dynamic data only, can be made with an error of about an order of magnitude. The dynamic compression results (figure 7.5) do appear to converge on the \( \ln \dot{\varepsilon}_p \) axis giving \( \dot{\varepsilon}_0 = 5 \times 10^5 \text{sec}^{-1} \), with an error of about half an order of magnitude. The lower accuracy of the tensile results is probably due to the lower accuracy of the tensile tests at the higher strain rates; but the tests do back up the compression data and confirm trends and results independently.

To determine other constants such as \( V \) and \( U_b \), graphs of stress against equivalent temperature \( T^* = kT \ln(\dot{\varepsilon}_0/\dot{\varepsilon}_p) \) were plotted (figure 7.6 and 7.7) for the tensile and compressive data, assuming that \( \dot{\varepsilon}_0 = 5 \times 10^5 \text{sec}^{-1} \) for all points. The data are fitted reasonably well by two distinct straight lines, as would be expected if the material behaviour is fitted by equations 6.20 and 6.22. The stress level with increasing \( kT \ln(\dot{\varepsilon}_0/\dot{\varepsilon}_p) \) appears to be tending to a constant level of approximately \( 200 \text{MNm}^{-2} \), which is equivalent to \( \sigma_L \) in equation 6.20. When \( T = 0 \) or \( \dot{\varepsilon}_p = \dot{\varepsilon}_0 \), then the stress level will be given from equation 6.20 by

\[
\sigma = \sigma_0 = \sigma_L + \frac{U_b}{V}
\]

By extrapolating the lines back to the stress axis, the values of \( \sigma_0 \) are \( (530 \pm 50) \text{MNm}^{-2} \) for the compressive results and \( (550 \pm 50) \text{MNm}^{-2} \) for the tensile.

Also, from 6.20 the slope of the lines in figures 7.6 and 7.7 give the activation volume \( V \) as \( (2 \pm 1) \times 10^{-28} \text{m}^3 \) in each case. An estimate of the
Figure 7.4  Tension 321 bar results, L and Q types.

Figure 7.5  Compression 321 bar results, L and Q types.
Figure 7.6 Tension 321 bar results, average of L and Q types.

Figure 7.7 Compression 321 bar results, average of L and Q types.
activation energy for the short range barrier is then given by:

\[ U_b = V (\sigma_0 - \sigma_L) = 6 \times 10^{-20} \text{J} \]

The total energy required to overcome the barrier is given by:

\[ U = U_0 = 10^{-19} \text{J} \]

Lindholm (1977) describes the behaviour of an aluminium alloy in terms of two sets of thermal activation constants, one set for quasi-static and another for dynamic strain rates. Such an interpretation may be possible for the 321 results obtained, but unfortunately there is insufficient data to confirm this or obtain estimates for the quasi-static tests. If further samples had been available, tests at a range of quasi-static rates (10^{-5} to 10^{-1} sec^{-1}) and temperatures could have been carried out.

An alternative interpretation is that the strain rate dependence is low for quasi-static rates because the temperatures are greater than the critical temperature \( T_0 \) given in equation 6.21, which is 220K for a strain rate of 10^{-3} sec^{-1}. The deviation of the data from the solid lines in figure 7.6 and 7.7, (especially in the region of the elbow), could indicate that the transition at \( T_0 \) is not as marked as the simple theory predicts, either because the barrier is not a good fit to a rectangle near its base or because other forces need to be accounted for.

Tests at below room temperature would be of interest at the dynamic strain rates to extend the experimental range in figures 7.6 and 7.7.
and hence increase the confidence in the extrapolation of the curves to the stress axis. Further tests at temperatures \( > 600^\circ C \) should show a decreasing flow stress dependence on strain rate. The further data would be useful to determine how close the stress against \( kT \ln(\dot{\varepsilon}_o/\dot{\varepsilon}) \) plot is to a straight line intersecting with a lower limiting stress level. This would indicate a rectangular barrier, which would correspond to the Seeger model for the intersection of glide dislocations with stationary forest dislocations (Lindholm (1977)).

It is unlikely that the barriers are purely rectangular and equally spaced, but this model gives a reasonable description of the dynamic mechanical behaviour of 321 stainless steel bar material.
CHAPTER 8 GENERAL CONCLUSIONS AND RECOMMENDATIONS

FOR FURTHER WORK

8.1 Technique

8.1.1 Introduction

The split Hopkinson pressure bar technique used for the determination of dynamic mechanical properties is a well established technique used in many forms in research laboratories all over the world. Some work has been carried out during this project to investigate possible faults in the technique and to modify it to increase its range. Most of this work has been experimental in nature and has proved useful, particularly for development of the equipment at Loughborough.

8.1.2 Compression Testing

Investigation of the effects of deliberately imposed sample defects and the quality of samples from various sources has led to practical criteria for tolerance of compression samples. Work on alternative techniques for fabrication and finishing samples is necessary, particularly to reduce time of manufacture and to improve their overall quality. The use of a flat bed grinder was investigated towards the end of the project and early results seem to indicate that good quality samples would result and effects of the grinding on the surface hardness would not be a problem. A rig for holding samples over a lapping bed or polishing wheel had been ordered before the author finished and could prove to be a useful technique, as, like the
grinder, several samples can be prepared at a time, thus saving time and ensuring consistency.

Consideration of the slower velocity bending waves had previously led to criteria for strain gauge location (Griffiths, Parry and Worthington (1979)). Investigation of dispersion effects on the stress pulses by the author introduced a new set of requirements which particularly with careful design of the system were consistent with the first. This part of the work also showed that some previously unexplained features of the pulses observed were in fact due to the magnetism of the 431 bar material used and could be removed by de-magnetising the bars before use. The problems associated with bending waves and strain gauge siting are now more important with the tensile technique and further development on tensile testing will have to include this. As most of the bending waves are generated at the impact between the projectile and first bar, a longer initial bar could be used to contain the bending waves.

8.1.3 Digital Capture and Analysis System

The application of a micro-computer to the Hopkinson bar to enable automatic analysis of results has been a very useful improvement to the technique as it frees the researcher from hours of tedious calculations. The main benefit of this automation is the fact that the amount of experimental data is greatly increased: this is particularly important for materials such as stainless steel where many data points are required to give an indication of trends.
Further work could be done on the computer programme written by the author to enable other users to easily carry out the analysis and to save storage space and increase speed of analysis. One improvement could be the use of a compiled computer language (i.e. compiled Basic or Pascal) in the micro-computer as much of the processing time is taken up in the interpretation of the lines which has to be repeated for each pass through a loop.

8.1.4 Pulse Shaping

The use of pulse shaping in compression testing of austenitic stainless steels on the Hopkinson bar has enabled constant plastic strain rate tests to be carried out. This enables more reliable data to be obtained, and is particularly necessary at the lower dynamic rates (< 400 sec\(^{-1}\)) where the yield point is most variable and where without pulse shaping the strain rate could vary greatly. This technique could be used to investigate further the effects of particular strain rate histories on behaviour, particularly in the region of the yield point. The application of pulse shaping to other materials should be possible using the techniques outlined in section 3.4. In particular the test of the use of the same material for a shaper as that being tested could be investigated further, particularly for materials such as copper which have a low yield point and large amount of work hardening and show a large variation in strain rate if pulse shaping is not used.

8.1.5 Elevated Temperature Tests

The development of an oven to enable tests at elevated temperatures was a useful addition to the range of tests
conducted. The testing temperature is limited by the properties of the 431 bar; above about 600°C other materials may have to be used or compensation for the effects of the modulus change on the pulse transmission may have to be applied. The major developments required for the improvement of elevated temperature testing is the selection of a more suitable lubricant. Silicone spray seems to work but graphite paste or molybdenum disulphide could prove to be more suitable. Tests at low temperature (-50 to -150°C) could be carried out by fitting an insulating vessel around the sample and use of dry ice or liquid nitrogen. Such tests would probably show an increase in yield point (see 1.6) and the effects on strain rate sensitivity would be interesting to observe.

8.1.6 Tensile Testing

The modification of the Hopkinson bar to enable tensile testing was reasonably successful. Dynamic tensile tests over a wide range of strain rates (80 - 1600 sec\(^{-1}\)) were carried out over a range of temperatures (20 - 600°C) with stainless steel samples taken from 321 bar material. Advantages of this technique over other dynamic tensile techniques were discussed earlier (Chapter 4), but include the simplicity of fabrication, ease of conversion between compression and tensile testing, reasonably good access to sample, fast rise time of signal and good control over strain rates. Many of the shortcomings of the design could be improved by further development. The stress drop which occurs immediately
after the material yield point could be reduced by changing the attachment of the sample to the bar. The samples supplied to the author all had screw threads for attachment and improvements might possibly be achieved by a different type of fitting.

The use of plasticine to fill the thread for the tensile tests on 431 samples proved successful and would have been tried on 321 samples if any more had been available. The small cross-sectional area of the tensile samples and the high load transmitting capability of the larger screw thread enable the worker to test very high strength materials, stronger than the bar material, which could not be easily tested in compression.

8.2 Results and Interpretation

8.2.1 Discussion of Results

Most of the dynamic tests carried out in this work were on samples of austenitic stainless steel. The general conclusion about these results is that they serve to illustrate the trends observed at high strain rates in these materials and in many cases the results serve to demonstrate the validity of the techniques used. In particular the lack of strain rate sensitivity of the initial 321 bar compression samples served to show that the increase in strength observed in samples at elevated strain rates is not due to the technique, but is a material property. This is also shown by the change in the shape of response of differing materials, particularly the tensile tests at elevated temperature, where the initial strain rate sensitivity (at $\dot{\varepsilon} < 1000 \text{sec}^{-1}$) disappeared
The trends observed in these materials were discussed in detail in chapters 5 and 7 but at room temperature there was a trend of increasing yield point with strain rate. This was approximated by a logarithmic function in the dynamic range. The overall response of the 321 tensile and compressive bar tests with strain rate and temperature can be expressed as an increase, with temperature, of the strain rate above which strain rate sensitivity occurs.

The comparison between tensile and compressive results are good, with similar trends of strain rate sensitivity and rates of work hardening being observed. This latter point illustrates the necessity for calculating true stress and strain, a task which could be extremely time consuming without the use of a computer for the analysis. The good comparison also illustrates the need for careful documentation and specification of material samples, as only when equivalent samples were taken for compressive and tensile tests was the comparison possible.

The comparison with the results from other grades of austenitic stainless steel and from tests by other workers show similar trends but at differing stress levels, the approximately logarithmic response being observed in most cases. The difficulty in specifying the material sample could account for the lack of published data on the dynamic mechanical response of this commonly used material. However, use of the trends shown in chapter 5 and the result of a static test on a representative sample of a stainless
steel under consideration would probably provide accurate enough data for most engineering applications.

Tests on annealed samples of 321 bar and rod material showed a decreasing yield point but a retention of strain rate sensitivity with increasing annealing temperature. It was interesting to observe that the 321 material from different sources with a factor of two difference in yield point had a very similar strength after annealing.

The repeated tests on samples (section 5.4) shows that the mechanical response of austenitic stainless steel is affected by strain rate history effects and these will have to be considered in any complete analysis or application of the results.

Many constitutive equations and theoretical mechanisms to explain strain rate sensitivity have been proposed. One of the most successful is thermal activation theory which considers the straining of materials taking place by the motion of dislocations. The results obtained in this work on dynamic tests on 321 stainless steel are reasonably consistent with this theory as shown in section 7.3 the behaviour with respect to strain rate and temperature can be approximately fitted by a single curve. It is the author's belief that many mechanisms are responsible for this behaviour, each assuming a different level of importance under differing conditions further complicated by the fact that the materials tested were alloys containing several phases. Any complete theory would have to take into account at least the more important and would be a
major piece of theoretical and experimental work to undertake, but would be of great value to increase the understanding of mechanical response of materials and also for practical applications and analyses of structure and their response to high rates of loading.

8.2.2 Suggestions for Further Work

The previous section included several suggestions for further improvements to the experimental technique. After a series of tests it is usually possible to indicate areas where further work could be of value. The study of the initial part of the tests, particularly elastic modulus and strain rate variations in the elastic/plastic region are difficult to study with the Hopkinson bar arrangement used. More detailed instrumentation of the samples, with pressure transducers and strain gauges could prove to be beneficial and effects of stress wave propagation are usually the limiting factor in any such experiment.

The logarithmic plots of strain rate show the comparatively limited range of the strain rate investigated, and other techniques could be applied to study the conditions at very low strain rates (< $10^{-5}$ sec$^{-1}$) intermediate strain rates (1 sec$^{-1}$) and very high strain rates (> $10^3$ sec$^{-1}$). The very high strain rates are the most difficult to achieve and produce reliable results but would be of great interest for the investigation of controlling mechanisms, and investigation of some situations where high strain rates occur in certain areas (i.e. near tip of cutting tool or near tip of propagating fracture). The intermediate strain rates
could be investigated using specialised equipment (i.e. cam plastometer), but as the changes likely to be observed are small (particularly at elevated temperatures) these may be of little value. The very low strain rates can be investigated reasonably easily using creep test machines which are reasonably easily available and would prove a useful extension to the results presented.

Elevated temperature tests on other grades (other than 321) of austenitic stainless steel would be interesting to see if the trends observed are generally obtained.

One of the general observations to emerge from this work is that the values of yield point only have a meaning for an extremely well characterised material. Any analysis of a particular case has to be made on the basis of at least the result of a static test on a representative sample, and knowledge of likely trends with variation of temperature and strain rate.
REFERENCES


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TEXT CUT OFF IN ORIGINAL
Appendix 1  Listing of Basic programme 'HOPK' used for analysis of Hopkinson bar tests, run on Commodore PET micro-computer.

1 DEF FNX(V)=<LOG(ABS(V))/LOG(10))
4 DIME(400),ET(400)
5 DIM C1(400),C2(400)
6 DIM V(150),H(150)
7 DIM SS(150),ES(150),TI(150),EO(150)
8 DIM V$(0)
10 PRINT "PROGRAMME FOR DATA INPUT FROM TRANSIENT"
20 PRINT "RECORDER AND HOPKINSON BAR ANALYSIS"
25 PRINT "PLEASE ENTER TODAY'S DATE"
26 INPUT D$
30 PRINT "DO YOU WANT TO GO DIRECTLY TO THE"
31 PRINT "ANALYSIS SECTION?"
40 INPUT A$
50 IF A$="YES" GOTO 1040
55 IF A$="NO" GOTO 30
60 PRINT "Prepare for loading. Enter 'NOW', when"
70 PRINT "Transient Recorder in punch mode and"
80 PRINT "Interface switched to 'load'."
90 INPUT A$
95 PRINT "OK"
100 IF A$="NO" GOTO 30
120 POKE 59459,128
130 J=0
140 FOR I=1 TO 800
150 POKE 59471,128
160 POKE 59471,0
170 PP=PEEK(59471)
180 J=J+1
190 IF 03 AND PP<33 AND I=1 GOTO 210
200 GOTO 250
210 PRINT "ERROR!! Transient Recorder not in punch"
220 PRINT "Mode, or interface not connected to 5"
230 PRINT "Volt square wave and switched to 'skip'."
240 GOTO 60
250 IF PP<33 GOTO 1050
260 PP=(PP-48)*100
270 POKE 59471,128
280 POKE 59471,0
290 PP=PP+(PEEK(59471)-48)+10
300 POKE 59471,128
310 POKE 59471,0
320 PP=PP+(PEEK(59471)-48)
330 IF PP<1000 GOTO 360
340 PRINT "ERROR!! Transient Recorder not on."
350 GOTO 60
360 IF PP>0 GOTO 410
370 PRINT "ERROR!! Interface switched to skip."
380 PRINT "Transient Recorder memory will have to""390 PRINT "be reset."
400 GOTO 60
410 PRINT "LOADING",PP,800-I
420 T=I/2
430 TT=INT(I/2)
440 IF T=TT THEN 449
445 C1(TT+1)=PP
446 GOTO 450
449 C2(T)=PP
450 NEXT I
PLEASE RETURN TRANSIENT RECORDER TO
DISPLAY, BY CONNECTING 5 VOLT SQUARE
"WAVE TO INTERFACE AND SWITCH IT TO 'SKIP'
RETURN INTERFACE TO 'LOAD' WHEN FINISHED
DO YOU WANT TO DISPLAY DATA ON SCREEN?
INPUT A$
IF A$="NO" GOTO 540
IF A$<"YES" GOTO 470
PRINT"C1 C2"
FOR I=1 TO 400
PRINTC1(I),C2(I)
NEXT I
DO YOU WANT TO WRITE DATA ON TAPE?
INPUT A$
IF A$="NO" GOTO 700
IF A$<"YES" GOTO 540
PRINT"ENTER FILENAME"
INPUT C$
OPEN 5,1,1,C$
PRINT""FOR I=1 TO 400
PRINT#5, C1(I)
NEXT I
PRINT"WRITING",C$,400-I
CLOSE 5
WRITING COMPLETE.
DO YOU WANT TO LOAD ANOTHER DATA SET?
INPUT A$
IF A$="YES" GOTO 60
IF A$<"NO" GOTO 100
PRINT"FILENAME OF DATA TO BE USED."
INPUT C$
OPEN 5,1,0,C$
PRINT"X"
FOR I=1 TO 400
INPUT#5, C1(I)
PRINT#5, C2(I)
NEXT I
LOADING C; 400-1
CLOSE 5
IF LOAD COMPLETE, DO YOU WANT TO DISPLAY
DATA ON SCREEN?
INPUT A$
IF A$="NO" GOTO 1120
IF A$<"YES" GOTO 1140
ACTUAL CALCS
INPUT C$
OPEN 5,1,1,C$
PRINT""FOR I=1 TO 400
INPUT#5, C1(I)
PRINT#5, C2(I)
NEXT I
LOAD COMPLETE, DO YOU WANT TO DISPLAY
DATA ON SCREEN?
INPUT A$
IF A$="NO" GOTO 1207
IF A$<"YES" GOTO 1202
PRINT"SCALES AND/OR CALIBRATION FACTORS?"
1208 PRINT"ENTER VOLTS FULL SCALE, CH1"
1209 INPUT SX
1210 IF SX<50 OR SX<1 GOTO 1208
1211 PRINT"ENTER VOLTS FULL SCALE, CH2"
1212 INPUT SY
1213 IF SY>50 OR SY<1 GOTO 1211
1214 PRINT"ENTER SWEEP IN MILLI-SEC"
1215 INPUT SZ
1216 IF SZ>80 OR SZ<2 GOTO 1214
1217 PRINT"CALIBRATION FACTOR IS"
1218 PRINT"=(H+1) t2/(HF*GAIN)""
1219 PRINT"ENTER FACTOR FOR CH1"
1220 INPUT F1
1221 IF F1<0 OR F1>100 GOTO 1219
1222 PRINT"ENTER FACTOR FOR CH2"
1223 INPUT F2
1224 IF F2<0 OR F2>100 GOTO 1222
1225 F1=F1/1000
1226 F2=F2/1000
1227 PRINT"ENTER PROJECTILE LENGTH IN CM"
1228 INPUT LM
1229 IF LM<0 OR LM>50 GOTO 1227
1230 JX= INT((2*LM*.524)+30)
1231 PRINT"ENTER SAMPLE LENGTH IN MM"
1232 INPUT LS
1233 IF LS<0 AND LS<20 GOTO 1232
1234 PRINT"RE-ENTER SAMPLE LENGTH IN MM": GOTO 1232
1235 L0=0
1236 INPUT DS
1237 IF DS<2 AND DS>15 GOTO 1236
1238 PRINT"RE-ENTER SAMPLE DIAMETER IN MM": GOTO 1236
1239 PRINT"ENTER APPLIED VOLTAGE"
1240 INPUT VA
1241 IF VA>1 AND VA<200 GOTO 1240
1242 PRINT"RE-ENTER APPLIED VOLTAGE": GOTO 1240
1243 IF C1(I)>255 THEN C1(I)=C1(I)
1244 IF C2(I)>255 THEN C2(I)=C2(I)
1245 FOR I=1 TO 0399
1246 IF ABS(C1(I)-C1(I+1))>50 THEN C1(I+1)=C1(I)
1247 IF ABS(C2(I)-C2(I+1))>50 THEN C2(I+1)=C2(I)
1248 NEXT
1249 S1=0
1250 FOR I=1 TO 150
1251 V(I)=0
1252 H(I)=0
1253 S(I)=0
1254 ESI(I)=0
1255 TASK(I)=0
1256 NEXT
1257 S2=0
1258 FOR I=1 TO 50
1259 S1=S1+C1(I)
1260 S2=S2+C2(I)
1261 NEXT
1262 A1=S1/50
1263 A2=S2/50
1264 FOR I=1 TO 400
1265 E1(I)=C1(I)-A1
1266 ET(I)=C2(I)-A2
1267 NEXT
1454 FOR I=1 TO 400
1455 IF EI(I) > 15 GOTO 1461
1456 IF EI(I) < -15 GOTO 1451
1457 NEXT
1458 FOR I=1 TO 400
1459 EI(I) = -EI(I)
1460 NEXT
1461 FOR I=1 TO 400
1462 IF ET(I) > 15 GOTO 1490
1463 IF ET(I) < -15 GOTO 1465
1464 NEXT
1465 FOR I=1 TO 400
1466 ET(I) = -ET(I)
1467 NEXT
1468 FOR I=1 TO 400
1469 IF EI(I) > 15 GOTO 1571
1470 IF EI(I) < -15 GOTO 1479
1471 NEXT
1472 INPUT A$
1473 IF A$ = "NO" GOTO 1535
1474 IF A$ = "YES" GOTO 1571
1475 FOR I=1 TO 400
1476 IF ET(I) > 15 GOTO 1578
1477 NEXT
1478 I = I - 1: PL = 1
1479 IF EI(I) > 0 GOTO 1581
1480 GOTO 1578
1481 S3 = 0: S4 = 0: PRINTI
1482 FOR J=1 TO (I-9) STEP 1
1483 S3 = S3 + EI(J): S4 = S4 + EI(J+135)
1484 NEXT
1485 A3 = S3/10: A4 = S4/10
1486 FOR J=(I-4)TO(JX+5+I)
1487 EI(J) = EI(J) - ((A3*(JX+10+I-J))/(135)+A4)
1488 NEXT
1489 GOTO 1560
1490 IF ET(I) < 15 GOTO 1561
1491 IF EI(I) < 15 GOTO 1564
1492 NEXT
1493 I = I - 1
1494 IF M < 2 GOT0 1519
1495 FOR I=1 TO 400
1496 IF M < 0 GOT0 1591
1497 NEXT
1498 REM START FOUND
1499 AT = 0
1500 FOR J=1 TO JX
1501 II = I + J
1502 EI(J) = EI(II) *(F1/VA)* (S2/ .256)
1503 ET(J) = ET(II) *(F2/VA)* (S2/ .256)
1504 AT = AT + EI(J) * (S2/2048000)
1505 ES(J) = (10480000/LS)*AT
1506 SS(J) = ET(J)*2.13*10+11*12.7*12.7/(DS*DS)
1507 TI(J) = J*S2*101-3/2048
1508 NEXT
1509 PRINT "DO YOU WANT TO DISPLAY GRAPHS ON SCREEN"
1510 INPUT A$
1511 IF A$ = "NO" GOTO 1500
1512 IF A$ = "YES" GOTO 1570
1513 X = 40
1514 Y = A$
1515 FOR J=1 TO JX
1516 II = I + J
1517 EI(J) = EI(II) *(F1/VA)* (S2/ .256)
1518 ET(J) = ET(II) *(F2/VA)* (S2/ .256)
1519 AT = AT + EI(J) * (S2/2048000)
1520 ES(J) = (10480000/LS)*AT
1521 SS(J) = ET(J)*2.13*10+11*12.7*12.7/(DS*DS)
1522 TI(J) = J*S2*101-3/2048
1523 NEXT
GOSUB 5060
PRINT "GRAPH OF ":V$;" AGAINST ":H$"
FOR I=20 TO ISTEP-1
PRINT ";V$(I)
NEXT
PRINT"
INPUT "ANOTHER GRAPH?":A$
GOTO 1770
PRINT "DO YOU WANT TO CORRECT THE ELASTIC SLOPE"
PRINT "STRESS/STRAIN GRAPH?"
INPUT A$
IF A$="NO" GOTO 2560
IF A$="YES" GOTO 1900
PRINT "USE THE GRAPH PLOTTING ON THE PRINTER TO"
PRINT "FIND THE STRESS/STRAIN POINT WHERE THE"
PRINT "CURVE DEPARTS FROM A STRAIGHT LINE AND"
PRINT "ELASTIC MODULUS (FROM UNLOAD PART)."
X=80
Y=120
V$="SS"
H$="ES"
COSUB 5060
COSUB 2030
GOTO 2400
OPEN 5, 4
OPEN 6, 4, 6
IF D$=" " THEN PRINT#5, D$
PRINT#5, 11 GRAPH OF ":V$;" AGAINST ":H$;" ":C$"
PRINT#5, 11
IF CO=11 THEN PRINT#5, SPC(60); "STRAIN CORRECTED"
IF CW=1 THEN PRINT#5, SPC(60); "TRUE STRESS/STRAIN"
PRINT#5, ";V$"
PRINT#5, ";V$; UV$
PRINT#6, CHR$(13)
IF AA<10 GOTO 2120
A1$="10.0 8.0 6.0 4.0 2.0": GOTO 2150
A1$="5.0 4.0 3.0 2.0 1.0": GOTO 2150
A1$="2.0 1.6 1.2 0.8 0.4"
FOR I=1 TO 5
FOR K=1 TO 7
PRINT#5, V$(I)
NEXT K
NEXT I
A2$=" 0.0 1.0 --2 ---3 ---4 ---5 ---6"
IF A0<10 GOTO 2280
A0$=" 0.0 2.0 4.0 6.0 8.0"
GOTO 2320
A3$=" 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0"
PRINT#5, A2$
PRINT#6, CHR$(24)
PRINT#5, H$"
PRINT#5, RH; UH$
CLOSE5
CLOSE6
RETURN
PRINT "DO YOU NEED ANOTHER GRAPH?"
IF A$="YES" GOTO 1940
IF A$="NO" GOTO 2400
PRINT"ENTER STRAIN AT DEPARTURE FROM"
PRINT"STRAIGHT LINE"
INPUT EL
PRINT"ENTER STRESS AT DEPARTURE FROM"
PRINT"STRAIGHT LINE"
INPUT SL
PRINT"ENTER ELASTIC MODULUS"
INPUT E9
FOR I=1 TO N
EO(I)=ES(I)
IF ES(I)<EL GOTO 2530
ES(I)=ES(I)/E9
NEXT
PRINT"DO YOU WANT TO CALC TRUE STRESS/STRAIN?"
INPUT A$
IF A$="NO" GOTO 2640
IF A$="YES" GOTO 2660
CW=1
FOR I=1 TO N
SS(I)=SS(I)-EL*(EL-(SL/E9))
NEXT
PRINT"DO YOU WANT TO PRINT GRAPHS OF RESULTS?"
INPUT A$
IF A$="NO" GOTO 2720
IF A$="YES" GOTO 2740
OPEN 5,4
PRINT#5, HOPKINSON BAR RESULTS ";C$
PRINT#5," TIME STRESS EORRIG. ECORR. EREFL ETRANS"
IF CW=0 GOTO 2790
IF CO=11 GOTO 2785
PRINT#5," TRUE TRUE"
GOTO 2790
OPEN 5,4
Y$="S=.9999;ESZ S.9999;ESZ S.9999;ESZ S.9999;ESZ S.9999;ESZ"
PRINT#2,Y$
PRINT"ENTER MICRO-SEC INTERVAL FOR TABLE"
INPUT IN
FOR I=1 TO N STEP IN
T2=INT(FNX(TI(I)))/100
T1=TI(I)/1000
IF CO=11 GOTO 2817
PRINT#2,Y$
2817 S2=INT(FNX(SS(I))))
2818 S1=SS(I)/10*E2
2819 E2=INT(FNX(ES(I))))
2820 E1=ES(I)/10*E2
2821 I2=INT(FNX(EI(I))))
2822 I1=EI(I)/10*I2
2823 G2=INT(FNX(ET(I))))
2824 G1=ET(I)/10*G2
2825 IF CO=11 GOTO2835
2826 PRINT#1,T1,T2,S1,S2,E1,E2,I1,I2,G1,G2
2827 GOTO2836
2828 PRINT#1,T1,T2,S1,S2,E1,E2,I1,I2,G1,G2
2829 NEXT
2830 CLOSE1
2831 CLOSE2
2832 CLOSE5
2833 PRINT"DO YOU WANT TO PRINT TABLE OF PARAMETERS"
2834 INPUT A$
2835 IF AK="NO" GOTO 10000
2836 IF AK"YES" GOTO2840
2837 OPEN5,4
2838 OPEN6,4,6
2839 PRINT5."PARAMETERS ENTERED DURING ANALYSIS"
2840 PRINT#5:"DATE ENTERED (IF ANY)
2841 PRINT#5:"FILENAME USED (IF ANY)
2842 PRINT#5:"VOLTS FULL SCALE, CH1 ="; S1
2843 PRINT#5:"VOLTS FULL SCALE, CH2 ="; S2
2844 PRINT#5:"SWEEP IN MS" =; S3
2845 PRINT#5:"CALIBRATION FACTOR, CH1 ="; F1
2846 PRINT#5:"CALIBRATION FACTOR, CH2 ="; F2
2847 PRINT#5:"PROJECTILE LENGTH IN CM" =; S4
2848 PRINT#5:"APPLIED VOLTAGE" =; V1
2849 PRINT#5:"SAMPLE LENGTH IN MM" =; LS
2850 PRINT#5:"SAMPLE DIAMETER IN MM" =; DS
2851 IF PL=O GOTO 3060
2852 PRINT#5;"REFLECTED BASELINE CORRECTED"
2853 PRINT#5;"BASE AT START OF REFL PULSE" =; A3
2854 PRINT#5;"BASE AT END OF REFL PULSE" =; A4
2855 IF CO=11 GOTO 3110
2856 PRINT#5;"ELASTIC SLOPE CORRECTED"
2857 PRINT#5;"STRAIN AT DEPART FROM LINEAR" =; E4
2858 PRINT#5;"STRESS AT DEPART FROM LINEAR" =; S5
2859 PRINT#5;"ELASTIC MODULUS USED" =; E6
2860 PRINT#5;"PROJECTED BASELINE CORRECTED"
2861 PRINT#5;"BASE AT START OF REFL PULSE" =; A5
2862 PRINT#5;"BASE AT END OF REFL PULSE" =; A6
2863 IF CO=11 GOTO 3110
2864 PRINT#5;"ELASTIC MODULUS CORRECTED"
2865 PRINT#5;"STRAIN AT DEPART FROM LINEAR" =; E7
2866 PRINT#5;"STRESS AT DEPART FROM LINEAR" =; S8
2867 PRINT#5;"ELASTIC MODULUS USED" =; E8
2868 PRINT#5;"REFLECTED BASELINE CORRECTED"
2869 PRINT#5;"BASE AT START OF REFL PULSE" =; A5
2870 PRINT#5;"BASE AT END OF REFL PULSE" =; A6
2871 IF CO=11 GOTO 3110
2872 PRINT"THE TWO VARIABLES ARE THE SAME"
2873 PRINT"PLEASE RE-ENTER".
2874 FOR I=1TO150
1
3c. NEXT
5139 IF V$<"E" GOTO 5143
5140 FOR I=1 TO 150
5141 V(I)=ES(I); UV$="1"
5142 NEXT
5143 IF V$<"T" GOTO 5147
5144 FOR I=1 TO 150
5146 IF H$<"S" OR H$="E" OR H$="T" GOTO 5163
5148 FOR I=1 TO 150
5150 IF H$<"S" OR H$="E" OR H$="T" GOTO 5163
5152 FOR I=1 TO 150
5153 H(I)=ES(I); UH$="4"
5154 NEXT
5155 IF H$<"T" GOTO 5159
5156 FOR I=1 TO 150
5158 H(I)=TI(I); UH$="6"
5159 IF H$="S" OR H$="E" OR H$="T" GOTO 5163
5160 PRINT"RE-ENTER HORIZONTAL VARIABLE.X"
5161 INPUT H$; NE
5162 GOTO 5130
5163 IF V$<"S" OR V$="E" OR V$="T" GOTO 5163
5164 PRINT"RE-ENTER VERTICAL VARIABLE.X"
5165 INPUT V$; NE
5166 GOTO 5130
5169 NH=0
5170 FORI=1 TO 2000
5171 IFV(I)=0 AND I>10 GOTO 5210
5172 FORI=1 TO 2000
5173 IFH(I)=0 AND I>10 GOTO 5260
5174 NH=NH+1
5175 NEXT
5176 IFNH>NV THEN 5270
5177 NE=NH
5178 GOTO 5322
5179 PRINT"THE NUMBER OF ELEMENTS IN THE TWO ARRAYS"
5180 PRINT"ARE NOT EQUAL."
5181 PRINT"THERE ARE ";NH;" IN ";V$
5182 PRINT"THERE ARE ";NH;" IN ";H$
5183 PRINT"ENTER THE NUMBER OF ELEMENTS TO BE"
5184 PRINT"USED IN EACH ARRAY.X"
5185 INPUT NE
5186 FORI=1 TO 2000
5187 IFH(I)=0 GOTO 5000
5188 IFH(I)<0 GOTO 5000
5189 NEXT
5190 REM RANGE OF VALUES IN EACH ARRAY
5191 HX=H(1)
5192 HI=H(1)
5200 NEXTI
5201 IFAH="YES" GOTO 5000
5202 FORI=1 TO 2000
5203 IFH(I)<0 THEN H(I)=0
5204 IFV(I)<0 THEN V(I)=0
5205 NEXT
5206 GOTO 50340
5207 PRINT"THIS SECTION WILL NOT PLOT NEGATIVE ",
5208 PRINT"POINTS. DO YOU WANT THE NEGATIVE POINTS"
5209 PRINT"THAT ARE IN YOUR DATA MADE = TO 0.";
5210 INPUTAH$;
5211 IFAH$="YES" GOTO 5000
5212 FORI=1 TO 2000
5213 IFH(I)<0 THEN H(I)=0
5214 IFV(I)<0 THEN V(I)=0
5215 NEXT
5216 GOTO 505340
5217 PRINT"REM RANGE OF VALUES IN EACH ARRAY
5218 HX=H(1)
5219 HI=H(1)
5220 VW=V(1)
5380 VI=V(I)
5390 FOR I=ITONE
5400 IF H(I)<H(X) THEN H(X)=H(I)
5410 IF V(I)<V(X) THEN V(X)=V(I)
5420 NEXT I
5430 PRINT "MAXIMUM VALUES FOR VERTICAL SCALE ARE FROM”; VI, " TO “; VX.
5440 PRINT "MAXIMUM VALUES FOR HORIZONTAL SCALE ARE FROM “; HI, " TO “; HX.
5450 PRINT "PLEASE SELECT MAXIMUM VALUE FOR VERTICAL SCALE USING FORM 5.2 OR 1EX.
5460 PRINT "WHERE X= POWER OF 10.X".
5470 INPUT RV
5480 IF RV<0 GOTO 5498
5490 RR=INT(LOG(RV)/LOG(10))
5500 RR=(RV/(10^RR))
5510 IF RR<5.01 AND RR>=4.99 THEN AA=5: GOTO 5550
5520 IF RR<2.01 AND RR>=1.99 THEN AA=2: GOTO 5550
5530 IF RR<1.01 AND RR>=0.99 THEN AA=10: GOTO 5550
5540 PRINT "RE-ENTER USING FACTOR 5.2 OR 1EX.
5550 GOTO 5540
5560 PRINT "PLEASE SELECT MAXIMUM VALUE FOR HORIZONTAL SCALE.
5570 PRINT "WHERE X= POWER OF 10.0".
5580 INPUT RH
5590 IF RH<0 GOTO 5580
5600 RR=INT(LOG(RH)/LOG(10))
5610 RR=(RH/(10^RR))
5620 IF RR<5.01 AND RR>=4.99 THEN A=5: GOTO 5650
5630 IF RR<2.01 AND RR>=1.99 THEN A=2: GOTO 5650
5640 IF RR<1.01 AND RR>=0.99 THEN A=10: GOTO 5650
5650 PRINT "RE-ENTER USING FACTOR 5, 2 OR 10.
5660 GOTO 5540
5670 REM START THE ACTUAL CALCULATIONS
5680 FOR I=ITONE
5690 V(I)=" "
5700 GOTO 5620
5710 NEXT I
5720 FOR I=ITONE
5730 PRINT "CALCULATIONS PROCEEDING “;HE-I,".
5740 J=INT((H(I)/RH)*Y)+1
5750 JJ=INT((V(I)/RV)*X)+1
5760 IF JY GOTO 6450
5770 IF JJ<=K GOTO 6450
5780 IF (JJ/2)=JJ/2 AND JJ/2 THEN II=2: GOTO 6450
5790 IF (JJ/2)>JJ/2 AND INT(J/2)=J/2 THEN II=1: GOTO 6450
5800 IF INT(J/2)<J/2 THEN II=4: GOTO 6450
5810 IF II=3 THEN II=4: GOTO 6450
5820 REM II FOUND
5830 J=INT((J/2)+.5)
5840 JJ=INT((JJ/2)+.5)
5850 A$=MID$(V(JJ), JJ, 1)
5860 IF A$=" " THEN A$=" "
5870 IF II=1 THEN A$=" ": GOTO 6430
5880 IF II=2 THEN A$=" ": GOTO 6430
5890 IF II=3 THEN A$=" ": GOTO 6430
5900 A$=" " : GOTO 6430
5910 GOTO 6450
5920 IF A$=" " AND A$=" " AND A$=" " AND A$=" ": GOTO 6450
5930 IF A$=" " AND A$=" " AND A$=" " AND A$=" " AND A$=" ": GOTO 6450
5940 PRINT "CALCULATIONS COMPLETE.
5950 END
REMA 390 IF A$=""THEN A$="/":GOTO6430
5840 IF A$="/"THEN A$="/":GOTO6430
5850 IF A$="\"THEN A$="":GOTO6430
5860 IF A$="/":GOTO6450
5870 IF A$="/":THEN A$="/":GOTO6430
5880 IF A$="/":THEN A$="/":GOTO6430
5890 IF A$="/":THEN A$="/":GOTO6430
5900 IF A$="/":THEN A$="/":GOTO6430
5910 IF A$="/":GOTO6450
5920 IF A$="/":THEN A$="/":GOTO6430
5930 IF A$="/":THEN A$="/":GOTO6430
5940 IF A$="/":THEN A$="/":GOTO6430
5950 IF A$="/":THEN A$="/":GOTO6430
5960 IF A$="/":GOTO6450
5970 IF A$="/"AND A$="/"AND A$="/"AND A$="/"GOTO6430
5980 ON II GOTO 5990,6016,6030,6050
5990 IF A$="/":THEN A$="/":GOTO6430
6000 GOTO6450
6010 IF A$="/":THEN A$="/":GOTO6430
6020 GOTO6450
6030 IF A$="/":THEN A$="/":GOTO6430
6040 GOTO 6450
6050 IF A$="/":THEN A$="/":GOTO6430
6060 GOTO6450
6070 IF A$="/"AND A$="/"AND A$="/"GOTO64180
6080 IF A$="/":GOTO64180
6090 ON II GOTO 6090,6100,6110,6120
6100 GOTO 6450
6110 A$="/":GOTO6430
6120 GOTO6450
6130 ON II GOTO 6140,6150,6160,6170
6140 A$="/":GOTO6430
6150 GOTO6450
6160 GOTO6450
6170 A$="/":GOTO6430
6180 IF A$="/":GOTO66220
6190 IF A$="/":GOTO66270
6200 IF A$="/":GOTO66320
6210 IF A$="/":GOTO66370
6220 ON II GOTO 6230,6240,6250,6260
6230 GOTO 6450
6240 GOTO 6450
6250 A$="/":GOTO6430
6260 A$="/":GOTO6430
6270 ON II GOTO 6280,6290,6300,6310
6280 A$="/":GOTO6430
6290 A$="/":GOTO6430
6300 GOTO6450
6310 GOTO6450
6320 ON II GOTO 6330,6340,6350,6360
6330 GOTO 6450
6340 A$="/":GOTO6430
6350 GOTO 6450
6360 A$="/":GOTO6430
6370 ON II GOTO 6380,6390,6400,6410
6380 A$="/":GOTO6430
6390 GOTO 6450
6400 A$="/":GOTO6430
6410 GOTO6450
6420 GOTO6450
6430 REM ALLOCATE A$
6440 IF J=1 THEN V$(JJ)=A$+MID$(V$(JJ),2):GOTO60450
6440 V$(JJ)=LEFT$(V$(JJ),J-1)+A$+MID$(V$(JJ),J+1)
6450 NEXT
6460 RETURN
10000 PRINT "DO YOU WANT TO FINISH?"" N"
10010 INPUT A$
10020 IF A$="YES" THEN END
10030 IF A$<"NO" GOT01000
10070 PRINT "DO YOU WANT TO RETURN TO ANALYSIS WITH"
10080 PRINT "THE SAME DATA SET?" N"
10090 INPUT A$
10100 IF A$="YES" GOT01200
10105 IF A$<"NO" GOT010070
10110 GOT030
Appendix 2  Computer output for dynamic compression test number P210 on 321 grade stainless steel.

GRAPH OF SS AGAINST TI

SS
1E+09 N/M*M

10.0-

8.0-

6.0-

4.0-

2.0-

0.0-

0.0  0.4  0.8  1.2  1.6  2.0

TI 2E-04 SEC
GRAPH OF ES AGAINST TI

ES
10
8
6
4
2
0

TI
2E-04 SEC
GRAPH OF SS AGAINST ES

SS
1E+09 H/M*M
10.0

ES
0.0 2.0 4.0 6.0 8.0 10.0
<table>
<thead>
<tr>
<th>TIME</th>
<th>TRUE STRESS</th>
<th>TRUE STRAIN</th>
<th>EREFL</th>
<th>ETRANS</th>
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<tr>
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<td>+7.94E-4</td>
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<tr>
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<td>-7.18E-4</td>
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<td>-1.23E-3</td>
<td>+6.39E-3</td>
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<td>+6.79E-3</td>
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</tr>
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</table>
PARAMETERS ENTERED DURING ANALYSIS

FILENAME USED (IF ANY) = P210
VOLTS FULL SCALE, CH1 = .5
VOLTS FULL SCALE, CH2 = .1
SWEEP IN MS = 2
CALIBRATION FACTOR, CH1 = 1.136E-03
CALIBRATION FACTOR, CH2 = 5.856E-03
PROJECTILE LENGTH IN CM = 25
APPLIED VOLTAGE = 90
SAMPLE LENGTH IN MM = 4.33
SAMPLE DIAMETER IN MM = 9.99
REFLECTED BASELINE CORRECTED
BASE AT START OF REFL PULSE = 6.5
BASE AT END OF REFL PULSE = -.2
Appendix 3 Listing of Fortran programme 'ORACLE' used for prediction of strain rates in Hopkinson bar experiment.

```
DIMENSION T(100), ETRANS(100), EREFL(100)
DIMENSION STRESS(100), STRAIN(100)
DIMENSION ERDT(100)
DATA YES /3/ YES/
5000 WRITE(1,10)
10 FORMAT('INPUT MOD1 AND MOD2 MULT BY 10**11')
READ(1,*)E1, E2
   E1=E1*10.0**11.0
   E2=E2*10.0**11.0
   WRITE(1,20)
20 FORMAT('INPUT YIELD STRESS MULT BY 10**8')
READ(1,*)SY
   SY=SY*10.0**8.0
   WRITE(1,30)
30 FORMAT('INPUT MAX STRAIN IN PERCENTAGE')
READ(1,*)EMAX
   EMAX=EMAX/100.0
39 WRITE(1,40)
40 FORMAT('INPUT T1 T2 OR T3 IN MICRO SECONDS')
READ(1,*)T1, T2, T3
   IF(T1. GT. T2. OR. T2. GT. T3. OR. T3. GT. 200)60 TO 39
   ERDTP = 0.0
ICO=0
   EREFLP = 0.0
   GUESS = 0.1
   MM = 100
   STRESS = EMAX* 3.43*10.0**11.0
DO 1000 I =1,100
   STRESS(I) = GUESS* 10.0**7.0
   T(I)=I*2
   IF(T(I). GT. T2)GOTO101
   STRLIM=0.95*STRESS
   IF (STRESS(I-1). GT. STRLIM)GOTO10-3
   GOTO101
10-7 CONTINUE
   STRESS(I)=STRESS
   STRAIN(I)=STRAIN(I-1)
   EREFL(I)=0.0
   ETRANS(I)=EMAX
   GOTO1000
103 CONTINUE
   STRESS(I)=STRESS
   STRAIN(I)=STRAIN(I-1)
   EREFL(I)=0.0
   ETRANS(I)=EMAX
   GOTO1000
101 CONTINUE
   IF(T(I). LT. T3)GOTO 1001
   II=I
   GO TO 1002
1001 CONTINUE
   IF(T(I). GT. T1)GOTO 1011
   EINC=(T(I)*EMAX)/T1
   GO TO 1018
1011 CONTINUE
   IF(T(I). GT. T2)GOTO 1012
   EINC = EMAX
   GO TO 1018
1012 CONTINUE
   IF(T(I). GE. T3)GOTO 9990
   EINC = EMAX-((<T(I)-T2)*EMAX)/(T3-T2))
```
GO TO 1018
9990 EINC = 0.0
WRITE(1,3)
3 FORMAT('EINC = 0.0')
1018 CONTINUE
IF(STRESS(I).LT.SY.AND.ICO.LT.I)GO TO 2000
IF(I.LT.5)GO TO 2000
IF(STRESS(I-1).GT.STRESS(I-2))GO TO 2000
ICO=ICO+1
IF(ICO.GT.1)GO TO 1041
SSMAX=STRESS(I-1)
WRITE(1,1)SSMAX
1 FORMAT(' EINC = ',E10.3)
1041 CONTINUE
ESMAX=((SSMAX-SY)/E2)+(SY/E1)
EDIFF=(SSMAX/E1)
ELIT=(EDIFF*STRESS(I))/SSMAX
STRAIN(I)=(ESMAX-EDIFF)+ELIT
GO TO 1040
2000 CONTINUE
IF(STRESSM.GT.SY)GO TO 1030
STRAINM=STRESSM/E1
GO TO 1040
1030 STRAIN(I)=((STRESS(I)-SY)/E2)+(SY/E1)
1040 CONTINUE
ETRNS(I)=STRESS(I)/(3.43*10.0**11.0)
ERRT(I)=STRAIN(I)/(2.42*10.0**6.0)
EREFL(I)=((ERRT(I)-ERDTP)*5.0*10.0**5.0)
M=1
TEST=EINC-(EREFL(I)+ETRNSM)
DO 90 J=1,6
DEX=-J
CREM=20.0*10.0**DEX
2009 STRESSM=STRESSM*(I+CREM)
PREVT=TEST
M=M+1
IF(M.GT.MM)GO TO 890
IF(I.LT.5)GO TO 2010
IF(STRESS(I).LE.SY.AND.ICO.LT.I)GO TO 2010
ICO=ICO+1
IF(ICO.GT.1)GO TO 1051
SSMAX=STRESS(I-2)
1051 CONTINUE
ESMAX=((SSMAX-SY)/E2)+(SY/E1)
EDIFF=(SSMAX/E1)
ELIT=(EDIFF*STRESS(I))/SSMAX
STRAIN(I)=(ESMAX-EDIFF)+ELIT
GOTO 2020
2010 CONTINUE
IF(STRESS(I).GT.SY)GO TO 2011
STRAIN(I)=STRESS(I)/E1
GO TO 2020
2011 STRAIN(I)=((STRESS(I)-SY)/E2)+(SY/E1)
2020 CONTINUE
ETRNS(I)=STRESS(I)/(3.43*10.0**11.0)
ERRT(I)=STRAINM/(2.42*10.0**6.0)
EREFL(I)=((ERRT(I)-ERDTP)*5.0*10.0**5.0)
TEST=EINC-(EREFL(I)+ETRNS(I))
TTEST=TEST*PREVT
IF(TTEST.LT.0.0)GO TO 90
IF(ABS(TTEST).LT.ABS(PREVT))GO TO 2009
CREM=-CREM
GO TO 2009
890 STRAIN(I)=STRAIN(I)+10.0
90 CONTINUE
   ERDT(I) = ERDT(I)
   EREFL(I) = EREFL(I)
1000 CONTINUE
1002 CONTINUE
   DO 777 I=1,100
      IF(STRESS(I).GT.0.0)GO TO 779
      STRESS(I)=10.0**7.0
      STRAIN(I)=0.0
      EREFL(I)=0.0
      ETRANS(I)=0.0
   777 CONTINUE
   779 CONTINUE
      STRESS(II)=0.0
      STRAIN(II)=STRAIN(II-1)
      WRITE(1,80)
80 FORMAT(' TIME STRESS STRAIN EREFL ETRANS')
   DO 82 I=1,II
      WRITE(1,81)T(I),STRESS(I),STRAIN(I),EREFL(I),ETRANS(I)
81 FORMAT(5(E10.3,3X))
82 CONTINUE
   CALL TRENDD
      CALL GRAF(STRAIN,STRESS,II,0)
      CALL PICCLE
      CALL GRAF(T,ETRANS,II,0)
      CALL PICCLE
      CALL GRAF(T,STRAIN,II,0)
      CALL PICCLE
         CALL DEVENDD
            GO TO 5000
9999 CALL EXIT
END
Appendix 4 Sample drawings and material test certificates for samples prepared by Foulness from 3" x \(\frac{1}{2}"\) 321 stainless steel.

SPECIFICATION SHEET

The following 'Test Specimens' are required for a scientific study of the variation in material properties for a given type and batch of Stainless Steel (B.S. 970: Part 4. 321S12). This is the reason why exceptional care must be taken to log the origin and sequence of cutting the specimens from each of the five bars supplied.

To this end a colour code is designated for the specimens and a lotter and number system for the offcuts. Both must be rigidly adhered to.

Four colour coded boxes will be supplied to accept the finished specimens.

The following notes are a requirement:

1. The 'Tensile Test Specimens' must be manufactured in such a manner as not to induce axial torque, i.e. Threads to be cut using a sharp single point tool - not die cut or chased.

2. Manufacture by grinding or negative rake tools is not permitted.

3. Any scrap specimen to be colour coded and returned suitably labelled.

---

<table>
<thead>
<tr>
<th>No. of Specimens Required</th>
<th>No. of Specimens Required</th>
</tr>
</thead>
<tbody>
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<td>Bar 5</td>
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Material to be supplied free issue in the following sizes:

3" x \(\frac{1}{2}" x 47\(\frac{1}{4}" Long. 5 Pieces

The Colour Code is defined on - Sketch No. 123
The Cutting Sequence and Offcut Code on - Sketch No. 124
The 'L' & 'Q' Axis on - Sketch No. 125
COLOUR CODING FOR SPECIMENS

TENSILE TEST SPECIMENS TYPE 'L' CODED WHITE

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CYLINDRICAL TEST SPECIMENS TYPE 'L' CODED WHITE

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CYLINDRICAL TEST SPECIMENS TYPE 'Q' CODED BLACK

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EXAMPLE TENSILE SPECIMEN

BAR NO 1
RED

SPECIMEN NO 3 OR 4
YELLOW

TYPE 'L'
WHITE

EXAMPLE CYLINDRICAL SPECIMEN

BAR NO 2
YELLOW

SPECIMEN NO 3 OR 4
RED

TYPE 'Q'
BLACK

NOTE
CONTAIN THESE MARKINGS TO ONE HALF OF CIRCUMFERENCE
Note
Specimens To Be Machined From As Near The Bar Centre As Practicable On

Sketch No. 125

Impbd 10 158
NO. 1 SIZE CENTRE BIT PERMITTED EACH END

GRIND

$3 \pm 0.01$
($11785/1177$)

BLEND MUST BE SMOOTH WITHOUT UNDERCUT

NOTE:
1. MACHINE ALL OVER.
2. DIMENSIONS ARE IN MM'S (INCHES)
3. SCALE 4/1
4. TOLERANCE WHERE NOT GIVEN TO BE

FIGURE . DYNAMIC TENSILE TEST SPECIMEN
FIGURE 2. COMPRESSION TEST SPECIMEN.

DIM IN MM
SCALE 5:1
MATERIAL: SS TYPE 321
# SPECIAL TESTING WORKS LIMITED

**BACON LANE, SHEFFIELD S3 2NH**

**DATE**: 29th February, 1980

**TEST REPORT No.** 622

---

**TO MESSRS.** Bransall & Cox Limited,

**ORDER No.:** D/y Note 45169

**DATE RECEIVED:** 22.2.80

---

## Test Results

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<th>TEST No.</th>
<th>MARKS ON SPECIMEN</th>
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<th>CAST No.</th>
<th>UNLOADING FIELD POINT</th>
<th>TONS SD.</th>
<th>TONS SD. IN</th>
<th>% REDUCTION OF AREA [%]</th>
<th>% CRACK</th>
<th>12000FT LBS</th>
<th>KOF CMT</th>
<th>JOULES</th>
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**ANALYSIS AS GIVEN**

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**REPRESENTING:**

---

**SIGN:** [Signature]

FOR AND ON BEHALF OF SPECIAL TESTING WORKS LTD.
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NOTICE: The claim for loss, damage or shortage found in the material shall be allowed unless it is notified in writing within seven days after receipt of goods, and all claims will be held subject to a general terms and conditions of sale and delivery included in the invoice.
Appendix 5 Test certificates for 1/2" diameter stainless steel rod used for manufacture of compression samples.

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<th>QUANTITY ORDERED</th>
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<td>1/2&quot; dia</td>
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WAREHOUSE INSTRUCTIONS
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### MECHANICAL PROPERTIES

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<th>Elongation %</th>
<th>Hardness</th>
<th>Impact</th>
<th>I.C. Test</th>
<th>Remarks</th>
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### MECHANICAL PROPERTIES

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Rad. of area 71.3%
### CHEMICAL ANALYSIS

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### MECHANICAL PROPERTIES

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<th>Hardness</th>
<th>Impact</th>
<th>T.C. Test</th>
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