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**Mechanical Behaviour of ARMCO Iron
at High Strain Rates and Elevated Temperatures**

by

Pierre Pelletier
B A Sc (Chemical Engineering)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of

Master of Engineering
in Mechanical Engineering

Department of Mechanical and Aerospace Engineering

Ottawa-Carleton Institute

for Mechanical and Aerospace Engineering

**Carleton University
Ottawa, Ontario
May 19, 1995**

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**Mechanical Behaviour of ARMCO Iron
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submitted by

Pierre Pelletier

B A Sc (Chemical Engineering)

in partial fulfilment of the requirements
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Thesis Supervisor

Chair, Department of Mechanical and Aerospace Engineering

Carleton University

June 1995

ABSTRACT

The study of material behaviour and properties at high strain rates has received more interest in the past years due to the need to obtain adequate crash worthiness and metal forming computer simulations.

In this work, tensile split Hopkinson bar (TSHB) tests were done on three stocks of ARMCO iron at strain rates in the range 550 to 1600 s^{-1} and temperatures between room temperature and 750°C. An existing TSHB was modified to allow interrupted testing using momentum trapping techniques which enables the recovery of specimens prior to fracture.

The most desirable properties were displayed by the stock material with the smallest grain size. The effect of temperature on ARMCO iron was a decrease of yield strength and an increase of strain hardening with increasing temperature. Annealing of ARMCO iron produced a reduced yield strength and an increase in strain hardening. Using the true stress-strain curves obtained from experiments, parameters for the Johnson-Cook constitutive model were obtained for the as-received and annealed material with the finest grains.

The study also involved computer simulations of the complete TSHB apparatus and specimen-only models. Both optical and scanning electron microscopy were done on tested specimens to examine the failure surfaces.

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Figure 3 6 - Modified arrangement for pulse trapping on the incident bar side

a) Schematic view

b) Photograph

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750°C and strain rates between 500 and 1600 s⁻¹ were conducted, in addition to quasi-static tests at room temperature

Computer simulations of the experiments at high strain rates, including constitutive model studies, were also done.

In the remainder of this chapter, a review of the technical literature on the behavior of materials at high strain rates will be presented. Two subjects will be covered in this review, the first pertaining to the split Hopkinson bar, and the second considering models of material behaviour at high strain rate. These models are mathematical equations used to represent the experimentally determined physical properties of material. Constitutive models will be described in that section

1.1 SPLIT HOPKINSON BAR

John and Bertram Hopkinson introduced the concept of using a cylindrical bar for evaluation of material response to impulse loads [1-3]. The original apparatus consisted of a long cylindrical bar with a smaller cylindrical rod (time piece) of the same material attached by magnetic attraction to one end of the bar. Bertram Hopkinson used this apparatus to study the pressure produced by the impact of a bullet by capturing the momentum transferred to time pieces of different length [4,5] This system is still in use today and is the standard method to determine the output of detonators.

Pochhammer [6] and Chree [7] independently solved the equations of motion describing the propagation of longitudinal waves in an infinitely long cylindrical bar. These equations represent the theoretical basis of the Hopkinson bar.

Davies [8] improved the experimental technique by introducing electrical condenser units to measure the displacement of the surface of the bar caused by the propagation of the wave. Davies [8] demonstrated experimentally that Hopkinson's assumptions were an oversimplification and using the solution of Pochhammer and Chree,

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LIST OF SYMBOLS

A	Instantaneous or current gauge cross-sectional area of the specimen
A_b	Cross-sectional area of the bar
A_0	Initial gauge cross-sectional area of the specimen
C_m	Intercept of the $v_s - v_p$ curve
C_{ij}	Longitudinal sound velocity. Different subscripts and superscripts (1,2, α , β) are used to describe different regions of the bars in elevated temperature studies
d	Current gauge diameter of the specimen
d_0	Initial gauge diameter of the specimen
E	Young's modulus. Different subscripts and superscripts (1,2, α , β) are used to describe different regions of the bars in elevated temperature studies
E_i	Internal energy density
E_v	Output voltage from the Wheatstone bridge
GF	Gauge factor of the strain gauges used on the Hopkinson bar
J_2	Second invariant of the deviatoric stress
K_1	Lorentz constant
K_0, K_1, K_2	Material constants (Johnson-Cook constitutive model)
k	Microstructural stress intensity

k_s	Thermal conductivity of the material used in the calculation of the density
$\bar{t}$	Average grain diameter
L	Current gauge length of the specimen
L_s	Length of the striker
L_0	Initial gauge length of the specimen
m	Mass of a given length of material used in the calculation of the density
m	Material constant (Johnson-Cook constitutive model)
N_T	Number of twins (Zerilli-Armstrong constitutive model)
n	Material constant (Johnson-Cook constitutive model)
P_1	Force at incident bar-specimen interface
P_2	Force at specimen-transmitter bar interface
p	Pressure
q	Material constant (Zerilli-Armstrong model)
R	Resistance of the strain gauges and resistors used in the Wheatstone bridge
R	Electrical resistance of the material used in the calculation of the density
R_b	Bar radius
R_n	Notch radius (notched specimens)
r_s	Gauge radius of the specimen (notched specimens)
S_{exp}	Experimental engineering strain
S_1	Slope of the $v_{11} - v_p$ curve
s_{ij}	Deviatoric stress
T	Temperature

T^*	Homologous temperature
T_{ref}	Reference temperature
T_{melt}	Melting point
t_l	Time for stress to attain equilibrium within the specimen
u	Displacement (Superscripts α and β denotes the incident bar-specimen and the specimen-transmitter bar positions respectively)
V_c	Input voltage to the Wheatstone bridge
V_s	Velocity of the striker
v_p	Particle velocity
v_s	Shock velocity
v_{spec}	Prescribed velocity in the specimen for simulations
v_1	Velocity at incident bar-specimen interface
v_2	Velocity at specimen-transmitter bar interface
Y	Yield stress in uniaxial tension
$\beta_0, \beta_1, \beta_2$	Parameters for a simple elastic, perfectly plastic with strain hardening constitutive model
Γ_0	Grüneisen gamma
ΔT_l	Duration of the incident pulse
$\Delta \sigma'_G$	Influence of solute and original dislocation density on flow stress
ϵ	Strain
ϵ_l	Incident pulse strain The superscript " α " indicates the corrected value at the incident bar-specimen interface and the superscript "t" indicates a temperature step.
ϵ_{lm}	Amplitude of the incident pulse

ϵ_R	Reflected pulse strain The superscript " α " indicates the corrected value at the incident bar-specimen interface and the superscript "t" indicates a temperature step
ϵ_T	Transmitted pulse strain The superscript " β " indicates the corrected value at the transmitter bar-specimen interface and the superscript "t" indicates a temperature step
ϵ_{axial}	Engineering axial strain
ϵ_{diam}	True diametral strain
ϵ'^{α}	Correction for reflected part of strain pulses due to temperature at the incident bar-specimen interface
ϵ''^{β}	Correction for reflected part of strain pulses due to temperature at the specimen-transmitter bar interface
ϵ_{ij}^p	Plastic strain tensor
$\bar{\epsilon}^p$	Effective or equivalent plastic strain
$\dot{\epsilon}$	Strain rate
$\dot{\epsilon}_s$	Strain rate in the specimen
$\dot{\epsilon}_0$	Reference strain rate (Johnson-Cook constitutive model)
$\dot{\epsilon}^*$	Dimensionless plastic strain rate
$\dot{\bar{\epsilon}}$	Equivalent strain rate
$\phi_0, \phi_1, \phi_2, \phi_3, \phi_4, \phi_5$	Material constants (Zerilli-Armstrong model)
λ	Temperature distribution in the incident bar
λ_p	Pulse wavelength
λ_{pc}	Pulse component wavelength
μ	Reduced density difference equal to $(\rho/\rho_0 - 1)$
ρ	Density of the material
ρ_s	Density of the specimen

ρ_0	Initial density of the material
σ	Stress
σ_{eng}	Engineering stress
σ_m	Mean stress or pressure
σ_s	Average stress in the specimen
σ_{true}	True stress
σ^*	Triaxiality
$\bar{\sigma}$	Effective stress
ζ	Temperature distribution in the transmitter bar

Chapter I

INTRODUCTION

Although the study of material behavior at high strain rates started at the beginning of the 19th century, its importance was really established around World War II, followed by major developments at the end of the forties and in the fifties [1]. The drive to improve ammunitions using computer simulations and the interest to obtain a better knowledge of dynamic failure of machine elements induced a blossoming in the research in this area in the seventies. Nowadays, interest in crash worthiness, foreign object damage (F O D), metal forming and earthquake analysis, in addition to munitions and dynamic failure of machines, are stimulating the research on this subject in the scientific community.

The purpose of the research undertaken in this thesis was to obtain a better knowledge of the behavior at high strain rates of an extremely pure type of iron (ARMCO iron) and involved the testing of iron with a tensile split Hopkinson bar apparatus. Nowadays, the major use of this pure iron is in the production of liners which are deformed by the detonation of an explosive charge in a system called the Explosively Formed Projectile (EFP). The ARMCO iron studied was obtained from different types of stock shape (plates of two thicknesses and billet) in order to see the effect of processing on the mechanical properties. Experiments at temperatures between room temperature and

750°C and strain rates between 500 and 1600 s⁻¹ were conducted, in addition to quasi-static tests at room temperature

Computer simulations of the experiments at high strain rates, including constitutive model studies, were also done.

In the remainder of this chapter, a review of the technical literature on the behavior of materials at high strain rates will be presented. Two subjects will be covered in this review, the first pertaining to the split Hopkinson bar, and the second considering models of material behaviour at high strain rate. These models are mathematical equations used to represent the experimentally determined physical properties of material. Constitutive models will be described in that section

1.1 SPLIT HOPKINSON BAR

John and Bertram Hopkinson introduced the concept of using a cylindrical bar for evaluation of material response to impulse loads [1-3]. The original apparatus consisted of a long cylindrical bar with a smaller cylindrical rod (time piece) of the same material attached by magnetic attraction to one end of the bar. Bertram Hopkinson used this apparatus to study the pressure produced by the impact of a bullet by capturing the momentum transferred to time pieces of different length [4,5]. This system is still in use today and is the standard method to determine the output of detonators.

Pochhammer [6] and Chree [7] independently solved the equations of motion describing the propagation of longitudinal waves in an infinitely long cylindrical bar. These equations represent the theoretical basis of the Hopkinson bar.

Davies [8] improved the experimental technique by introducing electrical condenser units to measure the displacement of the surface of the bar caused by the propagation of the wave. Davies [8] demonstrated experimentally that Hopkinson's assumptions were an oversimplification and using the solution of Pochhammer and Chree,

he developed a theoretical foundation for the accuracy of the technique when one is assuming one-dimensional wave propagation

Kolsky [9] modified the original Hopkinson apparatus to enable indirect measurement of the dynamic response of a material by placing the specimen between two long bars. Kolsky used microphone condensers for data recording. This configuration was known as the first "split Hopkinson pressure bar" (SHPB) or alternatively, the Kolsky bar.

The milestones in the development of variations on the split Hopkinson bar to enable testing in tension, torsion and shear and a detailed description of them are presented in references [10] to [12]. In 1960, Harding, Wood and Campbell [13] reported a technique to perform tensile testing. The first tests in torsion with a split Hopkinson bar were reported by Baker and Yew [14] in 1966. In 1967, Ferguson, Hauser and Down presented the results from a double notch test that is the first shear test based on the split Hopkinson bar [12].

The first use of strain gauges to instrument split Hopkinson bars is credited to Hauser, Simon and Dorn in 1961 [1]. Testing of material at high strain rates and elevated temperature was first reported in 1963 by Chiddister and Malvern [15].

1.1.1 Split Hopkinson Bar General Principles

In order to see where the split Hopkinson bar stands among other tests, Figure 1.1 from reference [16] shows various tests used to measure mechanical properties of materials and their strain rate regime of application. This figure also indicates some of the considerations involved at the different strain rate ranges of dynamic testing. A more precise range of strain rates for the tensile split Hopkinson bar is given to be between 10^0 and 10^4 s^{-1} [1,10].

As illustrated in Figure 1.2, a split Hopkinson bar generally consists of two long elastic rods with a cylindrical specimen positioned between them. Using a light gas gun, a

striker bar is driven onto one of the bars called the incident bar. Upon impact, an elastic pulse is generated within the incident bar. The time-dependent strain, $\epsilon_i(t)$, is measured at a strain gauge station located on this bar. The duration and amplitude of the incident pulse are determined by the length of the striker bar and its velocity. When reaching the specimen, part of the incident wave is reflected back in the incident bar. This reflected pulse is represented by $\epsilon_r(t)$ and is also recorded using the gauges mounted on the incident bar. The remaining part of the incident pulse passes through the specimen and is transmitted into the transmitter bar. The transmitted pulse, recorded using strain gauges mounted on the transmitter (or output) bar, is represented by $\epsilon_t(t)$. Using the Hopkinson bar equations below, the dynamic stress-strain response can be determined from the strain gauge signals and the specimen geometry. The bars (striker, incident and transmitter) have to be made from a high-strength material such as AISI 4340 steel or maraging steel. The maximum stress which can be obtained in the specimen depends on the yield strength of the bars. The diameter of the bars is chosen depending on the desired strain rates; higher strain rates necessitate a smaller bar diameter in order to avoid lateral inertia effects.

1.1.2 Tension Mode

Four techniques to perform tensile split Hopkinson bar (TSHB) testing have been reported. The first technique [10,17] utilizes a solid incident bar and a hollow transmitter bar. A "top hat" specimen geometry is used, as illustrated in Figure 1.3 taken from reference [10]. This specimen geometry can be described as being four parallel tensile bar shaped specimens of equal cross-sectional area. Compressive pulse in the Hopkinson bar is resulting in tensile loading of the specimen gauge length. The main drawback of this technique is the complexity in the machining of the sample. This technique has the advantage of being conducted with the same equipment as for compressive testing.

The second method involves the use of specimen with a geometry based on a smaller version of the standard type of threaded tensile testing specimen. A tensile pulse is generated directly on the end of the incident bar as shown in Figure 1.4 taken from reference [10], which illustrates three different methods used to generate the pulse. With these techniques using threaded specimens, it is very important to have a tight fit of the specimen against the bar to ensure its even loading of the specimen and the absence of spurious wave reflections.

The third type of tensile bar is illustrated in Figure 1.5. This technique developed by Nicholas [18] uses a threaded specimen as discussed above. The bars are initially loaded by a compressive pulse which is transmitted across the specimen by a steel collar (detail A in Figure 1.5). The initial compressive pulse is then reflected as a tensile pulse off the free end of bar no. 2 which results in a tensile deformation of the specimen. The split collar, which initially carries almost all the compressive pulse, does not support any tensile loads because it is not fastened to the bars. The advantage of this technique is its similarity with a compression test while its main disadvantage is the high precision needed to manufacture the collar.

The fourth technique does not use an impact to produce the incident tensile pulse. In this method, developed by Staab and Gilat [19], the tensile wave is produced by releasing a load stored in a section of the incident bar. The system is illustrated in Figure 1.6a from reference [19]. The incident bar is clamped approximately at its mid span and the far end is stretched using a system of cables, pulleys and a hydraulic pump. A quick release mechanism rapidly releases the clamp resulting in the stored tensile pulse being propagated along the incident bar towards the specimen. The specimen used by Staab and Gilat [19] is a small cylinder situated between two flanges as illustrated in Figure 1.6b. The flange dimensions are selected to ensure impedance matches with the bars. An epoxy adhesive is used to cement the specimen to the bars. The advantage of this technique over

those presented earlier is that no gas gun is needed and the pulse does not present dispersive waves as in the more standard TSHB presented before. The ramp loading introduced by the release of the clamp could explain this absence because dispersive waves are seen when the rise time of input wave is very short [19]. However, great precision and care must be applied to ensure alignment of the clamp system to avoid bending waves when the mechanism is released.

One limitation of tensile Hopkinson bar, which applies to any uniaxial tensile test, is the occurrence of localized necking. When necking occurs, it is no longer possible to convert load-displacement data to true stress-strain data [10], reducing the range of application of the TSHB. The use of high-speed photography with precise synchronization of the exposures with the strain gauge record can be used to extend the range of application [10,20].

1.1.3 Hopkinson Bar Equations

When a material is stressed with a suddenly applied load, the deformations and stresses are not immediately transmitted to all parts of the body. The mechanical impact from the striker in a split Hopkinson bar is a case of suddenly applied or impulse load. Deformations and stresses progress through the material in the form of one or more stress disturbances traveling at a finite velocity [21]. The traveling velocity in a material is a characteristic of the material known as the sound velocity. The sound velocity in a material is given by

$$C_0 = \sqrt{E/\rho}, \quad (1.1)$$

in which E represents the Young's modulus and ρ is the density of the material. The amplitude of the disturbance, stress in the case of the split Hopkinson bar, is obtained with

$$\sigma = \rho C_0 v_p, \quad (1.2)$$

where v_p is the particle velocity or the velocity with which a point in the material moves as the disturbance moves across it. In the case of a bar impacting another at rest, v_p becomes equal to $V_s/2$ where V_s is the striking bar (striker) velocity. Equation (1.2) becomes:

$$\sigma = \frac{1}{2} \rho C_s V_s \quad (1.3)$$

When an elastic stress wave reaches a free surface in the material in which it is traveling, it is reflected. If the wave strikes the surface normally, the stress normal to the surface must be zero, therefore the reflected pulse must be opposite in sense to the incident pulse [21]. In the case of a bar with discontinuous cross section made of different materials, the incident elastic stress wave will be partly transmitted and partly reflected. Two conditions must be satisfied at the interface between the two sections:

- The forces in both bar sections at the interface must be equal
- Particle velocities at the interface must be continuous

The reflected and transmitted part of the wave depend on the impedance of the materials involved. The mechanical impedance of a material is equal to ρC_s .

The general assumptions of the split Hopkinson bar needed for the following equations to apply are:

- The bar remains elastic through the test
- The problem is one-dimensional so equations (1.1) to (1.3) apply
- The sample is deforming uniformly

Figure 1.7, based on reference [22], shows the situation around the specimen and the symbols used in the following equations:

The strain rate in the sample is given by

$$\dot{\epsilon}_s = \frac{v_1 - v_2}{L_s} \quad (1.4)$$

with v_1 , v_2 being the velocities at the incident bar-specimen and specimen-transmitter bar interfaces respectively and L_0 is the initial gauge length of the specimen. Utilizing the one-dimensional stress wave propagation equations and principles presented above, and replacing stresses by strains using the elastic relationship ($\sigma = E\epsilon$), the velocities at the interfaces can be written as

$$v_1 = C_0(\epsilon_I - \epsilon_R) \quad (1.5a)$$

and

$$v_2 = C_0(\epsilon_T) \quad (1.5b)$$

where ϵ_I , ϵ_R , and ϵ_T are the strains associated with the stress pulses. The subscripts I, R and T indicate the incident, reflected and transmitted pulses respectively

For a tensile bar, the incident and transmitted pulses, ϵ_I and ϵ_T , are tensile and positive. The reflected pulse, ϵ_R , is compressive. Considering equations 1.4, 1.5a and 1.5b, the equation for the strain rate in the specimen becomes

$$\dot{\epsilon}_s(t) = \frac{C_0}{L_0} [\epsilon_I(t) - \epsilon_R(t) - \epsilon_T(t)] \quad (1.6)$$

The average stress in the specimen is given by

$$\sigma_s(t) = \frac{P_1(t) + P_2(t)}{2A}, \quad (1.7)$$

in which P_1 and P_2 are the forces at the incident bar-specimen and transmitter bar-specimen interfaces. The instantaneous cross-sectional area of the specimen is represented by A . The forces at the interfaces, as defined based on one-dimensional wave propagation, are given by

$$P_1(t) = E[\epsilon_I(t) + \epsilon_R(t)]A_b, \quad (1.8a)$$

and

$$P_2(t) = E[\epsilon_T(t)]A_b, \quad (1.8b)$$

where E is the Young's modulus and A_b is the cross-sectional area of the bar. Equation (1.7) can therefore be written as

$$\sigma_s(t) = \frac{E A_b}{2 A} [\epsilon_i(t) + \epsilon_R(t) + \epsilon_t(t)] \quad (1.9)$$

Using the assumption that the specimen is deforming uniformly, the stress at both interfaces between the ends of the specimen and the bars is equal, thus $P_1(t) = P_2(t)$

Equations (1.8a) and (1.8b) yield

$$\epsilon_i(t) + \epsilon_R(t) = \epsilon_t(t) \quad (1.10)$$

Substituting equations (1.10) into equations (1.6) and (1.9) then yields

$$\dot{\epsilon}_s(t) = -\frac{2C_b}{L_0} \epsilon_R(t), \quad (1.11)$$

and

$$\sigma_s(t) = E \frac{A_b}{A} \epsilon_t(t) \quad (1.12)$$

which are the final form of the Hopkinson bar equations.

From these equations, originally developed by Kolsky [9], it can be seen that the stress-strain behavior of the specimen can be obtained directly from measurements made on the elastic bars in the TSHB test. The stress wave reflected at the incident bar-specimen interface, $\epsilon_R(t)$, travels back from the specimen and is measured at the strain gauge station on the incident bar. The strain from the transmitted pulse, $\epsilon_t(t)$, is measured, as it travels away from the specimen, by strain gauges fitted on the transmitter bar.

1.1.3.1 One-Dimensional Dispersion

A major accomplishment in the development of the split Hopkinson bar equations was to show that one-dimensional wave propagation occurs within the bars. At the point of impact between the striker and the incident bar however, because of non-uniformity at the interface, the wave generated is very complex and different types of elastic waves such as spherical dilatation waves also propagate [1]. This end effect dampens quickly after the wave has propagated about ten bar diameters. After that point, the wave propagation

behavior becomes fully described by the equations of motion in an infinite cylindrical solid as given by Pochhammer [6] and Chree [7] and applied to the Hopkinson bar by Davies [8]

Oscillations, known as the Pochhammer-Chree oscillations, are found on the incident wave [1]. The pulse generated in the bars is complex but can be represented as a Fourier series, i.e. the summation of many cosine waves [23]. The longitudinal wave velocity varies with the wavelength of each of these components leading to wave dispersion [1]. For $R_b/\lambda_{pc} \ll 1$, where R_b is the radius of the bar and λ_{pc} is the wavelength of the pulse component, the propagation velocity is equal to the longitudinal sound velocity (C_0) but for values of λ_{pc} approaching R_b , the velocity of the components with such short wavelengths decrease to $0.576C_0$ [8]. This longitudinal velocity variation with wavelength of pulse components leads to the dispersion of the initial wave and the presence of oscillations.

The Pochhammer-Chree solution of the equations describing propagation in infinitely long cylinders indicates that the longitudinal stress and displacement will vary across the bar cross-section principally for short wavelengths [6, 7]. Davies [8] showed that the axial displacement and stresses are uniform over the cross-section of the bar as long as $R_b/\lambda_p \ll 1$, where λ_p is the wavelength of the pulse. Davies also indicates that for $R_b/\lambda_p < 0.1$ the stresses and displacements at the surface of the bar differ from those at the center by less than 5%. The bars of the TSHB used in the current study, have a radius of 0.8 cm and the pulse wavelength is 60 cm, therefore, it can be considered that the strains measured by gauges at the surface of the bars are a very good approximation of the centerline strains. Clarke [24] presented dispersion correction methods but concluded that for the geometry of the bar used, which is the same used in this research, a dispersion correction is not required for the range of operating wavelengths used.

Another condition that must be satisfied for equations (1.11) and (1.12) is uniform deformation of the specimen. The first consideration is the time required for the stress to equilibrate within the specimen (t_E). Davies and Hunter [25] showed that it requires about three (exactly π) reverberations of the stress wave to attain equilibrium. For a plastically deforming solid obeying von Karman theory [1], equilibrium time is given by

$$t_E = \frac{\pi^2 \rho_s L_0^2}{d\sigma/d\varepsilon}, \quad (1.13)$$

where ρ_s is the density of the specimen, L_0 is the initial gauge length of the specimen and $d\sigma/d\varepsilon$ is the slope of the true stress vs true strain curve. For values of t_1 smaller than the value calculated in equation (1.13), the sample can not be assumed to deform uniformly. This produces errors in the stress-strain data so it is important to reach this time early in the test. This can be achieved by decreasing the specimen length but this must be done in conjunction with a decrease of the bar and specimen diameters. Because it is difficult to reduce t_E , another option to obtain valid data for lower strains, principally for hard brittle materials, is to increase the rise time of the incident wave [2]. In addition, a longer rising wave will contain fewer of the short wavelength components of the pulse that arise at the beginning and at the end of the wave. In this research, the material studied is very ductile so the errors at lower strains are unimportant and a typical arrangement of TSHB which produces a square wave incident pulse with a short rise time is acceptable.

1.1.4 Tests at Elevated Temperatures

The most common high temperature Hopkinson bar testing procedure is to use a tubular furnace heating only the sample and a short section of the bars [1, 15]. This will produce, however, a temperature gradient in the bar which can alter the stress wave propagating through the bars. This temperature gradient can either be measured with thermocouples or estimated by heat transfer calculations to correct the strain gauge signals.

as will be explained later. This procedure has been used at temperatures up to 620°C [15] but no indications have been given that it can not be used at higher temperatures.

Scientists at Southwest Research Institute (SRI) used short sections of aluminum oxide pressure bars in contact with the specimen inside the furnace when doing tests in compression [1]. The cold ends of these short sections of ceramic bars are put in contact with the pressure bars. Because the acoustic impedance of the aluminum oxide is almost equal to that of the bars and because the acoustic impedance of ceramics is almost unchanged by temperature increase, stress waves pass through the surfaces undisturbed. Ceramic specimens have been tested at up to 1500°C with this technique [1]. Because of the weakness of ceramic in tension, this technique can not be applied in the current research.

Another technique, developed by Frantz, Follansbee and Wright [4], involves having the specimen and the bars initially separated. The specimen is heated alone in a specially designed miniature furnace. Just before the striker bar is propelled toward the incident bar, the two pressure bars are mechanically put into contact with the specimen. For a contact time of 200 ms, which was the value used by the experimenters, it was found that the temperatures of the specimen and of the ends of the bars essentially remained constant. Therefore this technique does not require numerical corrections of the strain gauge data. Their technique was successfully used at temperatures up to 1000°C [4]. Since it is desired to put the bar in contact with the specimen in a very short time, this method is also limited to compression where the specimen is sandwiched between the bars. Other drawbacks of the technique, as explained in reference [4], are the need to have a furnace assembly made for each of the tests and the critical timing needed between the movement of the pressure bars to meet the specimen and the firing of the striker bar.

The only viable technique available for performing tests at elevated temperature in a tensile mode, as required in this research, is to use a tubular furnace to heat up the specimen and part of the bars.

1.1.4.1 Temperature Correction for Strain Gauge Data

When performing tests at high temperatures, some special considerations must be taken into account to correct measurements from strain gauges mounted on the incident and transmitted bar to calculate the stress and strain in the specimen. In typical split Hopkinson bar configurations, the strain gauge locations are chosen to be away from the specimen to avoid overlap between the incident and reflected pulses. In equations (1.11) and (1.12), the recorded pulses at the gauges are considered equal to those at the interface with the specimen based on wave propagation theory in long cylinders. Changes in the bar impedance due to a thermal gradient along the bar affects the reflected and transmitted pulses at the interfaces with the specimen as they travel toward the gauge stations. It is therefore necessary to correct the measured strain values to obtain the actual values at the interfaces with the specimen.

The method used in this research is based on reference [15] and consists of dividing the thermal gradient into discrete steps. At each temperature step along the bar, only part of the propagating wave is transmitted while part will be reflected. Using curves of the Young's modulus as a function of temperature for the bar material [26], the Young's moduli are calculated for each temperature step. The longitudinal velocity of sound is then given by equation (1.1) while the density of the bar material varies only slightly in the temperature range of interest so it is assumed to be constant. The transmitted and reflected part of the pulses at each temperature step, as shown in Appendix B, are calculated with

$$\frac{\epsilon_r^t}{\epsilon_i^t} = \frac{2E_1}{E_2 + \sqrt{E_1/E_2}} \quad (1.14)$$

and

$$\frac{\epsilon_R^t}{\epsilon_1^t} = \frac{\sqrt{E_2} - \sqrt{E_1}}{\sqrt{E_2} + \sqrt{E_1}}, \quad (1.15)$$

in which E_1 and E_2 as the moduli of elasticity on the two sides of the temperature step. Starting with the pulses recorded at the strain gauges, the pulses at the interfaces of the bars with the specimens, ϵ_1^α and ϵ_1^β , can be calculated. Superscripts α and β represent the incident bar-specimen and the transmitter bar-specimen interfaces respectively

An additional correction must be made to the strain values to take into account the parts of pulses ϵ_R and ϵ_1 coming from reflection at the thermal gradient and reloading the specimen. These are labeled ϵ'^α and ϵ''^β . The reflected pulse (ϵ_R^α) at the bar-specimen interface is difficult to obtain from the value at the gauge station because of numerous reflections affecting it, but Chiddister and Malvern [15] showed that it could be replaced by a combination of the incident and transmitted pulses at the interfaces with the specimen as explained in Appendix B. The equations for the strain rate and the stress in the specimen then become

$$\dot{\epsilon}_s(t) = \frac{2C_0^\alpha}{L_0} (\epsilon_1^\alpha(t) + \epsilon_1^\beta(t) - \epsilon'^\alpha(t)) \quad (1.16)$$

and

$$\sigma_s(t) = E^\beta (\epsilon_1^\beta(t) + \epsilon''^\beta(t)). \quad (1.17)$$

At room temperature, there is no reflection from thermal gradient therefore ϵ'^α and ϵ''^β are equal to zero and equations (1.16) and (1.17) reduce to equations (1.11) and (1.12) respectively

1.1.5 Novel Techniques for Split Hopkinson Bar

Some researchers [1, 2, 4] have worked on different techniques to improve the results obtained with Hopkinson bars or to get additional data from the experiments.

1.1.5.1 Pulse Shaping

As mentioned earlier, in order to obtain equilibrium of the stress in the specimen, a long rise time pulse could be needed. When testing very hard brittle materials such as ceramics and composites, which often achieve only very small strains before failing, it is desirable to apply load to the sample in a more gradual manner [2]. This approach ensures that uniform deformation is achieved in the specimen prior to the strain reaching the range of interest for the material being tested [25]. This assumption is required for the application of the split Hopkinson bar equations, as explained above. In order to increase the rise time of the incident pulse, a soft material disk, such as copper, is put at the striker/incident bar interface [2]. The choice of material for this cushion depends on the strain rate and the strength of the specimen [1]. An analysis of the plastic deformation of the cushion has been performed and is presented in reference [27]. Figure 1.8 from reference [2] illustrates pulse shaping obtained for two different striker velocities.

1.1.5.2 Interrupted Test

In order to study damage development in a specimen, it is often desired to conduct interrupted tests in which a series of specimens are tested to different levels of the strain. These tests are done by using different duration and/or amplitude of stress pulse to load the specimen obtained with different striker lengths and velocities. In the classical split Hopkinson bar configuration, the reflected pulse is reflected back toward the specimen when reaching the free end of the incident bar away from the specimen. This effect produces repeated loading in the specimen so it makes it impossible to interrupt damage after a single pulse [2]. To achieve interrupted tensile tests, a technique aimed at trapping the compression pulse reflected off the sample has been designed [2, 27]. The tensile loading is applied by a tubular striker riding on the incident bar and hitting an end cap or transfer flange at the end away from the specimen [27]. The momentum trap consists of a

rod of length at least equal to pulse length placed at the end of the incident bar as shown in Figure 1 9a. At the beginning of the experiment a precision gap is set between the transfer flange and the momentum trap rod. The gap is set such that when the striker has transferred the entire pulse to the incident bar, the gap just closes. Upon reflection off the sample interface as a compression wave, the reflected pulse travels into the momentum trap bar where it is trapped. A typical example of the incident pulse history obtained with this technique is shown in Figure 1 9b.

1.1.6 Split Hopkinson Bar Computer Simulation

The first computer simulation reference of the SHPB is attributed to Bertholf and Karnes [28] who performed a two-dimensional finite difference analysis, using the TOODY code, on a compressive test done on aluminum. They studied the effects of wave shape, friction, strain rate and length to diameter ratio of the specimens. Their contribution is particularly important because they were able to quantify the effects of some of errors, namely inertia and friction, and to show the limitations of the frequency equation when applied to semi-infinite bars. Bertholf and Karnes also defined some bar and specimen design principles which are still in use.

Kramer [29] proved that finite element methods (FEM) were accurate enough to calculate the stress wave propagation in solids by comparing results of a two-dimensional finite element code (HONDO) with the finite difference results obtained by Bertholf and Karnes [28]. Kramer indicated that element size should be chosen such that the wave does not propagate through it in one calculation step but he also noted that over-refinement did not substantially improve the results.

Smith and Glover [30] performed a computer simulation of the compressive split Hopkinson bar tests on mortar specimens using the hydrocode DYNA-2D (the code adopted in the present study). They modeled the complete system including the striker so

they did not have to use a velocity profile in the incident bar like the scientists mentioned above. They obtained an adequate simulation of the waves in the bars with calculated values of amplitude and duration within 2% of the experimental values. Smith and Glover also found that the pulse deviated from the rectangular shape obtained experimentally. Their explanation was that the assumption of uniaxial strain may not be totally appropriate [30].

Tedesco [5] did simulations of tensile tests done on plain concrete with a split Hopkinson bar using the ADINA code. His purpose was to get information on the failure mode in concrete, which was not possible from the study of experimental data. Two types of notches were simulated, a square type and a saddle type. He only modeled part of the incident and transmitter bar. He studied stress concentration factors in the notches and obtained results comparable with analytical methods.

Other authors, such as Rajendran [31], presented results of simulation of high rate tensile tests on metals but they only modeled the specimen alone or considered only small sections of the bars.

1.2 CONSTITUTIVE MODELS

In the area of high strain rate studies, tests on actual systems can be either difficult or expensive to perform and it may not be feasible to measure data of interest. One approach to alleviate this problem resides in the use of computer simulations to provide predictions. With the use of powerful computers, it is possible to find accurate numerical analysis solutions to unsteady, non-linear partial differential equations which are mathematical statements corresponding to physical observations. The basic equations can be divided into four categories.

1. Conservation equations

- Mass

- Linear momentum
- Angular momentum
- Energy

2. Constitutive relations

- Volumetric response
- Deviatoric response

3. Failure criteria

- Instantaneous
- Time-dependent (cumulative damage)
- Micro-mechanical

4. Post failure descriptions

This review will be limited to the constitutive models or relations as applied to high strain rate deformation of metals

It is common in continuum mechanics codes, such as hydrocodes, to divide the deformation behavior of materials into volumetric and deviatoric parts. The volumetric part is obtained from an equation of state which describes the relationship between thermodynamic properties such as pressure, energy, density and temperature [32]. The deviatoric or shear (distortional) part is described by constitutive models which will be discussed in this section

A constitutive model for the behavior of material can be defined as equation(s) describing the relationship between variables such as stress, strain, strain rate, temperature and internal state variables for a given material [33]. Reliability of the simulation resides in the choice of the appropriate model to describe the constitutive response of the material as it deforms and the quality of the experimental data used to define the factors in the model. The degree of complexity to be used when choosing a constitutive model depends, in general, on the intended application, the availability and ease of obtaining experimental

data, and the degree of precision required in describing the material behavior [34]. The split Hopkinson bar is the apparatus most often used to produce the experimental data to calibrate these models.

The majority of the models used for multiaxial behavior are based on a von Mises yield criterion which states that the yield behavior is related to J_2 , the second invariant of the deviatoric stress tensor [34],

$$J_2 = \frac{1}{2} s_{ij} s_{ij} = \frac{1}{3} Y^2, \quad (1.18)$$

where Y is the yield stress in uniaxial tension and s_{ij} is the deviatoric stress tensor. While Y can be considered as a material constant, it can be made a function of effective plastic strain or plastic work, to account for strain hardening, or a function of temperature or internal energy, to consider thermal softening. A simple strain hardening model can be incorporated into the von Mises yield criterion leading to

$$Y = \beta_0 (\beta_1 + \bar{\epsilon}^p)^{\beta_2}, \quad (1.19)$$

for example, where $\bar{\epsilon}^p$ is the effective plastic strain which is replacing the uniaxial plastic strain obtained from a uniaxial test and $\beta_0, \beta_1, \beta_2$ are factors determined from experimentation. The effective plastic strain is given by

$$\bar{\epsilon}^p = \sqrt{\frac{2}{3} \epsilon_{ij}^p \epsilon_{ij}^p}, \quad (1.20)$$

where ϵ_{ij}^p is the plastic strain tensor

1.2.1 Semi-Empirical Constitutive Models

Two of the most commonly used semi-empirical constitutive models are the Johnson-Cook and the Zerilli-Armstrong models due to the limited number of parameters needed in them [34]. They are called semi-empirical or engineering models because the equations are obtained partially from curve fitting to experimental data rather than application of the metal physics theories. The limitation of most of the models in this

category is that they are based on small strain theory and that they tend to suffer from this deficiency when applied to describe large strain behavior [34]

1.2.1.1 Johnson-Cook Model

The Johnson-Cook model [35] accounts for strain hardening, strain-rate hardening and thermal softening in the materials with the flow stress equation

$$\bar{\sigma} = (K_0 + K_1 \bar{\epsilon}^n) (1 + K_2 \ln \dot{\epsilon}^*) (1 - T^{*m}), \quad (1.21)$$

where K_0, K_1, K_2, m, n are material constants obtained from experiment, $\dot{\epsilon}^*$ is the dimensionless plastic strain rate given by $\dot{\epsilon}/\dot{\epsilon}_0$ with $\dot{\epsilon}_0$ being a reference strain rate, and T^* is a form of homologous temperature given by $(T - T_{ref})/(T_{melt} - T_{ref})$. T_{ref} is a reference temperature for which the room temperature is typically used and T_{melt} is the melting point of the material.

The first term enclosed in parentheses describes the flow stress as a power law function of strain usually measured at a strain rate of $1.0s^{-1}$ and room temperature. The second term represents the logarithmic effect of strain rate in elevating flow stress while the effect of temperature and thermal softening is incorporated in the third term. In this model, the strain rate and temperature effects are independent suggesting that they are independent of each other. In reality, this is not true for most metals and rate sensitivity increases with temperature while flow stress decreases.

This model has been evaluated by comparing experimental data obtained from the Taylor cylinder test with computer simulations using the EPIC computer code. The results were considered to be in good agreement for the ARMCO iron [35]. The material constants for ARMCO iron from reference [35] are presented in the first line of Table 1.1

In reference [36], Holmquist and Johnson present their studies of the model and possible improvements for it. They looked at the original data considering values for tension only as well as results from both torsion and tension tests. Their improved factors

for ARMCO iron are presented in lines 2 and 3 of Table 1.1 for tension only and tension/torsion data respectively. Holmquist and Johnson attribute the difference between their factors values and those obtained by Johnson and Cook with the same data to a more thorough analysis of the experimental data. Holmquist and Johnson [36] also introduced a modified version of the Johnson-Cook model given by the following equation,

$$\bar{\sigma} = (K_0 + K_1 \bar{\epsilon}^{p^n}) (\dot{\bar{\epsilon}}^{\cdot^{m_2}}) (1 - T^{\cdot^m}). \quad (1.22)$$

This modification was made to account for evidence that the strain rate is not a linear function of the natural logarithm of strain rate but rather an exponential function. Values of the material constants for ARMCO iron for this modified model are given in lines 4 and 5 of Table 1.1 for tension only and tension and torsion data respectively.

1.2.1.2 Zerilli-Armstrong Model

Zerilli and Armstrong [33, 37, 38] developed an approximate constitutive model based on dislocation mechanics which considers effects of strain, strain rate, temperature and grain size on flow stress in a coupled manner. This model was developed using the same experimental tensile data used by Johnson and Cook [35] to develop their model.

The Zerilli-Armstrong model is based on the observation that each material structure type (FCC, BCC, HCP) will have its own constitutive behavior, dependent on the dislocation characteristics for the particular structure [32]. For face-centered cubic (FCC) metals, they calculate the effective stress with

$$\bar{\sigma} = \phi_0 + \phi_2 \bar{\epsilon}^{p^{1/2}} \exp(-\phi_3 T + \phi_4 T \ln \dot{\bar{\epsilon}}) \quad (1.23)$$

The equation for effective stress in body-centered cubic (BCC) metals is

$$\bar{\sigma} = \phi_0 + \phi_1 \exp(-\phi_3 T + \phi_4 T \ln \dot{\bar{\epsilon}}) + \phi_5 \bar{\epsilon}^{p^q} \quad (1.24)$$

In these equations $\bar{\epsilon}^p$ is the equivalent plastic strain, $\dot{\bar{\epsilon}}$ is the equivalent strain rate, T is the absolute temperature, and $\phi_0, \phi_1, \phi_2, \phi_3, \phi_4, \phi_5, q$ are material constants.

The main characteristics of equation (1.23) are the temperature softening and strain rate hardening coupled dependence of the effective stress with increased strain hardening. In the case of BCC metals (equation (1.24)), the strain hardening factor is uncoupled from strain rate hardening and thermal softening effects. The rationale for the differing approaches is the stronger dependence of yield stress on temperature and strain-rate in BCC metals compared to FCC metals [34]. The parameter ϕ_0 in both equations represents the influence of solute additions and grain size which is given by the following equation

$$\phi_0 = \Delta\sigma'_G + k\ell^{-1/2} \quad (1.25)$$

The term $\Delta\sigma'_G$ represents the influence of solute additions and the original dislocation density on the effective stress. The second term produces the increment in stress needed from the higher polycrystalline flow stress required at relatively low temperature for the transmission of plastic flow between grain boundaries due to slip band-stress concentration [37]. In this second term, also known as the Hall-Petch term [39], the variable "k" represents the microstructural stress intensity and " ℓ " is the average grain diameter.

The failure of the model to describe adequately the Taylor cylinder tests done on iron samples lead Zerilli and Armstrong [38] to consider that plastic flow by slip could be replaced by twinning at high strain rates in presence of large grain size. Zerilli and Armstrong [38] considered the main effect of twinning to be a refinement of grain size. To take this effect into account they modified equation (1.25) to get factor ϕ_0 when it is applied to equation (1.24) in the case of ARMCO iron,

$$\phi_0 = \Delta\sigma'_G + k\ell^{-1/2} \left[(N_T + 1)^{1/2} - 1 \right] \quad (1.26)$$

The modification applies to the Hall-Petch term of the equation. The number of twins, represented by N_T , must be determined experimentally or predicted based on twinning

strain. The modification is essentially an increase in effective yield stress due to mechanical twinning. Taylor cylinder tests simulations of iron specimens gave excellent results with this modification [38].

1.2.2 Other Models

In order to situate the models presented in the last section, the general principles of models with better physical background although more complex will be presented in this section.

Unified viscoplastic constitutive models are a class of generalized three-dimensional models in which the strain rate is decomposed into elastic and inelastic or plastic components [34, 40]. The plastic strain rate component is time dependent and represents all non-elastic processes such as creep and time-dependent plasticity. The interest in this type of model in dynamic plasticity problems lies in their inherent rate dependence, the incorporation of state variables to handle loading history effects, and their ability to model isotropic and directional hardening. Cook [41] showed that, for strain rates less than 10^6 s^{-1} , the results obtained with the Bodner-Partom model, a typical viscoplastic model, are similar to those obtained with the Johnson-Cook model. Cook indicated however that the Bodner-Partom model has a sounder physical background, which embodies the concept of a limiting strain rate observed above 10^6 s^{-1} and finally that a yield criterion for loading/unloading conditions is not needed with this model. The major drawback of the viscoplastic models, such as the Bodner-Partom one, is the need of iterative solutions when used in hydrocodes which necessitates determination and verification of convergence factors while increasing the running time.

Follansbee, in cooperation with different contributors, has developed one of the most advanced models in terms of closeness to physical theory of materials [33, 42, 43]. The Mechanical Threshold Stress (MTS) model relates the macroscopic stress-strain

behavior to microscopic properties [32] and accounts for the fact that plastic deformation changes the structure in a way that is history dependent. In addition, this model can treat any arbitrary loading history rather than a narrow band of strain rates as in semi-empirical models. In the MTS constitutive model, expressions are developed to take into account the variation of yield stress with strain rate and temperature as well as the evolution of state variables with strain, strain rate and temperature [43]. The MTS model gives a precise definition of physical behaviour of material but necessitates a large number of experiments to determine its factors. The MTS model is also more difficult to incorporate into hydrocodes compared to the simpler semi-empirical models presented above.

1.3 PRESENT RESEARCH

In the present research, the main focus was on obtaining mechanical properties of ARMCO iron from different stock shapes at different strain rates and elevated temperatures in order to investigate the behavior of this material. The work involved the installation of a tubular furnace to do studies at elevated temperatures with the TSHB facility previously commissioned at Carleton University [24]. Some important work was done to improve the data reduction method and to understand some of the problems identified by Clarke [24] with the Carleton TSHB. The equipment was also modified to enable interrupted tests through the installation of a momentum trapping system. Optical microscopy, when possible, was used to provide a qualitative view of the failure mechanism. Computer simulation work was done on a full bar model to study wave propagation in the apparatus and eventually improve specimen-only simulations. The latter simulations were used to obtain the factors to perform engineering stress-strain to true stress-strain conversion.

This thesis is organized as follows. Chapter 2 presents a description of the material used in this research along with a résumé of the literature review on ARMCO iron. The

experimental method describing the equipment used, and the experimental techniques along with specimen design and preparation is given in Chapter 3. Chapter 4 presents the numerical models used and the simulation results. The experimental results are given and compared with the simulations in Chapter 5. The results are discussed in Chapter 6, and the conclusions and recommendations are presented in Chapter 7.

Chapter 2

MATERIAL

The material studied in this work, ARMCO iron, will be discussed in this chapter. Iron has a body-centered cubic type (BCC) crystallographic structure known as ferrite. The name "ARMCO" iron is the proprietary name of ARMCO Steel Corp., Middletown, OH, for a soft magnetic iron (ingot iron) [44]. This nearly chemically pure iron is manufactured by the basic open-hearth process used in steel processing but the material remains in the furnace at a temperature between 1600 and 1700°C from 1 to 4 hours longer than for steel in order to remove impurities [45]. The material is then cast in ingots, hence the name ingot iron, which are rolled into plates or shapes. Typically, ARMCO iron is 99.94% pure with 0.013% Carbon and 0.017% Manganese [45]. Ingot iron is used in construction where ductile rust-resistant metal is required, such as in tanks, boilers, and condenser tubes. In addition to this use, ARMCO iron is utilized to manufacture electromagnetic cores and as raw material for specialty steels [45]. In manufacture of electromagnetic cores, the powder form of the material is mainly used nowadays. The high ductility of ARMCO iron has also made it a material of choice in the manufacture of liners used in explosively formed projectiles (EFP) [46]. In these charges, a dish shaped liner of ARMCO iron is deformed at high strain rates by the detonation of an explosive charge to produce a precision-formed projectile flying at velocities of 2 to 4 km/s.

2.1 HIGH STRAIN RATE BEHAVIOUR

Data on the deformation and failure of ARMCO iron at high strain rates was obtained by Worswick, Qiang, Niessen and Pick [47] through Taylor cylinder impact specimens and the study of recovered projectiles from EFP charges. In the Taylor cylinders, strain rates reaching 10^5 s^{-1} were achieved for periods of 10 μsec . Deformation occurred through dislocation slip and mechanical twinning. Voids nucleated at grain boundaries or impurities and joined to form cracks. In the EFP projectiles, the strain rates exceeded 10^5 s^{-1} , based on computer simulations, with values decaying to 10^4 s^{-1} after 50 μsec . The deformation processes were dislocation slip and twinning as in the Taylor cylinders. The center of the projectiles showed the occurrence of recrystallization. Computer simulations indicate that temperatures of the order of 500°C are achieved in the center of the projectiles. Recrystallization in cold worked iron occurs in approximately 10 minutes at 600°C [47] therefore the driving energy for recrystallization in deformed EFP's must be very high. The study of damage in the projectiles showed evidence of cavitation and adiabatic shear localization. Fracture occurred through shear localization across the projectile wall causing coalescence of individual voids to form a crack. Shear localization did not occur in Taylor specimens presumably due to lower strains and temperatures achieved in the specimens. Metallurgical analysis conducted by Weimann, Doeringsfeld, Speck and Lopatin [48] on the different parts of recovered EFP's projectiles showed that the rear of the projectile was fully recrystallized and strain free. Annealing occurs in cold worked iron when subjected to a temperature of 1090K (817°C) for several hours which led them to conclude higher temperatures must be attained in the projectile formation. Church and Cullis [49] indicated that, in metal-explosive interactions, the iron can be deformed at strain rates up to 10^6 s^{-1} and reaches temperatures in excess of 900K (627°C) and effective strains over 2.5. From these values of temperature with EFPs found in the

literature, a maximum value of 750°C along with intermediate values of 250 and 500°C were selected as pertinent for this work on the high strain rate behaviour of ARMCO iron.

Johnson and Cook [35] performed experiments on ARMCO iron samples using both tensile and torsional split Hopkinson bars. Their results for true stress versus strain rate are presented in Figure 2.1 for strain values of 0.1 and 0.2 and in Figure 2.2 for a strain value of 0.1. These authors calculated a linear regression curve from their experimental points on the assumption of log-linear relationship over the full range of strain rates. The number of data points used by Johnson and Cook, however, was limited.

Like Johnson and Cook, Nicholas [22, 34, 50] considers that the degree of rate sensitivity in ARMCO iron follows an exponential relationship for tensile testing in the range 10^{-3} to 10^3 s^{-1} which is indicated by a linear variation of stress with the logarithm of strain rate. Although Nicholas only provides data at the two extremities of the range, he considers this approximation to be valid for modeling purposes based on comparison with similar materials and because the stress is seen to approximately double in the range mentioned. Nicholas data of true stress as function of strain rate is presented in Figure 2.2 for a strain of 0.1.

Compressive data obtained by Lindholm [51] are presented in Figure 2.1 for various strains in the 10^{-3} to 10^3 s^{-1} strain rate range. Lindholm's data [51] gives a more complete picture of the rate dependency of ARMCO iron. For strain values of 0.020 and 0.051, the variation of stress with strain rate appears to be almost linear so the exponential relationship suggested by Johnson and Cook and by Nicholas would be correct. For strain values above the 0.1 value, the stress data for strain rates below 1.0 s^{-1} does not follow the same relationship as the data for higher strain rates. Lindholm [51] indicated the presence of a negative slope of the curves at higher strains for the 0.01 to 1.0 s^{-1} range. Lindholm [51] associates this effect with strain aging which occurs by diffusion of interstitial elements, in this case carbon and hydrogen, into the active dislocation sites. The

stress required to maintain flow depends on the effective interstitial diffusion rates, the temperature and deformation rate during the test. For comparison with other authors, Lindholm's data at a strain value of 0.1 is plotted in Figure 2.2. Figures 2.1 and 2.2 indicate, as mentioned by Lindholm [51], that a straight line could be assumed for strain rates below 1.0 s^{-1} and another one for values above this strain rate.

Reinders and Kunze [52] did some studies in tension at different strain rates on samples of ARMCO iron with different grain sizes. The samples studied had grain sizes of 15, 80 and $300 \text{ }\mu\text{m}$. They obtained the characteristic increase of flow stress with increasing strain rate. Under quasi-static strain rates, the grain size dependence follows approximately a Hall-Petch relation, but under dynamic rates this relation is not valid. High strain rate results from Reinders and Kunze indicate that grain size dependence under these conditions is minimal and the material with the largest grain size is nearly as strong as the one with the smallest.

Goldthorpe [53] presents experimental data aimed at verifying that the well established characteristic of independence of work hardening with strain rate for BCC metals at small strains also applies at higher strains. His data from tensile and compressive split Hopkinson bars proves that the assumption is true for strain values of at least 1.0 at room temperature. He also checked the existence of a direct relationship between work hardening dependency and temperature. This proved to be approximately true for small strains. At larger strains and elevated temperatures, there is a strain aging effect. Goldthorpe was able to determine that strain hardening has a temperature dependence associated with that of the shear modulus. Goldthorpe [53] obtained a stress value of 690 MPa at a strain of 0.1 for a strain rate of $5 \times 10^3 \text{ s}^{-1}$ which was plotted in Figure 2.2 and is in the same range as those obtained by other authors.

Johnson and Cook [35] performed tests at elevated temperature on ARMCO iron using a tube furnace mounted on their tensile split Hopkinson bar. They concluded that

elevated temperature caused a softening effect on the flow stress. This effect was included in their constitutive model as discussed in Chapter 1

2.2 MATERIAL USED IN THIS RESEARCH

All the material used in this project has been produced by ARMCO GmbH, a subsidiary of Thyssen Stahl, situated in Köln, Germany and obtained through Koëinig industries in Switzerland. The samples were taken from material used by SNC Industrial Technologies Inc. and Mining Resources Engineering Limited (MREL) to produce EFP liners. This material manufacturer had been chosen originally because of the high purity and reproducibility of its material. Material from plates of 20 mm and 25 mm thickness was studied in addition to material from a billet of 15 cm diameter. The three stocks have a purity of about 99.93% and the percentages of the different impurities are given in Table 2.1.

Metallographic studies of this material showed important differences in the grain size depending on the stock shape which were attributed to the manufacturing technique and temperature. The 20 mm plate had the largest grain size with large grains in the range 150 and 300 microns, as shown in Figure 2.3. In the 25 mm plate, there was a central region which had very fine grains in the range of 30 to 35 μm (Figure 2.4a) while very large grains (350-500 μm) were seen near the surfaces of the plate (Figure 2.4b). The layers were not equal on each side with thicknesses of about 3 and 5 mm. There was a very abrupt transition between these layers of coarse grains and the central area. The grain size range in the billet material was 100 to 200 μm and, in general, the grains were slightly finer than those found in the 20 mm plate (Figure 2.5). At the beginning of the project, a study of material in plates in which the grain size had been modified by cold rolling followed by various heat treatment processes was considered. This material had been prepared from a 25 mm plate. The resulting microstructures were very similar to what was

found in the central area of the as-received 25 mm plate, so it was decided to abandon this part of the study

The grain orientation in the plates was considered to be an interesting factor in the studies, however, the samples provided had been cut from the original plates without indication of the rolling direction. Metallography of specimens along the two major axes of the 25 mm plate sections gave indications of the rolling direction in which the grains were slightly more elongated. Consequently, most of the samples were manufactured with their axes aligned with what was assumed to be the rolling direction. Some samples were also manufactured in a direction perpendicular to the rolling direction. In the case of the 20 mm plate, all the samples were taken in only one direction

It had been considered desirable to study material from a North American supplier of ARMCO iron to compare it with the European source. However, it was found that in North America, ARMCO iron is currently only available as metal powder or small rods. ARMCO Steel Corp., the owner of the trademark, produced their last batch 15 years ago for the US Air Force.

Chapter 3

EXPERIMENTAL METHOD

In this chapter, the equipment used to perform the experiments, the specimen design, and the testing procedure will be reviewed.

3.1 EQUIPMENT

3.1.1 TSHB and Ancillary Equipment

The Carleton University Tensile Split Hopkinson Bar (TSHB) apparatus used in this research to test specimens at elevated strain rates in tension is described extensively by Clarke [24] so this discussion will be limited to the main components and the modifications made as part of this research.

The facility was developed to test materials at strain rates up to 1500 s^{-1} depending upon the test specimen configuration and material [24]. A schematic view of the original TSHB apparatus used in about one-half of the tests is presented in Figure 3.1a and a photograph of the apparatus is given in Figure 3.1b. As part of this research, the TSHB was modified to allow interrupted testing. Figure 3.2a presents a schematic of the new configuration while Figure 3.2b is a recent photograph of the apparatus.

The specimen to be tested in the TSHB is threaded between two long horizontal, high strength steel bars known as the incident bar and the transmitter bar. The gas gun is

mounted concentrically around the incident bar and used to propel a hollow cylindrical striker along the incident bar toward the end cap at velocities up to 20 m/s. The end cap is a shoulder, with a diameter equal to the outside diameter of the striker, machined at the end of the incident bar away from the specimen. The tensile pulse is produced by the impact of the striker on the incident bar end cap. This stress pulse, equal in length to twice that of the striker, travels at the longitudinal sound velocity from the end cap towards the specimen. The incident pulse is recorded at a strain gauge station on its way towards the specimen. When reaching the specimen, part of the stress wave is reflected in the incident bar due to impedance mismatch between the materials of the bar and the specimen. The reflected pulse is recorded at the same strain gauge station as the incident wave. The remainder of the wave is transmitted through the specimen and into the transmitter bar where it is recorded at a strain gauge station. The stress, strain and strain rate in the specimen are obtained as a function of time from the data reduction of the signals recorded at both strain gauge static is using the equations presented in Chapter 1.

The incident, transmitter and striker bars are made of 4340 steel which possess a sufficiently high yield point (689.5 MPa) and enough toughness to ensure that the bars remain elastic during the test at the strain rates studied. The steel was annealed since high temperature testing would eliminate any hardening prior to heat treatment. The incident bar has a total length of 204.0 cm and a diameter of 1.6 cm except for the end cap which has a diameter of 2.7 cm. This end cap has a cylindrical shape with a length of 2.5 cm and is an integral part of the bar. The transmitter bar has a length of 190 cm and a diameter of 1.6 cm. The strikers used have an inside diameter of 2.2 cm and an outside diameter of 2.7 cm. Press fit Teflon or Nylon bushings are put at the ends of the striker bar to allow smooth running of the striker over the incident bar. In this research, a striker of 30 cm length has been used for almost all of the tests except for some of the initial tests where a 40 cm long striker was used.

The gas gun shown in Figure 3.3 is used to accelerate the striker to the necessary impact velocity (6 to 14 m/s). The gun, mounted concentrically around the incident bar, consists of two coaxial, thick walled cylinders with end caps [24]. The normal operating pressure for the gas gun ranges between 170 and 415 KPa (25 - 60 psi). Below that range, because of the inertia and frictional losses of the system, the striker velocity was found to vary considerably. Although tests done on the gas gun and the momentum trap showed that pressure in excess of 415 KPa (60 psi) can be used without yielding the incident bar, this limit has been set up to ensure a large safety factor. In the range of striker velocities considered, the incident bar is subjected to stresses between 120 and 285 MPa. Clarke [24], in her design calculations, showed that a maximum striker velocity of 27.3 m/s could be achieved to stay within 80% of the yield stress of the bar.

The striker is driven out of the gun by a pusher. The pusher is made of aluminum and is fitted with two o-rings which seal the holes in the inner cylinder wall once the pusher is set in place prior to firing. The chamber between the cylinders of the gas gun is pressurized with nitrogen after the pusher-striker assembly has been pushed in place. Once the desired pressure is obtained, nitrogen is then fed in behind the pusher. As the pusher is moved forward by the gas, the holes on the inner cylinder are opened and nitrogen rushes into the barrel, propelling the pusher-striker assembly toward the end cap end of the incident bar.

When the striker impacts the end cap, it accelerates the incident bar to a velocity which is half the striker velocity. In the original design shown in Figure 3.1, the incident bar movement is stopped by the momentum brake shown in Figure 3.4. This device is made of a steel rod with a diameter equal to the diameter of the end cap (2.7 cm) and a length of 15 cm inside which the momentum is transferred. This rod sits in a rubber block cut in two along its length and presenting a longitudinal cylindrical groove for the rod. The

rubber block-rod arrangement is assembled in a heavy steel case which is bolted to the base of the bar assembly

A plot of the strain pulses measured at the strain gauges with the arrangement shown in Figure 3.1 is presented in Figure 3.5. This figure shows the incident pulse followed by the reflected pulse at the specimen end of the incident bar. The compressive reflected pulse is then reflected at the end cap creating a tensile pulse which moves back toward the sample. Therefore, if the sample does not break at the first pulse, a large number of pulses would load it, ultimately producing its failure. It is therefore impossible to conduct an adequate failure analysis due to the large number of loading pulses.

In order to limit the number of pulses going through the specimen to one and be in a position to examine damage within the specimen as a function of a known applied strain, interrupted tests are conducted. Interrupted tests are achieved by trapping the reflected pulse as it reaches the end of the incident bar and the transmitted pulse as it reaches the end of the transmitter bar to avoid reloading of the specimen from the pulses reflections. The momentum associated with the reflected and transmitted pulses is absorbed in fixtures added at each end of the apparatus. At the incident bar end, a momentum trap consisting of a 4340 steel rod of a diameter equal to the incident bar (1.6 cm) and a length just greater than the longest striker (45.7 cm) was installed between the incident bar and the momentum brake. A precision gap is set between the end cap of the incident bar and the momentum rod so that the gap is just closed after the incident pulse has left the end cap area. Later on, as the compressive reflected pulse reaches the end cap, the pulse is transferred in the momentum rod. This pulse will reflect as a tensile pulse within the momentum trap rod but cannot re-enter the incident bar because a tensile pulse cannot be transmitted across the gap between the rod and the incident bar. A schematic of this arrangement is shown in Figure 3.6a and a photograph is presented in Figure 3.6b. On the transmitter side, a threaded end cap has been added at the end of the transmitter bar away

from the specimen and a hollow cylinder also made of 4340 steel with the same configuration as the strikers and a length of 45.7 cm has been fabricated to run on the transmitter bar. When the transmitted pulse reaches the end cap at the end of the transmitter bar, it is transferred to the hollow cylinder which is then stopped by a momentum brake system. Figure 3.7a presents a schematic of the new set-up at the end of the transmitter bar and a photograph is given in Figure 3.7b. For comparison with Figure 3.5, the signals recorded at the strain gauges are presented in Figure 3.8. This last figure shows that the incident bar signal is now limited to almost exclusively the incident and reflected pulses. In the transmitter bar, the reflection of the transmitted signal presents a major reduction.

As shown in Figures 3.1b and 3.2b, both the incident and transmitter bar, as well as the momentum trap bar, in the case of the interrupted tests design, are set in adjustable height shaft supports. In addition, both the incident and transmitter bar end caps rest on semi-cylindrical cradles.

All of the components mentioned above are laser aligned with the axis of the gas gun central bore. The gas gun was carefully leveled when it was originally set in place and this component, because of its large weight, is used as the reference from which the other parts of the system are aligned. Using special plugs and mirrors fitted into the holes of the gas gun end caps, the laser beam is positioned so that the light emitted travels along the center of the gun. The other components (bar holders and momentum brake) are then aligned with the laser. Following this alignment, the incident and transmitter bar are put in place and final adjustment is made until the bars slide freely.

The stress pulses in the bar are measured using strain gauges. In the assembly used for this research, two strain gauges were put on opposite sides of each bar at a distance of 80 cm from the specimen end of the bars. Kulite semi-conductor gauges model number UGP-1000-060 were selected over more common foil gauges because of their high gauge

factor (155 versus 2), so the signal does not need to be amplified before being recorded. As shown in Figure 3.9, the two strain gauges of each station are connected to a standard Wheatstone bridge arranged so as to cancel bending [54]. The other arms of the bridge consist of one fixed and one variable resistor. The input or excitation voltage to the bridge is supplied by a Hewlett-Packard model 6213A power supply capable of producing a constant DC voltage to within ± 0.1 mV. The excitation voltage used is 1400 mV. The output voltages from the Wheatstone bridge for each bar are recorded using a two channels Nicolet Pro 30 digital storage oscilloscope. This oscilloscope has 12 bit resolution with a maximum sampling rate of 10 million samples per second with a temporal accuracy of 1 ns.

The striker velocity is measured using two reflective infrared sensors mounted near the incident bar end cap support. When the striker passes the first sensor, a counter is triggered which is stopped when the striker passes the second sensor located 2.54 cm from the first sensor.

3.1.2 Furnace

One major objective of this research project was to conduct tests at elevated temperatures which was achieved by heating samples to the required temperature by means of an electrical tube furnace. The furnace used is a SATEC model #1TF01200C-1.2-4-8-8 which is illustrated in Figure 3.10. This single zone configuration furnace has a heated length of 10.16 cm and an inside working diameter of 3.1 cm. The furnace outside dimensions are 20.3 cm diameter by 20.3 cm overall length. The temperature range of the furnace for continuous operation is between 25 and 1150°C which easily covers the temperature range planned in this research. The temperature controller used for the furnace is a model TCS100 from SATEC.

3.1.3 Quasi-Static Testing Equipment

In order to compare the dynamic properties at high strain rates with the more common quasi-static properties obtained at low strain rates, tensile tests were performed with a standard uniaxial tensile tester using the same specimen design as for the TSHB. These comparisons will enable the observation of the differences between the two strain rate regimes

The uniaxial testing apparatus was an INSTRON model TTDL 2300 lbs Universal fitted with special adapters manufactured to hold the TSHB specimens. A load cell of 1 KN was used with a load range of 0-90 KN. A displacement velocity of 0.254 cm/min was used. This apparatus is connected to a micro-computer which produces load-displacement data files which are later converted to stress-strain plots.

3.2 SPECIMEN DESIGN

Two general types of specimen were used in this program, uniaxial and notched specimens. The uniaxial configurations were used to obtain the stress-strain curves under uniaxial conditions. The purpose of the notched configurations was to obtain tensile data under the higher triaxiality induced by the notch and to focus deformation within the smaller notched region thus obtaining higher strains for a given incident strain pulse.

All of the specimen configurations, both notched and uniaxial, used in this project featured left hand threads on one end of the specimen and right hand threads on the other so that they could be screwed onto the bars without turning the bars.

3.2.1 Uniaxial Specimen Design

The uniaxial specimen configuration which was used for most of the tests in this research program is based on scaled version of some various designs in the literature [2, 13, 18, 20, 22]. The scaling was made considering the bar dimensions used by the different

authors which lead to figures of merit relating the specimen gauge length and diameter to the bar diameter. This specimen configuration is labeled UA1. The first letter indicates that the specimen is uniaxial, the second letter refers to the gauge length and the number relates to the version. The general drawing for uniaxial specimens is presented in Figure 3.11 and the data for the different variations is given in Table 3.1. Staab and Gilat [19] indicated that the specimen gauge length over gauge diameter ratio could influence the results, so a shorter version (UB1) was designed and tested to examine this effect.

The modifications done to the bar to enable interrupted tests made also possible the study of the relations between the stress applied to the specimen and the metallography even if the specimen did not break on the first pulse.

3.2.2 Notched Specimen Design

The notched specimen design increased the possibility of obtaining failure of the specimen on the first tensile pulse compared to the uniaxial designs because of the stress concentration at the center of the notch and the higher triaxiality at that point. The triaxiality (σ^*) is defined as the ratio of the hydrostatic or mean stress (σ_m) over the flow or effective stress ($\bar{\sigma}$). The maximum value of triaxiality, based on a Bridgman [55] analysis, is presented in references [50] and [56] as

$$\sigma_{\max}^* = \frac{1}{3} + \ln \left(\frac{r_s}{2R_n} + 1 \right), \quad (3.1)$$

where r_s is the gauge radius of the specimen and R_n is the notch radius. The notch radius and depth control the triaxiality. The value of triaxiality in a specimen indicates the severity of stress state which will be experienced by the specimen during loading.

During the initial part of this project aimed at learning the functioning of the TSHB and to get a feeling for the ARMCO iron behaviour, configurations similar to those used by Clarke [24] were tested. These configurations are labeled NA1 and NJ1. The first letter

is related to the type of sample; "N" being used for notched specimens. The second letter indicates the type of notch. Letters "A" and "C" are specimens with the same triaxiality as those used by Hancock and Mackenzie [56] and labeled "A" notch and "C" notch by those authors. The "J" notch is a slight variation on the Hancock and Mackenzie "E" notch with the same triaxiality as a design used by Rajendran [50]. Finally, the number indicates the version of the specimen design. A general drawing for this type of specimen is given in Figure 3.12 and the dimensions are given in Table 3.2. In addition to NA1 and NJ1 configurations, another with a sharper notch (NC1) was used in the early tests.

Using equation (3.1) coming from Bridgman [55] analysis, the following maximum triaxiality values were obtained for the specimens. Specimen NA1 has a triaxiality of 0.74, NJ1 has 0.61, and specimen NC1 has a value of 1.03. Those specimens had shoulders on the sides of the notch with a diameter larger than the threads originally designed to increase the strain localization at the center of the notch. Because of these shoulders, however, it was difficult to ensure that the specimen threads were bottoming out on the bar threads which led occasionally to inadequate transfer of the pulse between the bars and the specimen. Designs NJ2 and NJ3, whose shoulders have the same diameter as the thread major diameter, were produced to test the importance of those bigger shoulders. These specimens have the same triaxiality as specimen NJ1 (0.61) but are certain to bottom out at the base of the threads ensuring adequate transfer of the incident pulse into the specimen. Specimen NJ2 is similar to specimen NJ1 with smaller shoulder diameter. Specimen NJ3 is a scaled geometry of a specimen used by Rajendran [50]. Following the tests with these configurations, specimen design NJ2 was chosen to conduct the experiments using the "J" notch design because the results obtained were similar to those obtained with design NJ1 while ensuring adequate transfer of the incident pulse. Design NJ3 also gave similar results to NJ1 but was more difficult to produce. Based on these

results, the shoulders on the NC1, "C" notch specimen, were modified to match those of the "J" notch. This new design was labeled NC2

Prior to an experiment, the dimensions of the specimen involved were measured with a vernier caliper and an optical comparator to check their precision and to obtain the actual value of the gauge length and the gauge diameter to be used in the data reduction for each specimen. The precision obtained on the gauge length and diameter, which are the critical dimensions, was within $\pm 0.13 \text{ mm}$ ($\pm 0.005''$). The precision for the other dimensions of the specimen was within $\pm 0.51 \text{ mm}$ ($\pm 0.020''$)

3.3 TESTING PROCEDURES

3.3.1 Calibration of Strain Gauges

Regularly throughout this research project, the calibration of the strain gauges was verified. Because of the long wire runs between the gauges and the recording equipment, in addition to the presence of the bridge in the circuit, the gauge factors and resistance were measured directly instead of utilizing those given by the manufacturer

The equipment used to perform the calibration is very similar to what is presented in reference [24] and it is illustrated in Figure 3.13. The only difference resides in the use of a split block instead of a split ring between the gas gun and the striker. The split ring had been originally developed for calibration with the 40 cm striker, so for the 30 cm striker a larger piece was needed.

The full non-linear Wheatstone bridge equation [57] has to be used instead of the linearized version normally used with foil gauges due to the large gauge factors of the semi-conductor gauges. The bridge arrangement used in the experiments and the labeling of the bridge components is shown in Figure 3.9. The equation to obtain the output voltage of the bridge from the resistance and the input voltage is

$$E_v = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} V_c, \quad (3.2)$$

where E_v is the output voltage from the Wheatstone bridge and V_c is the input voltage. R_1 is the resistance of the first gauge which is given by $R_1 = R_{1_0}(1 + GF_1 \epsilon)$, with R_{1_0} being the initial gauge resistance, GF_1 the gauge factor and ϵ the strain. R_3 is the resistance of the second gauge and is given by $R_3 = R_{3_0}(1 + GF_3 \epsilon)$. Substituting the definitions of R_1 and R_3 into equation (3.2) gives

$$E_v = \frac{(R_{1_0} + R_{1_0} GF_1 \epsilon)(R_{3_0} + R_{3_0} GF_3 \epsilon) - R_2 R_4}{(R_{1_0} + R_{1_0} GF_1 \epsilon + R_2)(R_{3_0} + R_{3_0} GF_3 \epsilon + R_4)} V_c \quad (3.3)$$

This equation requires knowledge of the gauge factors of each gauge and the initial resistance of both the gauges and the resistors. These values are obtained during the calibration. One gauge from each pair is hooked up to its respective bridge leaving the bridge circuit open. Using an ohm-meter, the resistance in the gauge is measured when a tensile load is applied to the bar. The load value is given by the voltage reading of the output of a load cell. A curve of the resistance in the gauge as a function of the load applied is obtained. From linear regression of this data, the initial resistance of the gauge (b_c) is obtained from the intercept and, using the slope (m_c) and the conversion factor between load and strain, the gauge factor is obtained with

$$GF = \frac{m_c \times CF}{b_c}, \quad (3.4)$$

where CF is a conversion factor taking into account the applied load to the bar, Young's modulus of the bar material, and various unit conversions.

3.3.2 Preliminary Tests

Before performing experiments with samples, preliminary tests aimed at testing the proper functioning of the system were conducted. These tests were normally done at the

beginning of each day of experimentation. In the first type, called incident bar only tests, there is no link between the incident and the transmitter bar, therefore the incident pulse is completely reflected at the end the incident bar. This test is useful to test the functioning of the gauges on the incident bar in dynamic testing, the velocity detector and the gas gun. It was also seen that some tests were needed to warm up the firing system and obtain repeatability of the velocity for a given pressure. Some of these incident bar only tests are done at different pressures between 30 and 60 psi. During the course of the research, some incident bar tests were performed with only one gauge, the other one being replaced by a dummy resistor of $900\ \Omega$, to see the extent of the bending in the bar. The results indicated a difference of only 2% compared to those obtained with a pair of gauges therefore minimal bending is present. Typically, 5000 points with a sampling interval of 200 ns were recorded for these incident bar only tests. The data reduction consisted of transforming the voltage into strain pulses using the same method as for the actual experiments.

The second type of preliminary test is called a tie test. In these tests, the specimen is replaced by a AISI 4340 steel tie illustrated in Figure 3.14. The purpose of this tests is to force the incident and transmitter bars to act as a single rod. This test is useful before a series of experiments to check the functioning of the gauges on the transmitter bar. From the study of the recorded pulses it was possible to see how the pulses add up and the temperature effect on the pulse transmission in the threads. Normally, two tie tests were performed right after the incident bar only series of tests. For these tie tests, 10000 points are recorded with a sampling interval of 200 ns, so the signal was recorded for a total duration of 2 ms. The trigger value on the oscilloscope was set at 20 mV with a pre-trigger time representing 2% of the total time or $40\ \mu\text{s}$. The data reduction of these tests is similar to that used for the actual experiments.

3.3.3 Room Temperature Experiments

Following the successful running of the preliminary tests, actual tests are carried out. The specimen is screwed into the bars, taking care that no torsion is applied across the gauge length. A precise gap based on the expected striker velocity is set between the end cap and the momentum trap bar using a feeler gauge. The input voltage to the bridges is set to 1400 mV. The variable resistor potentiometer button is adjusted to zero the output of each Wheatstone bridge and the oscilloscope is put in the ready mode. The settings for the oscilloscope are the same as for the tie tests: 10000 points with a 200 ns sampling interval, a trigger point at 20 mV and a pre-trigger of 2%

The recorded signals from both channels of the oscilloscope are recorded on floppy disk. The first step in the analysis of the signals is done using a suite of tests software called Viewpoint [58]. This software enables the transformation of the results from the oscilloscope format to the ASCII format for input to the data reduction programs. In addition, this software has the capability to do signal processing, such as Fast Fourier Transform and different type of filters which are used to remove noise from the recorded signals. Following verification with a fast Fourier transform of the signal, a low pass filter with a transition frequency of 50 KHz, a gain of 0.01 and a width of transition from pass to no-pass of 10 KHz was selected for these experiments.

The next step is the conversion of the filtered recorded voltages from the Wheatstone bridges to strain. Equation (3.3) can be arranged to give

$$E_v A - V_c B + (E_v C - V_c D)\epsilon + (E_v E - V_c F)\epsilon^2 = 0, \quad (3.5)$$

where A is equal to $(R_{1_0} + R_2)(R_{3_0} + R_4)$, B equals $(R_{1_0} R_{3_0}) - (R_2 R_4)$, C is equal to $(R_{1_0} GF_1(R_{3_0} + R_4)) + (R_{3_0} GF_3(R_{1_0} + R_2))$, D equals $R_{01} R_{03}(GF_1 + GF_3)$, and E is equal to $R_{01} GF_1 R_{03} GF_3$. Equation (3.5) has two roots for the strain value (ϵ) but it was found that

the absolute value of one root is always too large by several orders of magnitude to be physically reasonable so the smallest root is retained.

Two programs have been written in FORTRAN 77 to perform the data reduction on the preliminary tests and the experiments. These programs are presented in Appendix A. The first one, STRAIN, is used to do the conversion of voltage to strain of the experimental data files based on equation (3.5), to determine the beginning of the pulses and study the addition of the pulses to see how close this addition follows equation (1.3). This program was used for both the preliminary tests and the experiments. The second program used for data reduction of the experiments is called NICOLET. This program has a conversion part like STRAIN but its purpose is to take the process further by first calculating the engineering stress and strain in the specimen as well as the strain rate based on the equations presented in Chapter 1 (equations (1.11) and (1.12)). From these results and the conversion factors obtained from the computer simulation studies presented in Chapter 4, the true stress and strain values in the specimen are then calculated. Those results are put in files which can be processed by graphic programs to produce engineering stress versus strain, strain rate versus time and true stress versus strain graphs.

In general, the true stress-strain curves exhibit some ringing which is attributed to Pochhammer-Chree ringing [6,7] in the bars. As explained in Chapter 1, this effect is related to the wave dispersion. During the course of this research work, methods to remove the ringing were studied and it appeared that the best results were obtained by filtering the true stress-strain data. The frequencies of the ringing proved to be dependent on the specimen geometry and the experiment temperature. Reviewing the FFT curve permits determination of the frequencies which should be removed with a stop band filter. Both the FFT studies and filtering were done using the Viewpoint software [58].

As a consistency check, the measured striker velocity can be used to calculate the expected amplitude of the incident pulse (ϵ_{im}) using

$$\varepsilon_{lm} = \frac{V_s}{2C_0}, \quad (3.6)$$

where V_s is the velocity of the striker and C_0 is the longitudinal sound velocity in 4340 steel. This result is compared with the amplitude of the measured pulse. The duration of the pulse is obtained with

$$\Delta T_l = \frac{2L_s}{C_0}, \quad (3.7)$$

where L_s is the length of the striker. This expected duration is also compared with the recorded signal. The comparison of the measured pulse amplitude and duration with the values calculated using equations (3.6) and (3.7) gives some indication of the validity of the measured values.

3.3.4 Elevated Temperature Experiments

The general procedure for the tests at elevated temperature is quite similar to testing at room temperature. Testing takes place as soon as the required temperature is reached at the surface of the gauge length area of the specimen, as measured by a K-type thermocouple. The specimen is carefully centered longitudinally in the furnace to ensure that the heating curve is the same on both sides to facilitate data reduction.

Prior to the testing at high temperature, some experiments were done to obtain the set point for the furnace controller and an idea of the time needed to reach the required temperature at the surface of the sample. Some measurements were also done to obtain the temperature at different points along the heated portion of the incident and transmitter bar in order to do the temperature compensations using the method developed by Chiddister and Malvern [15]. These measurements were done using K-type thermocouples fixed on the bar and on a sample screwed onto the bars. A specimen with the NJ2 design was used to do this test. The first thermocouple was situated at the middle of the sample, followed by three additional thermocouples spaced at intervals of 2.5 cm, then two

thermocouples at a spacing interval of 5 cm. The first heating test showed that the bar supports were acting as heat sink and that, past their position, the temperature was within 10°C of room temperature even when the sample was heated to 750°C. Tests were also done with thermocouples situated at different positions on the surface of the sample to confirm that it was heated uniformly.

These heating tests produced the curves shown in Figure 3.15 for the three temperatures (250°, 500° and 750°C) used in this research. From these curves, it was decided to divide the distance of 25 cm from the specimen into four steps in temperature. Table 3.3 gives the temperature used for each step as well as the distance over which it is applied. Using these temperatures, the Young's moduli are computed using the temperature dependence given in reference [26], assuming the behaviour was linear as done in reference [15]. The Young's moduli values used in this research are also given in Table 3.3. These factors are used to perform the data reduction based on the method described in reference [15] and presented in detail in Appendix B. The FORTRAN 77 program NICOLETH, presented in Appendix B is used to do the conversion between the bridge voltage and the gauge strains and to calculate engineering and true stress and strain values as well as strain rate values based on equations (1.16) and (1.17). The filtering treatment described for the room temperature tests was also applied to high temperature tests.

Chapter 4

COMPUTER SIMULATIONS

Computer simulations of the TSHB were used to study the wave propagation within the apparatus and to aid in the interpretation of the experimental results. Specimen-only calculations in which only the specimen was simulated were used to obtain factors to convert the experimental engineering stress-strain data into true stress-strain curves. The specimen-only simulations were also used to perform Bridgman analysis [55] to obtain the "Bridgman factors" to convert the stress-strain data from notched specimen data into uniaxial data.

The numerical simulations were done with LS-DYNA2D [59] which is a version of the DYNA2D code produced by Livermore Software Technology Corporation (LSTC). LS-DYNA2D is a vectorized, lumped mass, explicit two-dimensional axis-symmetric and plane strain finite element code used for analyzing the large deformation, dynamic response in inelastic solids [60]. This code uses quadrilateral and triangular elements for spatial discretization of the model. The equations-of-motion are integrated by the central difference method (Petrov-Galerkin) [60]. LS-DYNA2D has a contact-impact algorithm permitting gaps and sliding with friction along material interfaces. It uses linear-quadratic bulk viscosity to smear shock fronts over several elements to dampen numerical oscillations. One interesting feature of the LSTC version of the program DYNA2D is a

general interface enabling a user to introduce his own constitutive model in a 'user subroutine' rather than making modifications to different parts of the program. LS-DYNA2D was modified for this research to enable the dumping of strain at every calculation cycle for up to five elements in the model. This modification was done to obtain a precise curve of strain versus time at different points in the bar, particularly at the strain gauge locations, hence improving the wave propagation study in the complete model of the TSHB.

Two methods have been used to prepare the input files containing the geometry and the mesh for the models for LS-DYNA2D. The first models were prepared with PATRAN [61] and then translated into the input file with PATDY2 [62]. Some models were prepared with LS-MAZE [63], the pre-processor developed by Hallquist for LS-DYNA2D. LS-ORION [64] was used as the post-processor for the analyses.

4.1 FULL BAR SIMULATION

The study of wave propagation in the TSHB was done with a model of the entire apparatus. This model includes the incident, transmitter, and striker bars along with the specimen. The uniaxial specimen UA1 and the notched specimen NJ2 were considered in the simulations.

4.1.1 Model and Load Conditions

Since all of the components of the TSHB considered in the model are axis-symmetric about their common axis, only one-half of their cross-section needed to be discretized. A schematic view of the parts of the model along with the applied boundary conditions is presented in Figure 4.1. A constraint is defined along the longitudinal axis ($r = 0$) to impede displacements in the radial direction. The specimen is fully tied to the incident and transmitter bars. All of the elements of the striker bar are assigned the initial

velocity at which it will impact the end cap portion of the incident bar. An intermittent contact boundary condition known as a slideline is defined at the interface between the end of the striker and the end cap.

The incident and transmitter bars are meshed without grading because these parts remain in the elastic regime during the simulation; therefore large deformations are not expected. In order to reduce the computing time, only part of the length of these bars were modeled, with the length of the bars chosen to be large enough to ensure that the waves are independent of their reflections at the position of the strain gauges. During the development of the model, the full length of the bars was simulated for comparison with the shorter bar model and the results proved to be similar for both cases. An initial mesh was selected based on references [24] and [30], then subsequently optimized.

The dimensions of the bars used in the model as well as the number of elements in both the axial and radial direction are presented in Table 4.1. A view of the mesh used for the striker and the incident bar is given in Figure 4.2. The meshing of the transmitter bar is similar to the incident bar. Since the majority of the experiments in this research were conducted using the 30 cm striker, only this striker was considered in the simulations.

Figures 4.3a and b show the mesh used to model the UA1 and NJ2 specimens. These meshes are viewed as being somewhat coarse, however, the purpose of the full bar simulations were mainly to study the wave propagation and not the precise deformation in the specimen. The meshes are finer in the central area where most of the plastic deformation occurs and graded to become coarser where the specimen meets the bar. The grading is very important because LS-DYNA2D uses a lumped mass formulation method and drastic changes in the size of adjacent elements can result in spurious reflection of stress waves.

The incident and transmitter bars, and the striker were modeled as elastic-perfectly plastic with material properties corresponding to AISI 4340, that is, a density of 7.8869

g/cm³ with values for Young's modulus, Poisson's ratio and yield stress being 206.9 GPa, 0.3, and 689.5 MPa, respectively. An elastic-plastic model was used in order to check for possible plastic deformation in the end cap or at the impact surface of the striker, even though the bars are expected to remain elastic throughout the loading.

The Johnson-Cook constitutive model [35], which has been described in Chapter 1, was used to model the specimen. The properties used in this model are presented in line 1 of Table 1.1. The alternate sets of properties presented in lines 2 and 3 of Table 1.1 were also considered but produced very minimal changes in the results for the strain rate studied.

The implementation of the Johnson-Cook model in LS-DYNA2D uses an equation of state to describe the material pressure-volume-energy relation. The Mie-Gruneisen [59] equation of state, which relates shock velocity (v_s) to particle velocity (v_p), was used. For ARMCO iron in the range of pressure of interest in our simulations, it is acceptable to consider the linear form of the shock velocity versus particle velocity relation also known as the Hugoniot. The form of the Mie-Gruneisen equation of state used for compressed materials was

$$p = \frac{\rho_0 C_m^2 \mu \left[1 + \left(1 - \frac{\Gamma_0}{2} \right) \mu - \frac{1}{2} \mu^2 \right]}{\left[1 - (S_1 - 1) \mu \right]^2} + \Gamma_0 E_I, \quad (4.1)$$

and for the expanded materials it was

$$p = \rho_0 C_m^2 \mu + \Gamma_0 E_I, \quad (4.2)$$

where p is the pressure, ρ_0 is the initial density of the material, C_m is the intercept of the $v_s - v_p$ curve, Γ_0 is the Gruneisen gamma, S_1 is the slope of the $v_s - v_p$ curve, μ , a density relationship, is equal to $\rho/\rho_0 - 1$, and E_I is the internal energy density. The coefficient values assigned for ARMCO iron for this equation of state were taken from reference [65] and are $C_m = 0.3574$ cm/ μ s, $S_1 = 1.92$ and $\Gamma_0 = 1.69$.

4.1.2 Results

Strain versus time predictions at the strain gauge positions are presented in Figure 4 4a for the uniaxial specimen and 4 4b for the J-notch specimen. Numerical ringing can be observed at the top of the incident pulse and in the transmitted pulse. Work has been done to reduce the extent of this numerical ringing through the use of artificial viscosity parameters and use of the Moss-White artificial viscosity method [66] but it could not be completely eliminated. Verification of the pulse addition according to equation (1.10) was done and proved correct. The incident pulse is the same for both specimen types. The amplitude of the transmitted pulse is larger for the J-notch specimen compared to the uniaxial one due to the stress concentration produced by the notch. Comparison with experimental curves will be discussed in the next chapter.

4.2 SPECIMEN-ONLY SIMULATION

Simulations considering just the specimen were used to help in interpreting the experimental results, to develop a correlation between measured engineering stress-strain and true stress-strain, and to perform Bridgman analyses [55] of the notched specimens. A specimen-only model enables shorter runs with finer meshes and the possibility to output more detailed data during the simulation, principally for the specimen deformation.

4.2.1 Model and Load Conditions

All of the specimen configurations presented in Chapter 3 were modeled in this study. Figures 4 5a, b and c present the meshes and boundary conditions for the most widely used specimens in the experimental work: the uniaxial specimen (UA1), and the selected versions of the J-notch (NJ2) and C-notch (NC2) specimens. As shown in these figures, the parts of the incident and transmitter bars which surround the threaded portion of the specimens are included in the model to provide a more realistic constraint on the

specimen. No displacement is allowed radially along the axis. The nodes at the transmitter end of the specimen are fixed in the axial direction.

The uniaxial specimen model shown in Figure 4.5a has a slight reduction in radius representing 1% of the nominal radius at the specimen center. In experiments involving uniaxial specimens, necking occurs because of defects in the crystal structure or impurities in the material. In principle, imperfections could be introduced by "numerical noise" coming from a finer mesh in the area of interest [49]. However, preliminary simulations of the uniaxial specimen did not trigger any necking, even after trying different arrangements of the mesh so small reduction in radius as an initial imperfection was added to initiate necking.

Deformation of the specimen is imposed by the application of a prescribed velocity history at the nodes at the incident end of the model. Two velocity-time histories have been considered. The first method uses a constant velocity as an "ideal" condition. The amplitude of the prescribed velocity (v_{spec}) is related to the nominal strain rate of the specimen by

$$v_{spec} = v_1 - v_2 = \dot{\epsilon}_s L_0, \quad (4.3)$$

where v_1 and v_2 are the velocities at the incident bar-specimen interface and the specimen-transmitter bar interface, respectively, $\dot{\epsilon}_s$ is the strain rate in the specimen and L_0 is the initial gauge length of the specimen. Since, in the model, the transmitter end of the specimen is constrained axially ($v_2 = 0$), we have $v_{spec} = v_1$. The time duration of the prescribed velocity is selected to be the same as the experimental duration of the incident pulse, which is given by equation (3.6) as

$$\Delta T_1 = \frac{2L_s}{C_0}, \quad (4.4)$$

where L_s is the length of the striker and C_0 is the longitudinal sound velocity in the bar material.

The second method considered to apply velocity-time history to the specimen was to recreate the pulse velocity obtained in the full bar simulation described above. Using LS-ORION, velocity-time curves were obtained for a node at each end of the specimen. By subtracting these curves, representing v_1 and v_2 as indicated in equation (4.3), we obtained a curve of the velocity across the specimen (v_{spec}) as a function of time for the duration of the incident pulse. The specimen velocity-time curves obtained with both methods are shown in Figure 4.6.

The material properties and constitutive models used in the specimen-only simulations were identical to those described above for the full bar simulations.

4.2.2 Correlation between Engineering Stress-Strain and True Stress-Strain

Using the results of the specimen-only simulations, a correlation between engineering stress-strain and true stress-strain to be used with the experimental data was produced. The reduction of experimental data using the equations presented in Chapter 1, leads to engineering stress-strain curves based on specimen gauge length and initial diameter at the center of the specimen. Constitutive model parameters, however, are determined from true stress-strain curves based on the true diameter throughout the test; therefore, some relationship between the engineering and the true values is required. The best method to obtain the correlation is through the use of high speed photography to monitor specimen diameter but this technique is very expensive and was not available.

The method used is based on the study of the results of a series of specimen-only simulations. Five strain rates were selected, so as to cover the possible experimental range, and the equivalent velocity curve was obtained with equation (4.3).

From the numerical results, a plot of true diametral strain (ϵ_{diam}) versus engineering axial strain (ϵ_{axial}) was created. The engineering axial strain is defined by

$$\epsilon_{\text{axial}} = \frac{L - L_0}{L_0}, \quad (4.5)$$

where L_0 and L are the initial and current gauge length respectively. The gauge length of the uniaxial specimens was taken as the length of the central cylindrical area of the specimen. For the notched specimens, the length between the outside of the shoulders was used. The true diametral strain is obtained with

$$\epsilon_{\text{diam}} = 2 \ln \left(\frac{d_0}{d} \right), \quad (4.6)$$

where d_0 and d are the initial and current gauge diameters respectively. A cubic polynomial was fit to the data of each specimen design and these equations were used to convert the measured experimental axial strain values to true diametral strain values. The parameters for the cubic polynomial for each specimen design are given in Table 4-2 and the curves for the specimens UA1, UB1, NJ2 and NC2 are presented in Figures 4.7a to d.

Values of ductility (true strain) and axial strain (engineering strain) determined from deformed specimens are also plotted on these figures to check the accuracy of the correlation. The gauge diameter at either the smallest point or at the failure point as well as the gauge length were measured with an optical comparator after the experiments. From these values, the ductility was calculated with equation (4.6) and axial strain was obtained with equation (4.5). For the uniaxial specimens, although the experimental data in Figures 4.7a and 4.7b covers a very small range of strain, the results indicate that the numerical curve gives an adequate prediction of the values. The level of scatter in the data is attributed to errors in the measurement, the difficulty in finding the smallest diameter, and the presence of more than one neck. The axial strain and ductility data is also plotted on Figure 4.7c for NJ2 specimens and 4.7d for NC2 specimens to compare with the numerical curves. Figure 4.7c indicates that the relationship is acceptable since the values are relatively close to the predicted curve considering the limitations in the measurement. For the C-notch, the differences shown in Figure 4.7d are larger but the final length of the

specimen is very difficult to measure exactly on a failed specimen and small dimensional errors can lead to large differences in the ductility values. Furthermore, the diameter at the center of the notch is also very difficult to measure precisely on this specimen geometry.

The experimental engineering stress (S_{exp}) can be converted into true stress (σ_{true}) with

$$\sigma_{true} = S_{exp} \frac{A_0}{A}, \quad (4.7)$$

where A_0 and A are respectively the initial and current gauge cross-sectional areas. The current gauge area is obtained by equating the following definition of the diametral strain

$$\varepsilon_{diam} = \ln \left(\frac{A_0}{A} \right), \quad (4.8)$$

to equation (4.6) so

$$\sigma_{true} = S_{exp} e^{\varepsilon_{diam}}. \quad (4.9)$$

The conversion method and equations introduced above were implemented in the programs NICOLET and NICOLETH presented in Appendices A and B to obtain the true stress-strain curves from the strain gauge traces recorded by the oscilloscope.

4.2.3 Bridgman Factor Calculations

Bridgman [55], through his analysis, developed the concept of triaxiality to relate notched and uniaxial specimens. He defines the triaxiality as the ratio of the hydrostatic or mean stress over the flow or effective stress. From the reduction of our experimental data, we can obtain the true stress-strain curve but, to be more accurate, the data to be put in the constitutive models should be the flow stress versus the effective plastic strain. In the case of uniaxial specimens tested with the TSHB, the true stress-strain curve is equivalent to the flow stress versus equivalent plastic strain curve prior to necking; however, this is not the case for the notched specimens.

Using specimen-only simulations and, based on Bridgman analysis [55], a Bridgman factor was determined which could be multiplied by the true axial stress obtained from the experiments to obtain the average flow stress value equivalent to the uniaxial specimens conditions. The flow stress is equivalent to the von Mises stress. Using the results from specimen-only simulations done for a nominal strain rate of 1000 s^{-1} , the axial stress and von Mises stress for elements at different radii along the axial center of the specimen were obtained for different times during the simulation and stored in a file. The program BRIDGMAN presented in Appendix C, was used to compute the average axial and flow stress at the axial center of the specimen. From these values, the Bridgman factor was obtained at different times. Figure 4.8a presents a curve of the Bridgman factor variation with time for the NJ2 specimen design. Although the large scale used seems to indicate a large variation of the factor, the average value is 0.787 with a standard deviation of 0.026. This standard deviation represents about 4% of the mean value so it was considered acceptable to use the mean value as a conversion factor over the whole range of measured stress. In the case of the NC2 design, Figure 4.9a presenting the Bridgman factor versus time, indicates that the average value is 0.672 and the standard deviation is 0.009 (1.3% of the mean value) so the use of the average value as the conversion factor over the whole stress range is also considered acceptable.

In addition to the Bridgman factor calculation, LS-ORION was used to store the effective plastic strain in a file to find a relationship between the effective plastic strain and the diametral strain for the notched specimens. In Figure 4.8b, it can be seen that the relationship between the effective plastic strain and the diametral strain for specimen NJ2 follows a straight line with a slope very close to 1.0 so a direct 1 to 1 relationship between those two values was used. Figure 4.9b shows a relationship between the effective plastic strain and the diametral strain very close to unity for the NC2 specimen so these values were also considered equivalent.

The use of the Bridgman factor and the relationship between effective plastic strain and diametral strain will be discussed in more detail in the next chapter.

Chapter 5

EXPERIMENTAL RESULTS

This chapter presents results from the Hopkinson bar testing of the uniaxial and notched specimens. In addition to the various specimen geometries, the test matrix considered a temperature range from room temperature to 750°C. Three different Armco iron stock materials were tested: fine and coarse grained plate and hot extruded billet, in order to compare the effect of these as-received material conditions on the high rate mechanical response. While the majority of tests were performed on as-received material, a number of specimens were annealed before room temperature testing to eliminate prior work hardening. Finally, a limited number of room temperature quasi-static tensile tests were performed to obtain a base line response to which the high strain rate data could be compared.

This chapter first presents results from quasi-static testing prior to examining the high rate results. The high rate data is presented in such a manner as to attempt to isolate the separate effects of strain rate, temperature and initial material condition on mechanical response. Following this mechanical test data, metallographic observations from fractured specimens are presented. This chapter closes with a comparison between measured data and predictions from the full bar simulations presented in Chapter 4

5.1 QUASI-STATIC TESTS

In order to be in a position to compare the results at high strain rate with some in a different range of strain rates, a limited series of quasi-static tests were done with an INSTRON uni-axial tensile tester. The nominal strain rate for the uniaxial specimen was 0.006 s^{-1} . As no diametral extensometer was available for this work, the conversion from engineering stress-strain to true stress-strain was done with the following equations,

$$\epsilon_{\text{diam}} = \ln(1 + \epsilon_{\text{axial}}), \quad (5.1)$$

$$\sigma_{\text{true}} = \sigma_{\text{eng}}(1 + \epsilon_{\text{axial}}), \quad (5.2)$$

where ϵ_{diam} is the true strain, ϵ_{axial} is the engineering strain, σ_{true} is the true stress and σ_{eng} is the engineering stress. The true stress-strain data is only valid up to the point of necking.

The true stress-strain curves obtained with uniaxial specimens made from as-received fine grained and billet stocks are presented in Figure 5.1. Specimens produced from coarse grained stock were also tested but the curves were lost due to a problem with the data acquisition system. Specimens produced with the fine grained material demonstrated a higher yield stress compared to the billet material (290 MPa versus 210 MPa). Both materials demonstrate strain hardening in the plastic region as shown by the positive slope of the curve past the yield stress. The yield point area is marked by the presence of an upper and lower yield points which is expected in materials like iron and low carbon steel and is due to the diffusion of carbon, an interstitial element, in the active dislocation sites [67]. Figure 5.1 also presents the results for an annealed specimen. Prior to the testing of this specimen, it was annealed by fastening it to the Hopkinson bar and heated to 750°C in the tubular furnace followed by air cooling. The specimen was then removed from the bar and stored in a vacuum dessicator prior to its testing with the INSTRON machine. The curve indicates a small reduction of the yield stress (270 MPa) compared to the as-received fine grained material but very similar hardening modulus.

The small and long uniaxial specimen configurations (UA1 and UB1) were both tested to see the gauge length effect on the true stress-strain curves. The stress-strain curves are compared in Figure 5.2. The yield stress values obtained are different with a value of 290 MPa for the UA1 specimen and 230 MPa for the UB1 specimen. The strain hardening moduli are quite similar for both gauge length. The yield stress results indicate some gauge length effect response at low strain rates, as indicated by Staab and Gilat [19], although only a limited amount of test data was recorded in this work.

5.2 TENSILE SPLIT HOPKINSON BAR EXPERIMENTS

In this section we will present general experimental results obtained with the Hopkinson bar including some initial studies to improve the testing technique.

A graph showing typical curves of measured strain at the strain gauges versus time for a specimen breaking at the first pulse is presented in Figure 5.3. Looking at the transmitted pulse, it can be seen that around 400 μ s, the strain goes to zero indicating failure of the specimen. This is supported by looking at the reflected pulse (negative part of the signal recorded at the incident bar gauge location). At 400 μ s, the reflected pulse increases because the incident stress pulse cannot propagate through the broken specimen and is reflected in its entirety. Figure 5.4 shows the measured strain curves versus time for a specimen which did not break on the first pulse. In this case, the transmitted pulse does not go abruptly to zero during the pulse duration, and the reflected pulse does not show an increase; therefore, the specimen simply unloads after propagation of the pulse is complete. These results were obtained with a J-notch (NJ2) specimen at room temperature.

The verification of the addition of the incident, reflected and transmitted pulse according to equation (1.10) is shown in Figure 5.5 for the pulses presented in Figure 5.3.

Since the addition curve has an amplitude close to zero, this indicates that the equipment and data reduction method were functioning according to the theory.

5.2.1 Testing Parameters Definition

At the beginning of this research, some tests were performed to select the specimen design, the striker length to be used and the gas gun pressures to obtain the required strain rates

For these tests, notched specimens produced with design NA1, NJ1, NC1 and NJ2 were produced from the 20 and the 25 mm plates. The 30 and 40 cm long strikers were used during this early phase. The A-notch and J-notch specimens exhibited ductile failure during these tests. The results from some of C-notch specimens indicated what looked like a brittle failure characterized by the crystalline aspect of the fracture surface [67]. From these tests, the NJ2 design was selected for the J-notch specimen for the reasons indicated in Chapter 3. It was also decided to limit the tests to the J-notch and C-notch design since the A-notch geometry was only marginally different from the J-notch.

Specimens with notch configurations were used because it is not possible to fail uniaxial specimens on the first pulse in the strain rate range available with the Carleton TSHB. The notched specimens, however, requires application of a Bridgman [55] correction factor to estimate uniaxial flow stress. The values of the correction factor determined in Chapter 4 had to be confirmed so a uniaxial specimen configuration (UA1) was then produced and tested. Because of the good results obtained during the preliminary tests and the adequate functioning of the momentum trapping equipment to stop subsequent pulses from re-entering the specimen, it was decided to add this uniaxial design to the testing matrix.

The preliminary results, as shown in Figures 5.3 and 5.4, were indicating that the 30 cm striker should be sufficient to ensure a sufficiently long pulse for the notched

specimens to produce failure on the first pulse. Consequently, this striker length was selected for all of the experiments.

Review of the results obtained by Clarke [24] for brass and the initial tests in this work showed that the true stress-strain curves were almost identical in the strain rate range available with the Carleton University Hopkinson bar. Furthermore, the large quantity of experiments required to test three ARMCO iron stocks at different temperatures lead to the use of the same pressure in the gas gun for all of the tests to facilitate comparisons. This choice also enabled a better control over the experiments, particularly for the determination of the gap between the incident bar end cap and momentum trap bar to obtain reliable pulse trapping. A pressure of 345 MPa (50 psi) was used in the gas gun. This produced striker velocities of 11.0 ± 1.4 m/s. It was found that when the incident bar was lubricated, unusually high striker velocities were obtained which is why some experiments were done at higher strain rate. The strain rates reported are those obtained on the curve of strain rate versus time obtained from experimental data where the strain rate reaches a plateau.

5.3 HIGH STRAIN RATE UNIAXIAL SPECIMENS

The experimental results obtained with the uniaxial specimens are summarized in Table 5.1 which indicates the specimen configuration (UA1 or UB1), material stock, striker velocity, strain rate, testing temperature, total axial engineering strain and true diametral strain calculated from measurements on recovered specimens. For the 25 mm plate material, it was decided to test the material in two directions as indicated in Chapter 2. The material stock was labeled as:

- (i) "fine grained" or "fine" for the 25 mm plate, taken in what was considered the rolling direction from metallographic studies.

- (ii) "fine-perp" or "perpendicular" for the 25 mm plate with specimen taken from the direction perpendicular to the rolling direction.
- (iii) "coarse grained" or "coarse" for the 20 mm plate.
- (iv) "billet" for the 15 cm billet material.

The tests were performed at four temperatures, room temperature, 250°C, 500°C and 750°C, for the fine grained stock material. For the other stocks, testing was limited to two temperatures, room temperature and 500°C. Some specimens were annealed for each of the material stock. This annealing was done on machined specimens with the following method. The specimen was fastened to the bar and put in the furnace which was heated until the specimen surface reached 750°C. The furnace was then switched off and the specimen was allowed to cool slowly until its temperature reached room temperature. The annealed specimens were then tested at room temperature.

No uniaxial specimens failed on the first pulse and results presented in Table 5.1 were all obtained using the interrupted testing arrangement. With the smaller gauge length in UB1, higher strain rates and total axial strain were achieved for an equivalent striker velocity.

5.3.1 Temperature Effect

The effect of temperature on the true stress-strain curves for specimens manufactured from fine grained material from the 25 mm plate is shown in Figures 5.6a and b. Figure 5.6a presents the curves without filtering and Figure 5.6b shows the filtered curves. The filtering was performed by applying a band stop filter to the stress-strain curves to remove the ringing. The frequency band to be stopped was determined with a fast Fourier transform as described in Chapter 3. The yield stress and the stress levels decrease with increasing temperature. It can also be noted that at room temperature, the curves reach a plateau and that there is only a limited strain hardening effect. For samples

tested at higher temperatures, the strain hardening effect is seen by a small positive slope of the curves. The curves in Figure 5.6b show a reduction of the amplitude of the ringing as the temperature increases, attributed to a reduction in the sound velocity in the specimen and a corresponding reduction of the Pochhammer-Chee ringing.

Figures 5.6a and b also indicate the influence of annealing on the properties of ARMCO iron. As can be seen, this treatment reduces the material yield stress and increases the level of strain hardening. It is interesting to note that the curves obtained are similar to those presented in the literature and that they are about 30% lower than the curves for the non-annealed specimens.

The axial strain values presented in Table 5.1 are highest for the elevated temperature tests. The specimens were in a softer condition and deformed more easily. Thus, for a constant striker velocity, higher temperature specimens will be loaded to higher strains. This effect is more noticeable in the coarse grained plate and billet materials which were tested at nominally constant striker velocities.

5.3.2 Variation Between Material Stock Sources

Figure 5.7a presents the filtered stress-strain curves obtained from the different stock material tested at room temperature. The two curves for the fine grained material which reached higher values of true strain before unloading were obtained at slightly higher strain rates (1200 and 1300 s^{-1} versus $\sim 1000 s^{-1}$). The figure shows that the highest values of stress are obtained with the fine grained stock taken in the rolling direction followed by the material taken in the perpendicular direction and finally by the specimens made with the coarse grained material. The curves for the billet material lie between the curves for the fine perpendicular and the coarse grained materials. The strain softening seen in sections of some curves comes from the filtering rather than a physical effect.

Figure 5.7b presents the filtered stress-strain curves for the specimens tested at 500°C. The curves indicate very similar results to those found at room temperature with the exception of the billet material. While the curves for each of the other stocks are very close to each other (within 10 MPa) for a given strain, the two curves for the billet material are considerably different and separated by about 50 MPa.

Figure 5.7c presents the filtered true stress-strain curves for annealed specimens from three types of stock materials. Not enough specimens from the fine grained stock taken in the direction perpendicular to the rolling direction were available to perform testing of this material in the annealed state. Although a limited number of curves are presented, the annealing effect was the same in all the stock materials, i.e. a reduction of the yield stress and stress level by 20 to 30%. The curves for all stock materials are very close to each other so the annealing has the advantage of reducing considerably the grain size and prior processing effects on the properties.

Review of the total axial strain and true strain data from the measurements taken on the uniaxial specimens presented in Table 5.1 does not permit definite conclusions on the comparisons of the different material stocks. As indicated above, for the fine grains specimens, very different striker velocities led to different strain rates so it is difficult to make comparisons.

5.3.3 Gauge Length Effect

As indicated in Chapter 3, specimen design UA1 and UB1 have been tested to see if there was a gauge length effect as indicated by Staab and Gilat [19] and if shorter specimens could be used in future tests. Figures 5.8a and 5.8b present a comparison of the true stress-strain curves for the two types of specimens at room temperature and 500°C respectively. The curves obtained are very similar in spite of the mild variation in strain rates between the tests. Thus it can be concluded that the reduction of gauge length

between UA1 and UB1 specimens does not produce a significant change in the results for stress level achieved.

5.3.4 Strain Rate Effect

The effect of strain rate on the true stress-strain curves is shown in Figure 5 9a which presents high strain rate and quasi-static curves obtained with uniaxial specimens UA1 made of fine grained material in both as-received and annealed states. The yield stress value for both the high strain rate and quasi-static curves is around 300 MPa. Comparison of the curves indicates that after the yield stress is achieved, the curves for specimens tested at high strain rate show a rapid increase of stress with strain and eventually reach a plateau for a strain value of about 5% while for the quasi-static curves there is a small strain hardening slope. The curves also show that past the point where the high strain rate curves reach a plateau, the true stress obtained at high strain rate for the as-received material is about twice the value obtained from quasi-static tests for given true strain. Figure 5 9a also shows that the influence of annealing of the material is quite significant on the true stress-strain curves done at high strain rate with a reduction in stress of approximately 25% while the difference is less than 5% for quasi-static tests.

In order to compare these results with those found in the literature for tests done at room temperature, the average values of stress for a strain of 10% from the curves for both the annealed and as-received materials are plotted on Figure 5 9b. This figure also presents published data, previously shown in Figure 2.2. The values from this research are in the same range as those presented by the other authors which suggests that the fine grained ARMCO iron material tested is comparable to what has been tested by these scientists. This agreement could also be seen as an indication that the equipment and data reduction method used in this research are functioning well.

5.3.5 Johnson-Cook Parameters

Using the stress-strain curves for the uni-axial specimens produced with the material from the 25 mm plate (fine grained), the factors for the Johnson-Cook model were computed using a non-linear multiple regression with the SPSS software [68].

The equation for the Johnson-Cook model, as discussed in Chapter 1, is given by:

$$\bar{\sigma} = (K_0 + K_1 \bar{\epsilon}^n) (1 + K_2 \ln \dot{\epsilon}^*) (1 - T^{*m}) \quad (5.3)$$

with $\dot{\epsilon}^* = \dot{\epsilon}/\dot{\epsilon}_0$ and $T^* = (T - T_{ref})/(T_{melt} - T_{ref})$. The parameters to be determined from the true stress-strain curves were K_0 , K_1 , K_2 , m , and n . Due to very limited range of strain rates in our high strain rate data and the small quantity of data available under quasi-static condition, it was not possible to capture the strain rate effect which is represented by the second bracketed term of equation (5.3). The value for parameter K_2 given by Johnson and Cook [35] which is 0.06 was therefore used. The stress-strain curves had been obtained with strain rates around 1000 s^{-1} , so this value was used as the reference strain rate ($\dot{\epsilon}_0$). The stress values were divided by the values obtained for the second bracketed term of equation (5.3) leaving the parameters for strain and temperature effects to be determined from the regression. The values obtained for the parameters are: $K_0 = 289 \pm 49 \text{ MPa}$, $K_1 = 704 \pm 488 \text{ MPa}$, $n = 0.6 \pm 0.4$, $m = 0.7 \pm 0.2$. As can be seen, principally in the case of parameters K_1 and n , the standard deviation is very large, so one can question the ability of this model to represent precisely the data. As indicated in Chapter 1, parameters K_1 and n are related to the strain hardening which was found to vary with temperature. The Johnson-Cook model considers the strain and temperature effects as separate which is one of its primary limitations.

The values from the results of the annealed specimens have also been determined. In this case, since experiments have been done at room temperature only, the value of parameter m found by Johnson and Cook [35] was used in addition to the K_2 parameter value. The following values were obtained: $K_0 = 202 \text{ MPa}$, $K_1 = 421 \text{ MPa}$, $n = 0.22$. The

standard deviation is not presented here because of the small quantity of curves available for the determination. The values obtained are close to those obtained by Johnson and Cook [35] and presented in Chapter 1

Figure 5.10 serves to compare the experimental true stress-strain curve data with the results of the regression using the Johnson-Cook model. Plotted for each temperature are one experimental curve for the as-received fine grained material and the corresponding curve computed with the Johnson-Cook model at the same strain rate. The closest agreement between the experimental and the computed curves is obtained at 250 and 500°C. The worst agreement is obtained at room temperature which can be explained by the fact that the stress-strain curve at room temperature exhibits very little work hardening whereas at elevated temperatures there is considerable work hardening. Using the Johnson-Cook models implies a constant degree for work hardening controlled by parameters K_1 and n . This systematic error is reflected in the large standard deviation in the K_1 and n values. Figure 5.10 also presents an experimental and a computed curve for the annealed material. The agreement is good for strain larger than 0.05. Only curves at room temperature were available to compute those factors which can explain the better agreement compared to the as-received material at room temperature.

5.4 NOTCHED SPECIMENS

Experimental results for J-notch specimens of the NJ2 design are summarized in Table 5.2. The results are presented in the same fashion as for the uniaxial specimen since no specimen failed on the first pulse. Only the fine and coarse grained materials were studied with this design but they were tested at room temperature, 250°C, 500°C and 750°C. Table 5.3 presents the experimental data for the C-notch specimens which were made only with fine grained stock material. In addition to the results presented for the

other types of specimen, an additional column was added to indicate if the failure occurred during the first pulse

The values of strain rates for the notched specimens are lower than those for uniaxial specimens because of the method used to measure the gauge lengths of each type. For the uniaxial specimens, the length of the cylindrical section in the middle of the specimen was used which is the method typically used for this type of specimen. For the notched specimens, the gauge length is more difficult to define so, as was done by Clarke [24], the distance between the outside of the flanges was used in this work.

5.4.1 Temperature Effect

The effect of temperature on the stress-strain curves obtained with the J-notch specimen are presented in Figure 5.11a and b for the fine grained material. Figure 5.11a gives the unfiltered stress-strain curves and Figure 5.11b shows the filtered ones. The curves at room temperature are showing strain softening after a certain level of strain as indicated by the negative slope of the curves. Although only two curves are presented here, the study of the curves obtained with fine grained material at room temperature with J-notch specimens were all showing this effect. One possible explanation for this strain softening is that ARMCO iron data obtained with annealed material has been used to perform the computer simulations to obtain the conversion curve between the engineering and true strain values. Since the as-received material has a lower strain hardening rate than the annealed material, faster localization would result and the conversion curve would introduce some error.

As far as temperature effect is concerned, as in the case of uniaxial specimens, the yield stress and the stress levels are decreasing with increasing temperature and, for samples tested at elevated temperatures, the strain hardening effect is shown by a small

positive slope of the curves for both stocks. The annealing of the specimens made with fine grained stock produced a reduction of the stress level by approximately 25% and development of significant strain hardening as shown in Figures 5.11a and b. The reduction of ringing amplitude in the curves as a function of temperature, as discussed for the uniaxial specimens, is also visible in Figure 5.11a.

Figures 5.12a and 5.12b presents respectively the unfiltered and filtered true stress-strain curves for the J-notch specimens made with coarse grained stock material. As shown in the figures, the strain softening effect at room temperature is not present with the coarse grained stock although there is almost no strain hardening. As in the case of the fine grained stock, Figures 5.12a and b show a reduction of the yield stress and the stress level with temperature and the appearance of strain hardening at elevated temperatures. Figure 5.12a indicates that the ringing is decreasing as the testing temperature is increased.

Figures 5.13a and 5.13b present the temperature effect on the stress-strain curves obtained from C-notch specimens manufactured from the 25 mm plate stock material (fine grained). Figure 5.13a presents the unfiltered true stress-strain curves and Figure 5.13b shows the filtered data. With this type of specimen, failure occurred on the first pulse for specimens tested at room temperature and 250°C and for one specimen at 500°C. The curves from the fractured specimens curves demonstrate a slow reduction of stress as the strain increases because there is gradual unloading as parts of the specimen are failing. For the specimens which did not fail on the first pulse, there is a sharp unloading. The curves at 250°C show that failure had started as shown by the slow reduction in stress but there is unloading at the end of the curve. Although the specimens were broken when they were taken out of the furnace, the complete failure might have occurred during removal of the specimen from the furnace. This was confirmed by examining the one specimen tested at 500°C which did not fail completely and was recovered in one piece. The specimen which did fail at 500°C is a clear failure which suggested a possible defect in the specimen. At

750°C and above, the curves present unloading only. These results show the increase of ductility brought by the increase of temperature and that, for the strain rate range studied and striker considered, partially failed specimens could be recovered at 250 and 500°C.

One stress-strain curve at room temperature for the C-notch (Figure 5.13b) indicates the absence of strain hardening while failure occurred too early in the other curve to make conclusions. The stress level needed to achieve a given strain gets lower as the temperature is increased as found with the uniaxial and the J-notch specimens and there is evidence of strain hardening for temperatures of 250°C and above. The curve for the annealed specimen tested at room temperature shows a stress level which is about 75% of the value from as-received material and the presence of a mild strain hardening which concurs with what was found with the annealed UA1 and NJ2 specimens. The increase in temperature also leads to a reduction in the ringing amplitude in the curves as shown in Figure 5.13a.

5.4.2 Material Stock Effect

Comparison of the curves in Figures 5.11b and 5.12b obtained with the J-notch specimens indicates that the yield stress is lower for the coarse grained stock than for the fine grained material as expected based on the Hall-Petch model. This difference decreases as the temperature is increased. The strain hardening slope is larger for fine grained material than for coarse grained stock at lower temperatures but as the temperature is increasing, the slopes are becoming very similar.

5.4.3 Verification of Calculated Bridgman Factor

In Chapter 4, Bridgman factors aimed at conversion of true stress obtained from notched specimens into average flow stress equivalent to uniaxial data have been introduced. It was also indicated that the equivalent plastic strain can be considered

equivalent to the true strain for both J-notch and C-notch specimens. The Bridgman factors were applied to curves obtained at room temperature for the fine grained stock material and the results are presented in Figure 5.14. The yield stress values for the corrected J-notch curves are close to those of the uniaxial specimens, however, the corrected curves from the notched specimens tend to exceed the uniaxial data. In the case of the C-notch, the difference is more important. This could be explained by the fact that the factor used is an average value.

5.5 METALLOGRAPHY

5.5.1 Quasi-Static Specimens

Scanning electron micrographs were obtained from fractured uniaxial, J-notch and C-notch specimens tested under quasi-static conditions and are shown in Figure 5.15a, b and c, respectively. The figures show that the fracture surfaces are dimpled which is characteristic of ductile failure from nucleation, growth and coalescence of voids. All of the micrographs were taken at the same magnification and it is interesting to note that, the dimple size increases with the level of stress concentration and triaxiality induced by the notches. The micrographs also show some indication of the depth of the structure where voids are present with the uniaxial specimen exhibiting deeper voids while the voids in the C-notch specimen seem to be shallow.

5.5.2 High Strain Rate Uniaxial Specimens

The threaded parts of tested uniaxial specimens were removed using an abrasive cut-off machine leaving the central gauge length which was mounted in bakelite. Using a belt sander, a thickness representing half the diameter of the mounted section was removed and, after polishing, the material was studied with an optical microscope. None

of the uniaxial specimen studied showed evidence of porosity or voids for the strain levels considered

5.5.3 High Strain Rate Notched Specimens

Optical and scanning electron microscopy (SEM) were carried out on fractured notched specimens. For the J-notch geometry, the specimens examined were from the early phase of the program which had failed on the first pulse. This phase was limited to specimens tested at room temperature

Figure 5.16a is an optical micrograph of J-notch specimen tested using the 40 cm striker during the preliminary tests. The figure shows that the fracture surface is dimpled which is characteristic of ductile failure from nucleation, growth and coalescence of voids. The picture also shows some smaller voids near the surface with some involved in the coalescence process. In Figure 5.16b, an optical micrograph of a failed C-notch is presented. As in the case of the J-notch specimen, the failure surface is dimpled but the voids are limited to a very small area near the fracture surface presumably due to the narrower deformation zone induced by the sharper notch. Both Figures 5.16a and b were taken at the same magnification and it is interesting to note that the dimples and the voids in the C-notch specimen are bigger which could be explained by the higher stress and strain concentration, and the higher triaxiality generated by the sharper C-notch.

Figures 5.17a and 5.17b are SEM micrographs of the surfaces of the other half of the failed specimens presented in Figures 5.16a and b respectively. Both figures show characteristic dimples at the surfaces. As indicated with the optical micrographs, it can also be seen in the SEM micrographs that the dimples are larger in size for the C-notch specimen.

Comparison between the elevated and quasi-static strain rate SEM micrographs shows a similar relationship between the dimples size at the surface and the stress

concentration brought by sharper notches. The micrographs of the quasi-static tests seemed to indicate a deeper defect zone for the quasi-static tests specimens compared to the high strain rate tests specimens.

5.6 COMPARISON WITH FULL BAR SIMULATIONS

In this section, the experimental data will be compared with the simulations for both the uniaxial and the notched specimens. The comparison between the old and new values of the Johnson-Cook model will also be discussed.

The incident and reflected pulses for the simulations performed with the Johnson-Cook model and the experimental data for a uniaxial specimen (UA1) manufactured using fine grained material are presented in Figure 5.18a. The timing of the beginning of the experimental curve was shifted to fit with the simulation curves. The striker velocities were 10.80 m/s for the simulation and 10.56 m/s for the experimental test. The numerical results were obtained with the values for the Johnson-Cook model determined from the annealed fine grained stock. The figure shows that the amplitudes of the pulses from the simulation are larger than the experimental one by about 10%. The corresponding curves for the transmitted pulses are presented in Figure 5.18b. The experimental curve was again shifted in time to match the starting time of the simulation curve. The figure shows that the amplitude of the simulation curve is very similar to the experimental to within 10%. The simulation curve also exhibits less ringing.

Calculations were also performed using previously published ARMCO iron parameters [35] for the Johnson-Cook model. These calculations (not shown) agreed very closely with the numerical data in Figure 5.18.

The results for the J-notch specimen are given in Figures 5.19a and b. Figure 5.19a presents the incident and reflected pulses. The predicted curve was obtained with a striker velocity of 10.8 m/s while the experimental curve was obtained with a striker velocity of

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PM-1 3½" x 4" PHOTOGRAPHIC MICROCOPY TARGET
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9.75 m/s. This explains the larger difference between the experimental and simulation curves when compared with the uniaxial curves. Once again, the Johnson-Cook parameters values obtained in this research were used in the numerical results, but the results are similar to those obtained with the standard Johnson-Cook parameters [35]. Figure 5.19b presents the transmitted pulses and the curves agree well. It can be concluded that the complete bar simulations are very representative of the experiments.

Chapter 6

DISCUSSIONS

6.1 EXPERIMENTAL APPARATUS

The tensile split Hopkinson bar apparatus has been modified during this research program to enable effective trapping of the reflected and transmitted pulses before they reload the specimens. The recorded pulses indicated a reduction of the reflected pulse amplitude by about 80% and the reduction of its duration by about two thirds. Although, the amplitude of the reflection of the transmitted pulse was only reduced by about one third, its duration was limited to about 20% of the original transmitted pulse. These reductions allowed recovery of unbroken specimens after single pulse loading so that meaningful metallographic studies could be performed.

A tubular furnace has been installed on the tensile split Hopkinson bar to enable testing at temperatures up to 900°C although temperatures in this research were limited to 750°C. Heating studies have been performed with a surrogate specimen to determine the temperature profile in the bar and to adapt a data reduction technique based on discrete temperature steps. This study showed that about 30 minutes were needed to reach 250°C at the surface of the sample and about 80 minutes were needed to reach 750°C. Unfortunately this duration is sufficient to induce some microstructural change and annealing in the material in the form of recovery and possible grain growth. A more

desirable system would permit very rapid heating of the specimen prior to testing. A short heating time would avoid complicating effects due to prolonged periods at high temperatures. One solution may reside in the use of a ring burner producing heat from the burning of butane as used by Radford [69]. Such a burner can be set very close to the specimen and would reach the required temperature very quickly thus limiting the grain modification effect. An additional benefit would be the reduction of the length of bar heated during the test which would facilitate the data reduction and reduce the wear in the bar.

The actual system used to control the pressure in the gas gun and to bleed gas behind the pusher to fire the gas gun does not provide adequate control of striker velocity. This lack of control makes the set-up of the gap between the end cap of the incident bar and the pulse trapping bar difficult since the required gap is based on the striker velocity. In this research, the use of only one striker and one working pressure for the gas gun provided some level of repeatability but limited the range of strain rate studied. It would be desirable to develop a method to obtain a more precise relationship between the gas pressure in the gun and the striker velocity. This would enable more repeatability and more precise comparison between experiments.

The use of a striker length of 30 cm provided an adequate stress pulse length for the C-notch specimen design since failure was obtained on the first pulse at room temperature which allows different levels of damage in the specimen to be reached by changing the striker velocity. This striker was not long enough, however, for the J-notch design because failure did not occur on the first pulse during room temperature testing. During the preliminary tests, failure was obtained with two J-notch specimens with the 30 cm striker but these failures were probably caused by a weakness induced by machining. Future work involving the J-notch specimen design should be done with the 40 cm long

striker and/or higher impact velocity. Additional tests should also be done with the longer striker using the smaller uniaxial specimen design (UB1).

The relationship between the strain and voltage recorded from a semi-conductor gauge was non-linear, therefore the full Wheatstone bridge equation must be used to perform the data reduction instead of the simplified equations normally used with foil gauges. With a data reduction method using the full bridge equation, the addition of the incident, reflected and transmitted pulses follows the split Hopkinson bar equation so it can be concluded that the assumptions presented in Chapter 1 are correct and that force equilibrium exists across the specimen.

Although the relationship between measured true and engineering strain on the recovered specimens seems to agree quite well with the relationship found by simulation, this method implies some a priori knowledge of the material properties. Furthermore this method could limit the ability of this apparatus to discern minor differences between different stocks of material. The use of a high speed camera would enable more precise correction, thus allowing greater accuracy.

The quasi-static stress-strain data presented here is limited to only two specimens. Testing of coarse grained material specimens along with specimens from the billet material both in the as-received and annealed state would provide more data to examine the strain rate effect. The quasi-static true stress-strain data is calculated from nominal strains which is an applicable approach for strains up to the point of necking in the specimen. This approach is acceptable to obtain the constitutive behaviour of the material but it would be interesting to get data right up until failure occurs. This could be achieved by using a diametral extensometer to measure the actual diameter in the neck region. The use of a diametral extensometer would also enable more accurate testing of notched specimens under quasi-static conditions for comparison with the high strain rate results in this thesis.

6.2 ARMCO Iron Material Behaviour

The experimental tests, metallography and numerical modeling done during this research program were aimed at obtaining a better knowledge of the behaviour of the ARMCO iron focusing mainly on the effect of elevated strain rates and temperature on this material in the as-received state. The influence of different stock shapes was also examined.

The metallographic study of the three stocks of ARMCO iron used in this study showed the presence of three different grain sizes. The core of the 25 mm plate, from which the specimens were machined, presented the finest grain size, which was about 30 μm . The specimens from the billet stock had a grain size between 100 and 200 μm and finally the grain size in the 20 mm plate was between 150 and 300 μm .

The relationship between the material behaviour and the grain size is defined by the Hall-Petch relationship which predicts that the yield stress is inversely proportional to the square root of the grain size. This relationship has been shown to be approximately valid for the quasi-static regime but not valid under dynamic rates for ARMCO iron by Reinders and Kunze [52]. The true stress-strain curves obtained at high strain rates with the three stock materials in this work show tensile strengths which vary inversely with the grain size, the highest value being obtained with the 25 mm plate stock and the lowest with the 20 mm plate. Specimens produced from the billet material produced intermediate results. According to the assumptions of the split Hopkinson bar instrument, the stress at low strain is not reliable because the specimen is not yet deforming uniformly unless one is using pulse shaping method which was not done in this work. A graph of the true stress at a strain of 0.1 versus the inverse of the square root of the grain size, presented in Figure 6.1, was used to examine the presence of a relationship similar to the Hall-Petch relationship. A least square regression was used to produce a line from the experimental data points and the line obtained, and illustrated in Figure 6.1, had a regression coefficient

(r^2) of 0.89. The current results did not indicate the presence of an optimal grain size. It is important to note that the results obtained with the billet material vary considerably. A more complete study of the billet material should be performed and additional tests should be done to confirm the results presented in this thesis. Additionally, pulse shaping technique as described by Nemat-Nasser [2] should be used to test the Hall-Petch relationship. The limited data at quasi-static strain rate, for which coarse grained tests was not available, show some inverse relationship of the yield stress with the grain size but more data would be needed to draw a conclusion.

Annealing of the fine grained material by heating specimens to 750°C and then letting them cool to room temperature before testing produced quasi-static true stress-strain curves very similar to the as-received state which would indicate that annealing does not produce important changes in this regime. The results from dynamic testing at high strain rates indicate that the microstructural change produced by annealing did have a more important effect as shown by a reduction of the tensile strength by about 75% and the presence of a slight strain hardening behaviour which is not seen in the as-received material. These results indicate that more work should be done on the effect of annealing of the material. This would include annealing material at different temperatures and durations prior to machining of the specimens and should be done on the three stock materials.

High strain rate tests at temperatures between room temperature and 750°C indicated a softening effect as shown by the inverse relationship between the material strength and temperature. The stress-strain curves for the tests done at 250°C and higher on the as-received materials present a degree of strain hardening which is not found at room temperature in the as-received stock.

6.3 Johnson-Cook Constitutive Model and Simulations

The improved knowledge of the material behaviour of ARMCO iron obtained from this research program was aimed at obtaining factors for constitutive models which are used in computer codes such as DYNA2D and, possibly, improving the results from computer simulations. The Johnson-Cook [35] constitutive model was selected for this study because of its simplicity and availability in numerous continuum mechanics codes

The following values have been obtained for the parameters in the Johnson-Cook constitutive model using non-linear multiple parameter regression for the as-received fine grain material (25 mm plate) $K_0=289$ MPa, $K_1=704$ MPa, $n=0.6$ and $m=0.7$ and, for annealed fine grain stock material $K_0=202$ MPa, $K_1=421$ MPa, $n=0.22$. The TSHB experiments were limited to a very small range of strain rates thus the strain rate dependent parameter, K_2 , determined by Johnson and Cook [35] was used in obtaining these fits. In the case of the temperature related parameter, m , for the annealed material, the value found by Johnson and Cook was also used because no experiments were done at temperatures other than room temperature during this program

The data obtained in this research has demonstrated that the rate of strain hardening will increase with temperature, even though the overall stress-strain curve will drop due to thermal softening. This behaviour suggests that thermal softening and strain hardening are coupled, thus the decoupled treatment obtained using the Johnson-Cook model, which essentially "scales" the stress-strain curve with temperature, will not accurately represent the material behaviour. This shortcoming was reflected by the large standard deviations associated with the strain hardening parameters obtained from the non-linear regressions.

Parameters for a more advanced constitutive model, such as the Zerilli-Armstrong model [37] which couples strain hardening and thermal softening should be determined

from the experimental data in this thesis and the results compared with those using the Johnson-Cook model to see what level of improvement could be produced.

A further shortcoming is expected in the Johnson-Cook model associated with the treatment of strain rate hardening. The regressions used to fit the Johnson-Cook parameters in this work were limited to the high strain rate tests. It is observed from Figure 5.9a that the shapes of the quasi-static and dynamic stress-strain curves are quite different. Consequently, the "scaling" approach used by Johnson and Cook to account for strain rate would lead to further errors and a lack of correlation using both high rate and quasi-static data. Thus application of simplified engineering constitutive models such as Johnson-Cook should be restricted to the strain rate and temperature range over which their constitutive parameters were obtained. For this reason, the current "fits" are thought to represent an improvement over previously published results since the regressions only considered high strain rate conditions.

There exists a requirement to develop simulations of the fracture process in this material, therefore quantitative metallography should be conducted on recovered specimens from the experiments already performed and, applying an image processing technique, the number and sizes of voids in the specimen should be determined. This data could then be used to calculate the parameters for ARMCO iron to be used in a fracture model, such as the Gurson [70] model.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

The objective of the current research work was to study the mechanical properties in tension of ARMCO iron at different strain rates and temperatures. In order to meet this objective, the research for this graduate program has made the following contributions

- The modification of the TSHB facility through the addition of (i) a tubular furnace, and (ii) a momentum trapping system to enable interrupted testing
- The use of the modified TSHB facility to investigate the high strain rate tensile behaviour of the ARMCO iron from different stock shapes and an INSTRON tensile tester to perform tests at a lower strain rate. These experiments have involved both mechanical testing and metallography
- The study of numerical models (i) to investigate wave propagation in the apparatus, (ii) to convert engineering stress-strain data into true engineering stress-strain curves, and (iii) to evaluate the ability of the computer simulations to reproduce experimental data.
- The determination of the Johnson-Cook [35] constitutive parameters through application of non-linear regression on the experimental data.

7.1 CONCLUSIONS

The following major conclusions are made from this research:

- The modified apparatus functioned properly, enabling testing at elevated temperature and interrupted tests.
- ARMCO iron demonstrates a decrease of flow stress and an increase of hardening rate with increasing temperature
- ARMCO iron shows a decrease in flow stress with increasing grain size.
- Values for the Johnson-Cook model parameters have been obtained. These values are suitable for a strain rate between 900 and 1500 s⁻¹, a temperature range between room temperature (20°C) and 750°C, and strain values between 0 and 30%.

7.2 RECOMMENDATIONS

In order to further the work done in this research project, the following tasks should be considered:

- Improve the firing control system of the gas gun to obtain more repeatable striker velocities.
- Replace the heating system by one which would provide faster heating of the specimen to better isolate the effects of thermal softening from thermally induced microstructural changes.
- Conduct a study of the effects of annealing at different temperatures and durations on the tensile properties of ARMCO iron.
- Carry on more tests on the different stocks of ARMCO iron at high strain rates to verify the applicability of the Hall-Petch relationship.
- Use the experimental data to obtain the parameters for a more advanced constitutive model, such as the Zerilli-Armstrong [37] model.

- Conduct a fracture study including quantitative metallography to obtain parameters values for ARMCO iron used in a Gurson based [70] fracture model

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TABLES

Table 1.1 - Parameters for the Johnson-Cook Constitutive Model

Author	Data used	K_0 (MPa)	K_1 (MPa)	K_2	n	m
Johnson & Cook	Tension/Torsion	175	380	0.06	0.32	0.55
Holmquist & Johnson	Tension	233	468	0.046	0.42	0.42
Holmquist & Johnson	Tension/Torsion	171	426	0.047	0.30	0.47
Holmquist & Johnson (modified)	Tension	223	449	0.048	0.42	0.42
Holmquist & Johnson (modified)	Tension/Torsion	167	415	0.049	0.30	0.46

Table 2.1 - Chemical Composition of the Different Stock

Stock	Elements					
	Carbon	Manganese	Phosphorus	Sulfur	Copper	Nitrogen
20 mm plate	0.002	0.05	0.003	0.003	0.014	0.004
25 mm plate	0.005	0.04	0.005	0.003	0.010	0.005
billet	0.004	0.05	0.004	0.003	0.010	0.005

Table 3.1 - Summary of Uniaxial Specimens Geometries

Specimen	Specimen length	Gauge length	Length between shoulders
	A (cm)	B (cm)	C (cm)
UA1	4.191	0.889	1.524
UB1	4.445	0.635	1.270

Table 3 2 - Summary of Notched Specimens Geometries

Specimen	Specimen length A (cm)	Shoulder diameter B (cm)	Notch radius C (cm)
NJ1	3.556	1.275	0.318
NA1	3.330	1.275	0.206
NC1	3.129	1.275	0.104
NJ2	3.556	0.953	0.318
NJ3	3.409	0.635	0.318
NC2	3.129	0.953	0.104

Table 3.3 - Data for Tests at Elevated Temperatures

Specimen Temperature °C	Step number	Step Temperature °C	Young's Modulus GPa	Distance from end of bar cm	Step length cm
250	1	25.0	208.41	80.0	55.0
	2	36.5	207.48	25.0	10.0
	3	69.6	204.83	15.0	5.0
	4	105.6	201.93	10.0	5.0
	5	185.0	195.55	5.0	5.0
500	1	25.0	208.41	80.0	55.0
	2	53.9	206.09	25.0	10.0
	3	122.4	200.58	15.0	5.0
	4	197.5	194.54	10.0	5.0
	5	366.5	180.96	5.0	5.0
750	1	25.0	208.41	80.0	55.0
	2	77.0	204.23	25.0	10.0
	3	211.6	193.41	10.0	5.0
	4	337.1	183.33	5.0	5.0
	5	559.2	165.48	5.0	5.0

Table 4 1 - Data for Full Tensile Split Hopkinson Bar Simulation

	Striker bar	Incident bar except endcap	Incident bar endcap	Transmitter bar
Length (cm)	30.00	139.20	2.54	139.20
External diameter (cm)	2.54	1.59	2.54	1.59
Internal diameter (cm)	2.22	N/A	N/A	N/A
Nb. of elements radially	2	8	10	8
Nb. of elements axially	128	583	11	583
Total number of elements	256	4664	110	4664
Initial velocity (m/s)	10.80	0 00	0 00	0.00

Note. There is a small section of bar of 40 elements (4 elements radially and 10 elements axially) beside the specimen on both ends to represent the threaded part of the bar.

Table 4 2 - Parameters Used in Equations for Engineering versus True Strain Conversion

The third degree polynomial function used for the conversion is:

$$\epsilon_{diam} = B_3 \epsilon_{axial}^3 + B_2 \epsilon_{axial}^2 + B_1 \epsilon_{axial} + B_0$$

Specimen type	Parameters			
	B ₃	B ₂	B ₁	B ₀
UA1	12.246	-0.6173	1.3607	-0.00087
UB1	5.425	1.3910	1.0935	-0.00012
NJ2	277.821	-32.2096	8.0921	-0.00158
NC2	-14.008	15.8193	5.3687	-0.00046

Table 5.1 - Experimental Results for Uniaxial Specimens

Specimen type	Stock	Striker vel (m/s)	Strain rate (s^{-1})	Temperature ($^{\circ}C$)	Axial strain %	True strain
UA1	fine	12.69	1200	RT	13.2	0.22
UA1	fine	13.58	1300	RT	13.9	0.21
UA1	fine	10.15	925	RT	11.5	0.12
UA1	fine	12.95	1275	250	15.1	0.23
UA1	fine	12.40	1250	250	14.5	0.20
UA1	fine	9.89	910	250	13.8	0.18
UA1	fine	11.73	1075	500	12.3	0.17
UA1	fine	15.80	1475	500	17.2	0.27
UA1	fine	10.51	950	500	10.0	0.15
UA1	fine	13.06	1175	500	13.2	0.20
UA1	fine	12.24	1070	750	13.3	0.22
UA1	fine	12.58	1075	760	14.1	0.20
UA1	fine	11.01	900	750	13.3	0.15
UA1	fine	10.20	950	annealed	9.9	0.14
UA1	fine	10.56	1001	annealed	11.8	0.17
UA1	fine-perp	9.75	915	RT	10.7	0.13
UA1	fine-perp	9.72	905	RT	10.1	0.15
UA1	fine-perp	10.34	925	500	11.0	0.15
UA1	fine-perp	10.34	925	500	12.1	0.18
UA1	coarse	9.65	900	RT	9.6	0.13
UA1	coarse	9.67	890	RT	9.7	0.15
UA1	coarse	10.33	950	500	10.7	0.17
UA1	coarse	10.48	950	500	10.3	0.15
UA1	coarse	10.54	1000	annealed	11.3	0.14
UA1	billet	9.24	850	RT	8.7	0.11
UA1	billet	9.13	840	RT	9.9	0.14
UA1	billet	10.21	910	500	9.8	0.14
UA1	billet	10.91	975	500	12.6	0.16
UA1	billet	10.70	980	500	12.7	0.14
UA1	billet	10.66	1025	annealed	10.5	0.14
UB1	fine	11.84	1575	RT	19.2	0.26
UB1	fine	9.83	1240	RT	18.0	0.22
UB1	fine	10.88	1340	500	19.2	0.25
UB1	fine	10.63	1330	500	16.1	0.23

Note: No specimen of this type failed in the first pulse in the strain rate levels studied

Table 5 2 - Experimental Results for J-notch Specimens

Stock	Striker vel. (m/s)	Strain rate (s ⁻¹)	Temperature (°C)	Axial strain %	True strain
fine	10.21	600	RT	7.3	0.50
fine	12.28	750	RT	7.9	0.59
fine	13.84	900	250	11.1	0.80
fine	16.21	1100	250	13.5	1.05
fine	9.84	575	500	8.3	0.57
fine	9.91	575	500	8.8	0.54
fine	12.07	710	750	8.2	0.64
fine	10.93	605	750	9.4	0.57
fine	9.42	570	annealed	8.7	0.48
fine	9.75	610	annealed	8.0	0.58
coarse	10.73	640	RT	7.5	0.42
coarse	10.86	630	RT	7.3	0.52
coarse	10.86	640	250	9.5	0.67
coarse	10.96	655	250	6.9	0.53
coarse	10.64	640	500	7.2	0.52
coarse	10.39	590	500	6.6	0.46
coarse	10.62	585	750	8.0	0.50
coarse	10.88	600	750	8.7	0.60

Note: No specimen of this type failed in the first pulse in the strain rate levels studied

Table 5.3 - Experimental Results for C-notch Specimens

Stock	Striker vel. (m/s)	Strain rate (s ⁻¹)	Temperature (°C)	Axial strain %	Ductility or true strain	Failure
fine	9.75	800	RT	14.3	0.83	yes
fine	10.51	925	RT	15.8	0.83	yes
fine	9.87	850	RT	11.7	0.79	yes
fine	9.34	850	RT	11.5	0.79	yes
fine	10.27	1010	250	16.5	1.14	yes
fine	10.03	1000	250	17.8	1.01	yes
fine	10.57	1030	500	20.4	1.07	yes
fine	10.52	1090	500	20.9	1.18	no
fine	10.62	1100	500	14.0	1.15	no
fine	10.51	1060	750	15.8	0.92	no
fine	10.93	1075	750	15.5	1.13	no
fine	10.35	1025	750	13.9	1.09	no
fine	10.77	1150	annealed	12.1	0.84	yes
fine	10.20	1100	annealed	11.6	0.79	yes

Figure 1.7 - Situation around the specimen

Figure 1.8 - Pulse obtained with pulse shaping technique (Taken from reference [2])

Figure 1.1 - Dynamic aspects of mechanical testing

Figure 1.2 - Typical split Hopkinson bar arrangement

Figure 1 5 - Arrangement for one TSHB and its specimen design

a) Bar arrangement

b) Specimen design

Figure 1.6 - Direct tension split Hopkinson bar arrangement

Figure 1.7 - Situation around the specimen

Figure 1.8 - Pulse obtained with pulse shaping technique (Taken from reference [2])

(a)

(b)

Figure 1.9 - Arrangement for interrupted test in TSHB and typical pulse obtained

Figure 2.1 - True stress versus strain rate for various strain values

Figure 2.2 - True stress versus strain rate for a strain value of 0.1 cm/cm

Figure 2 3 - Optical micrograph of the 20 mm plate material

a) Small grains in the central region

b) Large grains in the surface layers

Figure 2.4 - Optical micrograph of the 25 mm plate material

Figure 2 5 - Optical micrograph of the billet material

(1) Strain gauge	(5) Transmitter bar
(2) Specimen	(6) Incident bar
(3) Incident bar endcap	(7) Gas gun
(4) Momentum brake	(8) Striker

Figure 3.1a - Schematic view of the original arrangement of the TSHB

Figure 3.1b - Photograph of the original arrangement of the TSHB

(1) Gas gun	(7) Transmitter bar
(2) Striker	(8) Transmitter bar
(3) Transmitter bar	(9) Transmitter bar
(4) Transmitter bar	(10) Transmitter bar
(5) Transmitter bar	
(6) Transmitter bar	

Figure 3.2a - Schematic view of the modified arrangement of the TSHB

Figure 3.2b - Photograph of the modified arrangement of the TSHB

Figure 3.3 - Gas gun schematic

Figure 3.4 - Schematic of the incident bar momentum brake with lid removed

Figure 3.5 - Typical strain pulses recorded for a J-notch with the original TSHB arrangement

(1) Incident bar	(4) Momentum trap rod holder
(2) Incident bar endcap cradle	(5) Momentum brake
(3) Incident bar momentum trap rod	(6) Spacer

a) Schematic view

b) Photograph

Figure 3.6 - Modified arrangement for pulse trapping on the incident bar side

(1) Transmitter bar endcap, male	(5) Transmitter bar momentum trap brake holder
(2) Transmitter bar screwed-on endcap	(6) Transmitter bar
(3) Transmitter bar momentum trap cylinder	(7) Bar holder
(4) Transmitter bar momentum trap brake	(8) Support

a) Schematic view

b) Photograph

Figure 3.7 - Modified arrangement for pulse trapping on the transmitter side

Figure 3.8 - Typical strain pulses recorded for a J-notch with the modified TSHB arrangement

Figure 3.9 - Wheatstone bridge arrangement used in the experiments

Figure 3.10 - Furnace and controller system

Measurements are in inches

Figure 3.11 - Specimen design - uniaxial specimens

Measurements are in inches

Figure 3.12 - Specimen design - notched specimens

(1) Tie rod	(6) Nut
(2) Load Cell	(7) Cradle
(3) Threaded tie	(8) Gas gun
(4) Split block	(9) Striker
(5) Incident bar endcap	

Figure 3.13 - Schematic view of the calibration equipment

Measurements are in inches

Figure 3.14 - Tie tests specimen configuration

Figure 3.15 - Heating curves for elevated temperature tests

Figure 4.1 Model parts and boundary conditions

Figure 4.2 - First 40 cm of incident bar and striker bar meshes

Figure 4.3a - UAl specimen mesh for full bar simulation

Figure 4.3b - NJ2 specimen mesh for full bar simulation

Figure 4.4a - Strain pulses at the bar gauges position for uniaxial specimen (UA1)

Figure 4.4b - Strain pulses at the bar gauges position for J-notch specimen (NJ2)

Figure 4.5a - UA1 specimen mesh and boundary conditions (Specimen only simulations)

Figure 4.5b - NJ2 specimen mesh and boundary conditions (Specimen only simulations)

Figure 4.5c - NC2 specimen mesh and boundary conditions (Specimen-only simulations)

Figure 4.6 - Typical velocity profiles used in specimen-only simulations

Figure 4.7a - Engineering versus true strain conversion (UA1 specimen)

Figure 4.7b - Engineering versus true strain conversion (UB1 specimen)

Figure 4.7c - Engineering versus true strain conversion (NJ2 specimen)

Figure 4.7d - Engineering versus true strain conversion (NC2 specimen)

Figure 4.8a - Bridgman factor for NJ2 specimen

Figure 4.8b - Effective plastic strain versus diametral strain relationship (NJ2 specimen)

Figure 4.9a - Bridgman factor for NC2 specimen

Figure 4.9b - Effective plastic strain versus diametral strain relationship (NC2 specimen)

Figure 5.1 - Quasi-static curves for uniaxial specimens made of different stock material

Figure 5.2 - Comparison of quasi-static curves for different gauge lengths of uniaxial specimens

(TEST #124) STRIKER VELOCITY: 10.63 m/s

Figure 5.3 - Strain pulses for a specimen breaking on the first pulse

(TEST #141) STRIKER VELOCITY: 10.21 m/s

Figure 5.4 - Strain pulses for a specimen breaking on subsequent pulses

Figure 5.5 - Addition of strain pulses

Figure 5.6a - Unfiltered stress-strain curves for uniaxial specimens (fine grained material)

Figure 5.6b - Filtered stress-strain curves for uniaxial specimens (fine grained material)

Figure 5.7a- Room temperature stress-strain curves for as-received material (UA1 design)

Figure 5.7b - Stress-strain curves at 500°C (UA1 design)

Figure 5.7c - Room temperature stress-strain curves for annealed material (UA1 design)

Figure 5.8a - Stress-strain curves for two gauge lengths of uniaxial specimens at room temperature

Figure 5.8b - Stress-strain curves for two gauge lengths of uniaxial specimens at 500°C

Figure 5.9a - Comparison of quasi-static and high strain rate tests for uniaxial specimens

Figure 5.9b - True strain versus strain rate for a strain value of 0.1 cm/cm

Figure 5.10 - Comparison of experimental stress-strain curves with curves calculated with Johnson-Cook model

Figure 5.11a - Unfiltered stress-strain curves at different temperatures for NJ2 specimens (fine grained material)

Figure 5.11b - Filtered stress-strain curves at different temperatures for NJ2 specimens (fine grained material)

Figure 5.12a - Unfiltered stress-strain curves at different temperatures for NJ2 specimens (coarse grained material)

Figure 5.12b - Filtered stress-strain curves at different temperatures for NJ2 specimens (coarse grained material)

Figure 5.13a - Unfiltered stress-strain curves at different temperatures for NC2 specimens (fine grained material)

Figure 5.13b - Filtered stress-strain curves at different temperatures for NC2 specimens (fine grained material)

Figure 5.14 - Bridgman factor verification

Figure 5 15a - SEM micrograph of the fracture surface of a uniaxial specimen from quasi-static test

Figure 5 15b - SEM micrograph of the fracture surface of a J-notch specimen from quasi-static test

Figure 5 15c - SEM micrograph of the fracture surface of a C-notch specimen from quasi-static test

Figure 5 16a - Optical micrograph of the fracture surface of a J-notch specimen (NJ2)

Figure 5 16b - Optical micrograph of the fracture surface of a C-notch specimen (NC2)

Figure 5 17a - SEM micrograph of the fracture surface of a J-notch specimen (NJ2)

Figure 5 17b - SEM micrograph of the fracture surface of a C-notch specimen (NC2)

Figure 5.18a - Comparison of incident and reflected pulses from simulation and experiment (Uniaxial specimen)

Figure 5.18b - Comparison of transmitted pulse from simulation and experiment (Uniaxial specimen)

```

240  INCREFL = EZINC + EZREFL
      IF (NEX.EQ.2) GOTO 250
      IRTPLUS = EZINC + EZREFL + EZTRAN
      IRTMINUS = EZINC - EZREFL - EZTRAN
      IRTANN = EZINC + EZREFL - EZTRAN
      IRTES = EZINC + EZREFL

250  WRITE (299,FMT=920) (I*0.2),EZINC
      WRITE (300,FMT=920) (I*0.2),EZREFL
      WRITE (301,FMT=920) (I*0.2),INCREFL
      IF (NEX.EQ.2) GOTO 260
      WRITE (302,FMT=920) (I*0.2),EZTRAN
      WRITE (303,FMT=920) (I*0.2),IRTPLUS
      WRITE (304,FMT=920) (I*0.2),IRTMINUS
      WRITE (305,FMT=920) (I*0.2),IRTANN
      WRITE (306,FMT=920) (I*0.2),IRTES

260  CONTINUE

      CLOSE (298)
      CLOSE (299)
      CLOSE (300)
      CLOSE (301)
      IF (NEX.EQ.2) GOTO 270
      CLOSE (302)
      CLOSE (303)
      CLOSE (304)
      CLOSE (305)
      CLOSE (306)
      CLOSE (307)

270  PRINT *, 'DONE'

900  FORMAT (A)
910  FORMAT (F14.7,F14.7)
915  FORMAT (A10,F10.5)
920  FORMAT (F20.10,F20.10)
930  FORMAT ('ENTER EXCITATION VOLTAGE (V) & CHANNEL I2, IN MV. ')

```

END

```

C *****
  SUBROUTINE VOLSTR(VAL,J,NG,NFG,VE,GAGE)

  DIMENSION NG(*),NFG(*),VE(*),GAGE(2,*)
  INTEGER J

  NCH=1
  IF (J.EQ.2) THEN
    NCH=2
  ENDIF

  IF (NG(NCH).EQ.1) GOTO 220
  IF (NFG(NCH).EQ.2) GOTO 230

  GAGE(NCH,15)=GAGE(NCH,11)*(VAL-VE(NCH))
  GAGE(NCH,16)=GAGE(NCH,13)*VAL-GAGE(NCH,10)*VE(NCH)
  GAGE(NCH,17)=GAGE(NCH,12)*VAL-GAGE(NCH,9)*VE(NCH)

  BET=SQRT((GAGE(NCH,16)**2)-(4*GAGE(NCH,15)*GAGE(NCH,17)))
  RAC1=(-GAGE(NCH,16)+BET)/(2*GAGE(NCH,15))
  RAC2=(-GAGE(NCH,16)-BET)/(2*GAGE(NCH,15))

C   CHOOSING OF THE ADEQUATE ROOT
  IF (ABS(RAC1).LT.ABS(RAC2)) THEN
    VAL=RAC1
  ELSE
    VAL=RAC2
  
```

Figure 6-1 - Verification of the Hall-Petch relationship

APPENDICES

APPENDIX A

DATA REDUCTION PROGRAMS FOR HIGH STRAIN RATE TESTING AT ROOM TEMPERATURE

PROGRAM STRAIN

C CONVERTS NICOLET BRIDGE VOLTAGE DATA INTO AXIAL STRAINS
C AND COMPARES VARIOUS SUMMATIONS OF THE PULSES
C THIS PROGRAM USES THE COMPLETE BRIDGE EQUATION METHOD
C THE NUMBER OF SAMPLES IN THE FILE CAN BE UP TO 20000
C THE TIME BETWEEN RECORDED POINTS HAS BEEN FIXED AT 200ns
C THIS PROGRAM CAN BE USED IF ONE HAS ONE OR TWO GAGES MOUNTED
C THIS PROGRAM IS GOOD FOR EXPERIMENTS AND TIE TESTS
C THE STARTING POINTS OF THE PULSE ARE CALCULATED FROM A MAXIMUM
C VALUE OF THE PULSE THEN GO BACK TO THE CLOSEST NEAR ZERO POINT
C RATHER THEN USING THE TRIGGER VALUE.
C THE DURATION OF THE PULSE IS CALCULATED FROM THE LENGTH OF THE
C STRIKER AND THE SOUND VELOCITY IN 4340 STEEL.

```

CHARACTER*20 NAME1,NAME2,NAME0
CHARACTER*10 PRO
CHARACTER*72 JUNK
INTEGER I,INDEXI,INDEXR,NB,J,CH,NG(2),NFG(2),TEX,OFL,NP,NPOS,NEX
REAL CH1(2,20000),CH2(2,20000),GAGE(2,17),VE(2),VD,FACLFACR,FACT,GF
REAL EZINC,EZREFL,EZTRAN,INCREFL,IRTPLUS,IRTMINUS,IRTANN,IRTES
REAL OFS,C0,SL,DT,DG,DT2,TR,SUMXY,SUMX2,SUMY,SLOPE,SINT,XORI

```

```

C  C0 = SOUND VELOCITY (M/S)
PARAMETER (C0=5121.85, DIS=160.0)

C  ASK FOR THE TYPE OF EXPERIMENT
PRINT *, 'ENTER THE TYPE OF EXPERIMENT TO REDUCE.'
PRINT *, ' (1) FULL EXPERIMENT OR TIE TEST'
PRINT *, ' (2) INCIDENT BAR ONLY TEST'
READ *, NEX

C  ASK HOW MANY POINTS IN YOUR FILE
PRINT *, 'ENTER THE NUMBER OF POINTS IN YOUR FILES '
READ *, NB

C  ASK FOR THE STRIKER LENGTH
PRINT *, 'ENTER THE STRIKER LENGTH IN INCHES '
READ *, SL
DT=2*SL*2.54/C0*10000

C  ASK FOR DISTANCE FROM END OF BAR TO STRAIN GAGE
PRINT *, 'ENTER DISTANCE FROM END OF BAR TO GAGE IN CM.'
READ *, DG
DT2=2*DG/C0*10000

C  ASK FOR TRIGGER VALUE
PRINT *, 'ENTER TRIGGER VALUE IN MV.'
READ *, TR

C  READ DATA FROM FILES INTO ARRAYS

PRINT *, 'ENTER FILE NAME FOR CHANNEL 1:'
READ (*,900), NAME1
OPEN (UNIT=43, FILE=NAME1, STATUS = 'OLD')
IF (NEX.EQ.2) GOTO 5
PRINT *, 'ENTER FILE NAME FOR CHANNEL 2 '
READ (*,900), NAME2
OPEN (UNIT=44, FILE=NAME2, STATUS = 'OLD')

5  DO 10 I=1,NB
    READ (43,FMT=900) JUNK
    IF (NEX.EQ.2) GOTO 10
    READ (44,FMT=900) JUNK
10  CONTINUE

DO 20 I=1,NB
    READ (43,FMT=910) CH1(1,I),CH1(2,I)
    IF (NEX.EQ.2) GOTO 20

```



```

      READ (44,FMT 910) CH2(1,I),CH2(2,I)
20  CONTINUE

      CLOSE (43)
      IF (NEX.EQ.2) GOTO 25
      CLOSE (44)

C GET THE BRIDGE DATA

25  PRINT *, 'ENTER THE NAME OF THE FILE WITH THE BRIDGES DATA '
      READ (*,900), NAME0
      OPEN (UNIT=42, FILE=NAME0, STATUS='OLD')
      DO 30 I=1,5
      READ (42,FMT 900) JUNK
30  CONTINUE

      DO 50 I=1,2
      IF ((NEX.EQ.2).AND.(I.EQ.2)) GOTO 50
      DO 40 J=1,6
      READ (42,FMT 915) PRO,GAGE(I,J)
40  CONTINUE

C CALCULATE REQUIRED DATA

C CHECK FOR THE NUMBER OF GAGES
      IF (GAGE(I,4).EQ.0.0) THEN
          NG(I)=1
          NFG(I)=1
          GOTO 43
      END IF

      IF (GAGE(I,4).LT.3.0) THEN
          NG(I)=2
          NFG(I)=2
          GOTO 47
      END IF

      NG(I)=2
      NFG(I)=1
      GAGE(I,7) = GAGE(I,1)+GAGE(I,5)
      GAGE(I,8) = GAGE(I,2)+GAGE(I,6)
      GAGE(I,9) = GAGE(I,1)*GAGE(I,2)-GAGE(I,5)*GAGE(I,6)
      GAGE(I,10) = GAGE(I,1)*GAGE(I,2)*(GAGE(I,3)+GAGE(I,4))
      GAGE(I,11) = GAGE(I,1)*GAGE(I,2)*GAGE(I,3)*GAGE(I,4)
      GAGE(I,12) = GAGE(I,7)*GAGE(I,8)
      GAGE(I,13) = (GAGE(I,1)*GAGE(I,3)*GAGE(I,8))+(GAGE(I,2)*GAGE(I,4)*GAGE(I,7))
      GOTO 47

43  GAGE(I,7) = GAGE(I,1)*GAGE(I,2)+GAGE(I,1)*GAGE(I,6)+GAGE(I,5)*GAGE(I,2)
      GAGE(I,7) = GAGE(I,7)+GAGE(I,5)*GAGE(I,6)
      GAGE(I,8) = GAGE(I,1)*GAGE(I,2)-GAGE(I,5)*GAGE(I,6)
      GAGE(I,9) = GAGE(I,1)*GAGE(I,2)*GAGE(I,3)
      GAGE(I,10) = (GAGE(I,2)+GAGE(I,6))*GAGE(I,3)

C ACQUIRE TEST RUN EXCITATION VOLTAGES AND CALCULATE ADDITIONAL DATA

47  WRITE (*,930) I
      READ *, VE(I)

50  CONTINUE
      CLOSE (42)

C CALCULATE STRAINS FROM VOLTAGES
      DO 55 I=1,NB
      DO 52 J=1,2
      IF (J.EQ.1) THEN
          VD=CH1(2,I)*1000
          CALL VOLSTR(VD,J,NG,NFG,VE,GAGE)

```

```

      CH1(2,I)=VD
      GOTO 52
    END IF
    IF ((J.EQ 2).AND.(NEX.EQ.2)) GOTO 55
    VD=CH2(2,I)*1000
    CALL VOLSTR(VD,J,NG,NFG,VE,GAGE)
    CH2(2,I)=VD
52  CONTINUE
55  CONTINUE

    PRINT *, 'OFFSET DISTANCE BETWEEN INC AND TRANS. GAGES IN CM '
    READ *, OFS
    OFS=OFS/C0*10000

C  OPEN OUTPUT FILES

    OPEN (UNIT=298, FILE='ez.tunc.exp', STATUS = 'NEW')
    OPEN (UNIT=299, FILE='ez.inc.exp', STATUS = 'NEW')
    OPEN (UNIT=300, FILE='ez.refl.exp', STATUS = 'NEW')
    OPEN (UNIT=301, FILE='ez.inc+refl.exp', STATUS = 'NEW')

    IF (NEX.EQ.2) GOTO 57
    OPEN (UNIT=302, FILE='ez.tran.exp', STATUS = 'NEW')
    OPEN (UNIT=303, FILE='ez.inc+refl+tran.exp', STATUS = 'NEW')
    OPEN (UNIT=304, FILE='ez inc-refl-tran.exp', STATUS = 'NEW')
    OPEN (UNIT=305, FILE='ez inc+refl-tran.exp', STATUS = 'NEW')
    OPEN (UNIT=306, FILE='ez.test.exp', STATUS = 'NEW')
    OPEN (UNIT=307, FILE='ez.ttran.exp', STATUS='NEW')

C  GET STARTING INDICES FOR PULSES

C  DEFINITION OF FACTOR TO START LOOKING FOR FIRST MAXIMUM TAKING
C  THE TYPE AND NUMBER OF GAGES INTO ACCOUNT

C  DEFINITION OF FACTOR TO LOOK FOR PULSE BEGINNING
57  FACI=(GAGE(1,3)+GAGE(1,4))/(157*2)*0.5
    J=1
    CALL VOLSTR(FACI,J,NG,NFG,VE,GAGE)
    FACR=(GAGE(1,3)+GAGE(1,4))/(157*2)*0.75
    J=1
    CALL VOLSTR(FACR,J,NG,NFG,VE,GAGE)
    IF (NEX.EQ.2) GOTO 59
    FACT=(GAGE(2,3)+GAGE(2,4))/(157*2)*0.5
    J=2
    CALL VOLSTR(FACT,J,NG,NFG,VE,GAGE)

C  INCIDENT PULSE
59  J=1
    CALL VOLSTR(TR,J,NG,NFG,VE,GAGE)
    DO 60 I=1,NB
    IF (CH1(2,I).GE TR) THEN
      NPOS=I
      NPOS2=NPOS
      GOTO 70
    END IF
60  CONTINUE

C  SLOPE AND INTERCEPT CALCULATION FROM DATA NEAR THE TRIGGER POINT
70  SUMXY=0.0
    SUMX2=0.0
    SUMY=0.0
    DO 80 I=(NPOS-5),(NPOS+5)
      SUMXY = SUMXY + CH1(1,I) * CH1(2,I)
      SUMX2 = SUMX2 + CH1(1,I)**2
      SUMY = SUMY + CH1(2,I)
80  CONTINUE
    SLOPE = SUMXY/SUMX2
    SINT = SUMY/10.0

```

```

XORI = -SINT/SLOPE

DO 90 I = 1,NB
  IF (CH1(1,I) GE XORI) THEN
    NPOS = I - 1
    GOTO 100
  END IF
90 CONTINUE
100 DO 110 I = NPOS, 1, -1
  IF (CH1(2,I) LE FACI) THEN
    INDEXI = I
    GOTO 120
  ENDIF
110 CONTINUE

C REFLECTED PULSE

C FIRST GUESS AT STARTING POINT FOR REFLECTED PULSE
120 INDEXR = INDEXI + INT(DT2/0.2)
  IF (CH1(2,INDEXR) LT FACR) GOTO 140
  DO 130 I = INDEXR, (INDEXR + 2000)
  IF (CH1(2,I) LT FACR) THEN
    INDEXR = I
    GOTO 160
  END IF
130 CONTINUE
  GOTO 160
140 DO 150 I = INDEXR, (INDEXR - 2000), -1
  IF (CH1(2,I) GE FACR) THEN
    INDEXR = I
    GOTO 160
  END IF
150 CONTINUE

C TRANSMITTED PULSE
C FIRST GUESS AT STARTING POINT FOR TRANSMITTED PULSE
160 IF (NEX.EQ.2) GOTO 192
  INDEXT = INDEXI + INT((DT2 + OPS)/0.2)
  IF (CH2(2,INDEXT) GE FACT) GOTO 180
  DO 170 I = INDEXT, (INDEXT + 2000)
  IF (CH2(2,I) GE FACT) THEN
    INDEXT = I
    GOTO 192
  END IF
170 CONTINUE
  GOTO 192
180 DO 190 I = INDEXT, (INDEXT - 2000), -1
  IF (CH2(2,I) LT FACT) THEN
    INDEXT = I
    GOTO 192
  END IF
190 CONTINUE

C CONSIDER TIME LAG DUE SAMPLE FOR IRON (7.6 MICROSEC)
  INDEXT = I - 38
  GOTO 192
  END IF
190 CONTINUE

C PUT SPECIMEN STRAINS IN FILES

C PUT ALL THE STRAIN RESULTS IN FILES
192 DO 195 I = 1,NB
  WRITE (298,FMT=920) ((I-1-NPOS2)*0.2), CH1(2,I)
  IF (NEX.EQ.2) GOTO 195
  WRITE (307,FMT=920) ((I-1-NPOS2)*0.2), CH2(2,I)
195 CONTINUE

200 NP2 = INT(DT/0.2) + 500
  DO 260 I = 1,NP2
    EZINC = CH1(2,INDEXI + I)
    EZREFL = CH1(2,INDEXR + I)
    IF (NEX.EQ.2) GOTO 240
    EZTRAN = CH2(2,INDEXT + I)

```

```

240  INCREFL = EZINC + EZREFL
      IF (NEX.EQ.2) GOTO 250
      IRTPLUS = EZINC + EZREFL + EZTRAN
      IRTMINUS = EZINC - EZREFL - EZTRAN
      IRTANN = EZINC + EZREFL - EZTRAN
      IRTES = EZINC + EZREFL

250  WRITE (299,FMT=920) (I*0.2),EZINC
      WRITE (300,FMT=920) (I*0.2),EZREFL
      WRITE (301,FMT=920) (I*0.2),INCREFL
      IF (NEX.EQ.2) GOTO 260
      WRITE (302,FMT=920) (I*0.2),EZTRAN
      WRITE (303,FMT=920) (I*0.2),IRTPLUS
      WRITE (304,FMT=920) (I*0.2),IRTMINUS
      WRITE (305,FMT=920) (I*0.2),IRTANN
      WRITE (306,FMT=920) (I*0.2),IRTES

260  CONTINUE

      CLOSE (298)
      CLOSE (299)
      CLOSE (300)
      CLOSE (301)
      IF (NEX.EQ.2) GOTO 270
      CLOSE (302)
      CLOSE (303)
      CLOSE (304)
      CLOSE (305)
      CLOSE (306)
      CLOSE (307)

270  PRINT *, 'DONE'

900  FORMAT (A)
910  FORMAT (F14.7,F14.7)
915  FORMAT (A10,F10.5)
920  FORMAT (F20.10,F20.10)
930  FORMAT ('ENTER EXCITATION VOLTAGE FOR CHANNEL',I2,' IN MV ')

```

END

```

C *****
  SUBROUTINE VOLSTR(VAL,J,NG,NFG,VE,GAGE)

  DIMENSION NG(*),NFG(*),VE(*),GAGE(2,*)
  INTEGER J

  NCH=1
  IF (J.EQ.2) THEN
    NCH=2
  ENDIF

  IF (NG(NCH).EQ.1) GOTO 220
  IF (NFG(NCH).EQ.2) GOTO 230

  GAGE(NCH,15)=GAGE(NCH,11)*(VAL-VE(NCH))
  GAGE(NCH,16)=GAGE(NCH,13)*VAL-GAGE(NCH,10)*VE(NCH)
  GAGE(NCH,17)=GAGE(NCH,12)*VAL-GAGE(NCH,9)*VE(NCH)

  BET=SQRT((GAGE(NCH,16)**2)-(4*GAGE(NCH,15)*GAGE(NCH,17)))
  RAC1=(-GAGE(NCH,16)+BET)/(2*GAGE(NCH,15))
  RAC2=(-GAGE(NCH,16)-BET)/(2*GAGE(NCH,15))

C  CHOOSING OF THE ADEQUATE ROOT
  IF (ABS(RAC1).LT.ABS(RAC2)) THEN
    VAL=RAC1
  ELSE
    VAL=RAC2
  ENDIF

```

Data Reduction Method for Experiments at High Strain Rate and Elevated Temperatures

Figure B.1 illustrates the situation along the bars and the specimen when working at elevated temperature as well as a schematic representation of the various pulses considered and their directions. The required data to calculate the stress and strain in the specimen are the corrected values at the interface. At room temperature, based on the split Hopkinson bar assumptions, the strain values measured at the gauge are very close to those at the interface but at elevated temperature, the strain values are distorted by the temperature gradient in the bar. The measured strains at the gauges must therefore be corrected to obtain the real values at the interfaces. The method used to perform this correction which was developed originally by Chiddister and Malvern [15] will be presented in this appendix. Let α represent the specimen interface with the incident bar and β the interface with the transmitter bar, while λ and ζ denote the temperature distribution in the incident and transmitter bars respectively. The corrected values of strain pulses will be noted by the superscripts α and β . Therefore, ϵ_1^α represents the corrected value of the recorded pulse ϵ_1 or the amplitude it will have when reaching the interface α . ϵ_{R1}^α is the corrected reflected pulse from the specimen at α to appear at the gauge station as ϵ_{R1} . In this analysis, first order temperature reflections only will be considered assuming that reflection of a reflection shall be negligible.

The incident pulse ϵ_1 is partially reflected at λ , at $\alpha+\beta$ and at ζ . These reflections are noted ϵ_R' , ϵ_{R1} , ϵ_{R2} . At the transmitter gauge station, there is ϵ_{T1} , the transmitted part of the incident pulse which is superposed with ϵ_{T2} , the part of ϵ_{R1} reflected from λ and

```

                ENDIF
                GOTO 240
220      VAL=((GAGE(NCH,7)*VAL)-(GAGE(NCH,8)*VF(NCH)))/((GAGE(NCH,9)*VF(NCH))- (GAGE(NCH,10)*VAL))
        GOTO 240
230      GF=1/((1-GAGE(NCH,3))-(1-GAGE(NCH,4)))
        STR=VAL*(VF(NCH)*GF)
240      RETURN
      END

```

PROGRAM Nicolet

C CONVERTS NICOLET BRIDGE VOLTAGE DATA INTO AXIAL STRAINS
 C THEN DETERMINES SPECIMEN STRESS, STRAIN RATE, AND STRAIN
 C CALCULATES AVERAGE SPECIMEN STRESS BASED ON TRANSMITTED
 C PULSE AND (INCIDENT + REFLECTED) PULSE
 C CALCULATES STRAIN RATE BASED ON REFLECTED PULSE AND
 C (INCIDENT-REFLECTED-TRANSMITTED) PULSE
 C THIS PROGRAM USES THE COMPLETE BRIDGE EQUATION METHOD
 C THE NUMBER OF SAMPLES IN THE FILE CAN BE UP TO 20000.

```

  CHARACTER*20 NAME0,NAME1,NAME2
  CHARACTER*10 PRO
  CHARACTER*72 JUNK
  INTEGER LINDEX,LINDEXR,NBJ,L,NEX,N,NCW(2),NFG(2)
  REAL CH1(2,20000),CH2(2,20000),GAGE(2,17),VE(2),VD
  REAL L,D,ASPEC,PL,FINC,FTRAN,V1,V2,TRUEERIT
  REAL EZINC,EZRE(2000),EZREFL,EZTRAN,SUM,EZRIT,EZRITE(2000)
  REAL SAV(2000),STRAN(2000),SIR(2000),DOFS
  REAL ESPEC,ESPECR,C,E,ABAR,YMIN,DIS,SL,SUM2,EERIT(2000)
  REAL ESAVE(2000),ESTRAN(2000),ESIR(2000),EE(2000),F(4)
  PARAMETER (PI=3.141592654, E=2.0685E+05, C=5121.2)
  PARAMETER (ABAR=197.9326, DIS=160.0)
  REAL TRUEDE,TRUEA
  
```

C ABAR IS IN mm²
 C STRESSES ARE IN MPa
 C DATA FILES CAN HAVE UP TO 20000 SAMPLES
 C UPPER TRIGGER LEVEL MUST BE 20 mV

C ASK HOW MANY POINTS IN THE FILE
 PRINT *, 'ENTER THE NUMBER OF POINTS IN YOUR FILES. '
 READ *, NB

C ASK FOR THE STRIKER LENGTH
 PRINT *, 'ENTER THE STRIKER LENGTH IN INCHES: '
 READ *, SL
 DT=2*SL*.254/C*10000

C ASK FOR DISTANCE FROM END OF BAR TO STRAIN GAGE
 PRINT *, 'ENTER DISTANCE FROM END OF BAR TO GAGE IN CM '
 READ *, DG
 DT2=2*DG/C*10000

C ASK FOR TRIGGER VALUE
 PRINT *, 'ENTER TRIGGER VALUE IN MV '
 READ *, TR

C READ DATA FROM FILES INTO ARRAYS

```

  PRINT *, 'ENTER FILE NAME FOR CHANNEL 1: '
  READ (*,900), NAME1
  PRINT *, 'ENTER FILE NAME FOR CHANNEL 2: '
  READ (*,900), NAME2
  OPEN (UNIT=43, FILE=NAME1, STATUS='OLD')
  OPEN (UNIT=44, FILE=NAME2, STATUS='OLD')
  
```

```

  DO 10 I=1,13
    READ(43,FMT=900) JUNK
    READ(44,FMT=900) JUNK
  10 CONTINUE
  
```

```

  DO 20 I=1,NB
    READ(43,FMT=910) CH1(I,1),CH1(I,2)
    READ(44,FMT=910) CH2(I,1),CH2(I,2)
  20 CONTINUE
  
```

CLOSE (43)
CLOSE (44)

C ACQUIRE SPECIMEN STATISTICS

PRINT *, 'ENTER GAUGE LENGTH OF SPECIMEN (mm) '
READ *, L

PRINT *, 'ENTER GAUGE DIAMETER OF SPECIMEN (mm) '
READ *, D

ASPEC = PI*4.0*D*D

C GET THE BRIDGE DATA

PRINT *, 'ENTER THE NAME OF THE FILE WITH THE BRIDGES DATA '
READ (*,900), NAME0
OPEN (UNIT=42, FILE=NAME0, STATUS='OLD')
DO 30 I=1,5
READ (42,FMT=900) JUNK
30 CONTINUE

DO 70 I=1,2
DO 40 J=1,6
READ (42,FMT=915) PRO,GAGE(I,J)
40 CONTINUE

C CALCULATE REQUIRED DATA

C CHECK FOR THE NUMBER OF AND TYPE OF STRAIN GAUGES

IF (GAGE(I,4).EQ.0.0) THEN
NG(I)=1
NFG(I)=1
GOTO 50
END IF

IF (GAGE(I,4).LT.3.0) THEN
NG(I)=2
NFG(I)=2
GOTO 60
END IF

NG(I)=2
NFG(I)=1
GAGE(I,7)=GAGE(I,1)+GAGE(I,5)
GAGE(I,8)=GAGE(I,2)+GAGE(I,6)
GAGE(I,9)=GAGE(I,1)*GAGE(I,2)+GAGE(I,5)*GAGE(I,6)
GAGE(I,10)=GAGE(I,1)*GAGE(I,2)*(GAGE(I,3)+GAGE(I,4))
GAGE(I,11)=GAGE(I,1)*GAGE(I,2)*GAGE(I,3)*GAGE(I,4)
GAGE(I,12)=GAGE(I,7)*GAGE(I,8)
GAGE(I,13)=(GAGE(I,1)*GAGE(I,3)*GAGE(I,8))+(GAGE(I,2)*GAGE(I,4)*GAGE(I,7))

GOTO 60

50 GAGE(I,7)=GAGE(I,1)*GAGE(I,2)+GAGE(I,1)*GAGE(I,6)+GAGE(I,5)*GAGE(I,2)
GAGE(I,7)=GAGE(I,7)+GAGE(I,5)*GAGE(I,6)
GAGE(I,8)=GAGE(I,1)*GAGE(I,2)+GAGE(I,5)*GAGE(I,6)
GAGE(I,9)=GAGE(I,1)*GAGE(I,2)*GAGE(I,3)
GAGE(I,10)=(GAGE(I,2)+GAGE(I,6))*GAGE(I,3)

C ACQUIRE TEST RUN EXCITATION VOLTAGES

60 WRITE (*,930)1
READ *, VE(I)

70 CONTINUE
CLOSE (42)

C CALCULATE STRAINS FROM VOLTAGES


```

      DO 110 I = 1, NB
      DO 100 J = 1, 2
        IF (J-1) 80, 80, 90
80      VD = CH1(2,I)*1000
        CALL VOLSTR(VD,J,NG,NFG,VE,GAGE)
        CH1(2,I) = VD
        GOTO 100
90      VD = CH2(2,I)*1000
        CALL VOLSTR(VD,J,NG,NFG,VE,GAGE)
        CH2(2,I) = VD
100     CONTINUE
110     CONTINUE

      PRINT *, 'OFFSET DISTANCE BETWEEN INC. AND TRANS. GAGES IN CM '
      READ *, IDFS
      IDFS = IDFS * C*10000

C     OPEN OUTPUT FILES
      OPEN (UNIT = 296, FILE = 'inc.exp', STATUS = 'NEW')
      OPEN (UNIT = 297, FILE = 'tran.exp', STATUS = 'NEW')
      OPEN (UNIT = 298, FILE = 'crater.exp', STATUS = 'NEW')
      OPEN (UNIT = 299, FILE = 'erate.exp', STATUS = 'NEW')
      OPEN (UNIT = 300, FILE = 's av.exp', STATUS = 'NEW')
      OPEN (UNIT = 301, FILE = 's tran.exp', STATUS = 'NEW')
      OPEN (UNIT = 302, FILE = 's i r.exp', STATUS = 'NEW')
      OPEN (UNIT = 303, FILE = 'craterit.exp', STATUS = 'NEW')
      OPEN (UNIT = 304, FILE = 'crmc.exp', STATUS = 'NEW')
      OPEN (UNIT = 305, FILE = 'ceref.exp', STATUS = 'NEW')
      OPEN (UNIT = 306, FILE = 'cstran.exp', STATUS = 'NEW')
      OPEN (UNIT = 307, FILE = 'ceref.it.exp', STATUS = 'NEW')

C     GET STARTING INDICES FOR PULSES
C     DEFINITION OF FACTOR TO START LOOKING FOR FIRST MAXIMUM TAKING
C     THE TYPE AND NUMBER OF GAGES INTO ACCOUNT

C     DEFINITION OF FACTOR TO LOOK FOR PULSE BEGINNING
      FAC1 = (GAGE(1,3)-GAGE(1,4))/(157*2)*0.5
      J = 1
      CALL VOLSTR(FAC1,J,NG,NFG,VE,GAGE)
      FACR = (GAGE(1,3)+GAGE(1,4))/(157*2)*0.75
      J = 1
      CALL VOLSTR(FACR,J,NG,NFG,VE,GAGE)
      FACT = (GAGE(2,3)+GAGE(2,4))/(157*2)*0.5
      J = 2
      CALL VOLSTR(FACT,J,NG,NFG,VE,GAGE)

C     INCIDENT PULSE
      J = 1
      CALL VOLSTR(TR,J,NG,NFG,VE,GAGE)
      DO 120 I = 1, NB
      IF (CH1(2,I) GE TR) THEN
        NPOS = 1
        NPOS2 = NPOS
        GOTO 130
      END IF
120     CONTINUE

C     SLOPE AND INTERCEPT CALCULATION FROM DATA NEAR THE TRIGGER POINT
130     SUMXY = 0.0
      SUMX2 = 0.0
      SUMY = 0.0
      DO 140 I = (NPOS-5), (NPOS+5)
        SUMXY = SUMXY + CH1(1,I) * CH1(2,I)
        SUMX2 = SUMX2 + CH1(1,I)**2
        SUMY = SUMY + CH1(2,I)
140     CONTINUE
      SLOPE = SUMXY / SUMX2
      SINT = SUMY / 10.0

```

```

NORI =SINT SLOPE

DO 150 I =1,NB
  IF (CH1(1,I).GE NORD) THEN
    NPOS =I-1
    GOTO 160
  END IF
150 CONTINUE
160 DO 170 I =NPOS,1,-1
  IF (CH1(2,I).LE.FACT) THEN
    INDEXI =I
    GOTO 180
  ENDIF
170 CONTINUE

C REFLECTED PULSE

C FIRST GUESS AT STARTING POINT FOR REFLECTED PULSE
180 INDEXR =INDEXI+INT(DT2/0.2)
  IF (CH1(2,INDEXR) - FACT) 190,210,210
190 DO 200 I=INDEXR,(INDEXR+2000)
  IF (CH1(2,I).LT.FACT) THEN
    INDEXR =I
    GOTO 230
  END IF
200 CONTINUE
210 DO 220 I=INDEXR,(INDEXR-2000),-1
  IF (CH1(2,I).GE.FACT) THEN
    INDEXR =I
    GOTO 230
  END IF
220 CONTINUE

C TRANSMITTED PULSE
C FIRST GUESS AT STARTING POINT FOR TRANSMITTED PULSE
230 INDEXT =INDEXI+INT((DT2-IDDFS)/0.2)
  IF (CH2(2,INDEXT) - FACT) 240,260,260
240 DO 250 I=INDEXT,(INDEXT+2000)
  IF (CH2(2,I).GE.FACT) THEN
    INDEXT =I
    GOTO 280
  END IF
250 CONTINUE
260 DO 270 I=INDEXT,(INDEXT-2000),-1
  IF (CH2(2,I).LT.FACT) THEN
    INDEXT =I
    GOTO 280
  END IF
270 CONTINUE

C PUT THE EXPERIMENTAL STRAIN RESULTS IN FILES
280 DO 290 I =1,NB
  WRITE (296,FMT =920)((1-I-NPOS2)*0.2),CH1(2,I)
  WRITE (297,FMT =920)((1-I-NPOS2)*0.2),CH2(2,I)
290 CONTINUE

C CALCULATE SPECIMEN STRESS AND STRAIN RATE

300 NP2 =INT(DT/0.2)+500
DO 310 I =1,NP2
  EZINC=CH1(2,INDEXI+I)
  EZREFL =CH1(2,INDEXR+I)
  EZRE(I)=EZREFL
  EZTRAN=CH2(2,INDEXT+I)
  EZRIT=-(EZINC-EZTRAN)
  EZRITE(I)=EZRIT

  ESPECR =-2°C*EZREFL/1.*1000/0

```

```

ESPECRT1 = 2.0 * EZRT1 / 1. * 1000.0
ESPEC = C * (EZINC - EZREFL - EZTRAN) / 1. * 1000.0
SAV(I) = E * ABAR / ASPL * C * (EZINC - EZREFL - EZTRAN) / 2
STRAN(I) = E * ABAR / ASPEC * E / ZTRAN
SIR(I) = E * ABAR / ASPEC * (EZINC - EZREFL)

```

```

WRITE (298.FMT, 920) (I*0.2), ESPECR
WRITE (299.FMT, 920) (I*0.2), ESPEC
WRITE (300.FMT, 920) (I*0.2), SAV(I)
WRITE (301.FMT, 920) (I*0.2), STRAN(I)
WRITE (302.FMT, 920) (I*0.2), SIR(I)
WRITE (303.FMT, 920) (I*0.2), ESPECRT1
WRITE (304.FMT, 920) (I*0.2), EZINC
WRITE (305.FMT, 920) (I*0.2), EZREFL
WRITE (306.FMT, 920) (I*0.2), EZTRAN
WRITE (307.FMT, 920) (I*0.2), EZRT1

```

110 CONTINUE

```

DO 320 I = 1, 12
  CLOSE (295, I)
120 CONTINUE

```

C CALCULATE ENGINEERING STRESS-STRAIN CURVES

C OPENING FILES

```

OPEN (UNIT = 303, FILE = 's-e.av.exp', STATUS = 'NEW')
OPEN (UNIT = 304, FILE = 's-e.tran.exp', STATUS = 'NEW')
OPEN (UNIT = 305, FILE = 's-e.i-r.exp', STATUS = 'NEW')
OPEN (UNIT = 306, FILE = 's-e.rut.av.exp', STATUS = 'NEW')
OPEN (UNIT = 307, FILE = 's-e.rut.tran.exp', STATUS = 'NEW')
OPEN (UNIT = 308, FILE = 's-e.rut.i-r.exp', STATUS = 'NEW')

```

C CALCULATE ENGINEERING STRESS AND ENGINEERING STRAIN

```

SUM = 0.0
SUM2 = 0.0

```

DO 330 I = 1, NP2-1

```

ESAV(I) = (SAV(I) - SAV(I-1)) / 2.0
ESTRAN(I) = (STRAN(I) - STRAN(I-1)) / 2.0
ESIR(I) = (SIR(I) - SIR(I-1)) / 2.0
SUM = SUM + (EZRE(I) - EZRE(I-1)) / 2.0 * 2E-6
EE(I) = -2.0 * C * SUM / 1. * 1000.0
SUM2 = SUM2 + (EZRITE(I) - EZRITE(I-1)) / 2.0 * 2E-6
FERIT(I) = -2.0 * C * SUM2 / 1. * 1000.0

```

```

WRITE (303.FMT, 920) EE(I), ESAV(I)
WRITE (304.FMT, 920) EE(I), ESTRAN(I)
WRITE (305.FMT, 920) EE(I), ESIR(I)
WRITE (306.FMT, 920) FERIT(I), ESAV(I)
WRITE (307.FMT, 920) FERIT(I), ESTRAN(I)
WRITE (308.FMT, 920) FERIT(I), ESIR(I)

```

130 CONTINUE

```

DO 340 I = 1, 6
  CLOSE (302, I)
340 CONTINUE

```

C CALCULATE TRUE STRESS-STRAIN CURVES

C OPEN FILES

```

OPEN (UNIT = 303, FILE = 's-e.av.exp', STATUS = 'NEW')
OPEN (UNIT = 304, FILE = 's-e.tran.exp', STATUS = 'NEW')

```

```

OPEN (UNIT = 305, FILE = 's-e r exp', STATUS = 'NEW')
OPEN (UNIT = 306, FILE = 's-e rit av exp', STATUS = 'NEW')
OPEN (UNIT = 307, FILE = 's-e rit an exp', STATUS = 'NEW')
OPEN (UNIT = 308, FILE = 's-e rit r exp', STATUS = 'NEW')

```

C ACQUIRE SPECIMEN STATISTICS

```

C PRINT *, 'ARMCO iron J-notch std. ver. A, ver. B,
C 1 uniaxial long and short, c-notch (J A B U S C)'
C PRINT *, 'FOR OFHC copper J-notch ver. A (0)'
C READ (*,900) N

```

```

PRINT *, 'ENTER THE NUMBER FOR THE TYPE OF SAMPLE USED'
PRINT *, ' (1) J-NOTCH WITH LARGE SHOULDERS (NJ1)'
PRINT *, ' (2) J-NOTCH WITH SMALL SHOULDERS VER. A (NJ2)'
PRINT *, ' (3) J-NOTCH WITH SMALL SHOULDERS VER. B (NJ3)'
PRINT *, ' (4) C-NOTCH (NC1)'
PRINT *, ' (5) UNIAxIAL LONG (UAI)'
PRINT *, ' (6) UNIAxIAL SHORT (UBI)'
PRINT *, ' (7) J-NOTCH FOR OFHC COPPER'
READ (*,940) N

```

C CONVERT EXPERIMENTAL STRESS-STRAIN DATA TO TRUE STRESS-STRAIN

```

IF (N.EQ.1) THEN
  F(1) = 281.21
  F(2) = -33.5737
  F(3) = 8.21119
  F(4) = -0.00167224
ELSE IF (N.EQ.2) THEN
  F(1) = 277.821
  F(2) = -32.2096
  F(3) = 8.0921
  F(4) = -0.00157984
ELSE IF (N.EQ.3) THEN
  F(1) = 161.568
  F(2) = -20.4753
  F(3) = 6.24717
  F(4) = 0.000785055
ELSE IF (N.EQ.4) THEN
  F(1) = -14.0082
  F(2) = 15.8193
  F(3) = 5.36873
  F(4) = -0.000462324
ELSE IF (N.EQ.5) THEN
  F(1) = 12.246
  F(2) = -0.617301
  F(3) = 1.3607
  F(4) = -0.00087
ELSE IF (N.EQ.6) THEN
  F(1) = 5.4252
  F(2) = 1.391
  F(3) = 1.09353
  F(4) = -0.000115
ELSE IF (N.EQ.7) THEN
  F(1) = -466.842
  F(2) = 134.834
  F(3) = -1.61527
  F(4) = -0.00293152
END IF

```

```

DO 350 I = 1, NP2-1

```

```

  TRUEDE = F(1)*EE(I)**3 + F(2)*EE(I)**2 + F(3)*EE(I) + F(4)

```

```

C   TRUEERIT = F(1)*EERIT(I)**3 + F(2)*EERIT(I)**2 + F(3)*EERIT(I) + F(4)
  TRUEERIT = F(1)*EERIT(I)**3 + F(2)*EERIT(I)**2 + F(3)*EERIT(I)
  I = I + F(4)

```

```

  TRUEA = ASPEC/EXP(TRUEDE)

```

```

  TSAV = ESAV(I)*ASPEC/TRUEA

```

```

  TSTRAN = ESTRAN(I)*ASPEC/TRUEA

```

```

  TSIR = ESIR(I)*ASPEC/TRUEA

```

```

TRUEARIT=ASPEC1*XPCTRU*EDERIT)
ISAVRIT=ISAV(I)*ASPEC1*TRUEARIT
ISTRANRIT=ISTRAN(I)*ASPEC1*TRUEARIT
ISIRRIT=ISIR(I)*ASPEC1*TRUEARIT

```

```

WRITE(303,FMT=920)TRUEDE.TSAV
WRITE(304,FMT=920)TRUEDE.TSTRAN
WRITE(305,FMT=920)TRUEDE.TSIR
WRITE(306,FMT=920)TRUEERIT.TSAVRIT
WRITE(307,FMT=920)TRUEERIT.TSTRANRIT
WRITE(308,FMT=920)TRUEERIT.TSIRRIT

```

150 CONTINUE

```

C CLOSE FILES
DO 360 I=1,6
  CLOSE(302+I)
360 CONTINUE

```

PRINT *, 'DONE'

```

900 FORMAT(A)
910 FORMAT(F14.7,F14.7)
915 FORMAT(A10,F10.5)
920 FORMAT(F20.10,F20.10)
930 FORMAT('ENTER EXCITATION VOLTAGE FOR CHANNEL 12, IN MV ')
940 FORMAT(I2)

```

END

C *****
SUBROUTINE VOLSTR(VAL,J,NG,NFG,VE,GAGE)

```

DIMENSION NG(*),NFG(*),VE(*),GAGE(2,*)
INTEGER J

```

```

NCH=1
IF (J EQ 2) THEN
  NCH=2
ENDIF

```

```

IF (NG(NCH) EQ 1) GOTO 220
IF (NFG(NCH) EQ 2) GOTO 230

```

```

GAGE(NCH,15)=GAGE(NCH,11)*(VAL-VE(NCH))
GAGE(NCH,16)=GAGE(NCH,13)*VAL-GAGE(NCH,10)*VE(NCH)
GAGE(NCH,17)=GAGE(NCH,12)*VAL-GAGE(NCH,9)*VE(NCH)

```

```

BET=SQRT((GAGE(NCH,16)**2)-(4*GAGE(NCH,15)*GAGE(NCH,17)))
RAC1=(-GAGE(NCH,16)+BET)/(2*GAGE(NCH,15))
RAC2=(-GAGE(NCH,16)-BET)/(2*GAGE(NCH,15))

```

```

C CHOOSING OF THE ADEQUATE ROOT
IF (ABS(RAC1) LT ABS(RAC2)) THEN
  VAL=RAC1
ELSE
  VAL=RAC2
ENDIF
GOTO 240

```

```

220 VAL=((GAGE(NCH,7)*VAL)-(GAGE(NCH,8)*VE(NCH)))/((GAGE(NCH,9)*VE(NCH))-(GAGE(NCH,10)*VAL))
GOTO 240

```

```

230 GF=1/((1-GAGE(NCH,3))*(1-GAGE(NCH,4)))
STR=VAL*(VE(NCH)*GF)

```

```

240 RETURN
END

```

$$\sigma_1^{\alpha} - \sigma_R^{\alpha} - \sigma_{\alpha}^{\alpha} = \sigma_T^{\beta} + \sigma_{\alpha}^{\beta} \quad (\text{B-14})$$

Dividing this equation by E_{α} , which is equal to E_{β} , based on the same assumptions as those above, the following equation is obtained for the strain values

$$\epsilon_1^{\alpha} - \epsilon_R^{\alpha} - \epsilon_{\alpha}^{\alpha} = \epsilon_T^{\beta} + \epsilon_{\alpha}^{\beta} \quad (\text{B-15})$$

Using equation (B-11) and solving for ϵ_R^{α} produces the following equation for the displacement at interface α

$$u^{\alpha} = C_0^{\alpha} \int_0^t (2\epsilon_1^{\alpha} - \epsilon_T^{\beta} - 2\epsilon_{\alpha}^{\alpha} - \epsilon_{\alpha}^{\beta}) dt \quad (\text{B-16})$$

The nominal strain in the specimen is given by

$$\epsilon_s = \frac{u^{\alpha} - u^{\beta}}{L_0} \quad (\text{B-17})$$

Substituting from equations (B-12) and (B-16) gives the following equation for the nominal strain in the specimen

$$\epsilon_s = \frac{2C_0^{\alpha}}{L_0} \int_0^t (\epsilon_1^{\alpha} - \epsilon_T^{\beta} - \epsilon_{\alpha}^{\alpha}) dt, \quad (\text{B-18})$$

where ϵ_1^{α} and ϵ_T^{β} are obtained from the strain pulses ϵ_1 and ϵ_T recorded at the incident and transmitter bar gauges but corrected in amplitude using equation (B-7) because of the transmission through the thermal gradient. $\epsilon_{\alpha}^{\alpha}$ is a reflection pulse which can be determined from ϵ_1^{α} and ϵ_T^{β} . Time in equation (B-18) is measured from the instant the incident strain pulse reaches the specimen. If the equation (B-18) is not integrated, one obtains the strain rate.

Data Reduction Method for Experiments at High Strain Rate and Elevated Temperatures

Figure B 1 illustrates the situation along the bars and the specimen when working at elevated temperature as well as a schematic representation of the various pulses considered and their directions. The required data to calculate the stress and strain in the specimen are the corrected values at the interface. At room temperature, based on the split Hopkinson bar assumptions, the strain values measured at the gauge are very close to those at the interface but at elevated temperature, the strain values are distorted by the temperature gradient in the bar. The measured strains at the gauges must therefore be corrected to obtain the real values at the interfaces. The method used to perform this correction which was developed originally by Chiddister and Malvern [15] will be presented in this appendix. Let α represent the specimen interface with the incident bar and β the interface with the transmitter bar, while λ and ζ denote the temperature distribution in the incident and transmitter bars respectively. The corrected values of strain pulses will be noted by the superscripts α and β . Therefore, ϵ_1^α represents the corrected value of the recorded pulse ϵ_1 or the amplitude it will have when reaching the interface α . ϵ_{R1}'' is the corrected reflected pulse from the specimen at α to appear at the gauge station as ϵ_{R1} . In this analysis, first order temperature reflections only will be considered assuming that reflection of a reflection shall be negligible.

The incident pulse ϵ_1 is partially reflected at λ , at $\alpha+\beta$ and at ζ . These reflections are noted ϵ_R' , ϵ_{R1} , ϵ_{R2} . At the transmitter gauge station, there is ϵ_{T1} , the transmitted part of the incident pulse which is superposed with ϵ_{T2} , the part of ϵ_{R1} reflected from λ and

transmitted back through the specimen. There is also ϵ_{R1} , the double reflection of $\epsilon''^\alpha + \epsilon''^\beta$ from λ and from $\beta + \alpha$. The total reflected pulse recorded at the incident bar gauge station is the sum $\epsilon'_R + \epsilon_{R1} + \epsilon_{R2} + \epsilon_{R3}$ where ϵ_{R3} is the reflection of ϵ''^α from $\alpha + \beta$. The pulses ϵ''^α and ϵ''^β are the reflections of $\epsilon_{R1}^\alpha + \epsilon_{R2}^\beta$ from λ and $\epsilon_{R1}^\alpha + \epsilon_{R2}^\beta$ from ζ respectively. These two pulses (ϵ''^α and ϵ''^β) do not appear in the strain-time record taken at the gauge station and must be calculated with the method shown below.

To facilitate the calculation of these pulse reflection and transmission at the thermal gradient, it is shown in reference [15] that the continuous temperature gradient could be replaced by a discontinuous distribution made of a certain number of steps with uniform temperature assumed between steps. Five steps were used for a temperature of 650°C in reference [15]. The reflection from the discrete steps were worked out and the results were found to agree well with those obtained from the solution of a boundary-value problem for the elastic-wave equation with variable coefficients. At each temperature step we have:

$$\sigma_1 + \sigma_R = \sigma_1 \quad (B-1)$$

Using E_1 and E_2 as the moduli of elasticity on the two sides of the temperature step we obtain

$$E_1(\epsilon_1 + \epsilon_R) = E_2\epsilon_1 \quad (B-2)$$

Considering instantaneous displacement continuity, we have

$$u_1 + u_R = u_1 \quad (B-3)$$

If this relationship is differentiated with respect to time, and the elastic wave equation,

$$\varepsilon = \frac{l}{C_1} \frac{du}{dt} \quad (\text{B-4})$$

is considered, we obtain

$$C_{n_1}(\varepsilon_1 - \varepsilon_2) = C_{n_2}\varepsilon_1 \quad (\text{B-5})$$

The sound velocities on both sides of the interface are given by $C_{n_1} = \sqrt{E_1/\rho_1}$ and $C_{n_2} = \sqrt{E_2/\rho_2}$. The equation to obtain density (ρ) is

$$\rho = \frac{Rk_m}{K_1 l^2 T} \quad (\text{B-6})$$

where R is the electrical resistance of the material, k is the thermal conductivity, m is the mass of a given length (l) of the material specimen, K_1 is the Lorentz constant and T is the temperature. K_1 and m are constant while R , k , and l vary with temperature. The variables in equation (B-6) are not all available for 4340 steel but pure iron can be considered as a good approximation. Comparison between densities for iron at room temperature and 750°C give a difference of about 3%, therefore we can assume that the densities on both sides of a temperature step are equal. Assuming that ρ_1 and ρ_2 are equal, we get from equations (B-2) and (B-5)

$$\frac{\varepsilon_T}{\varepsilon_1} = \frac{2E_1}{E_2 + \sqrt{E_1 E_2}} \quad (\text{B-7})$$

and

$$\frac{\varepsilon_R}{\varepsilon_1} = \frac{\sqrt{E_2} - \sqrt{E_1}}{\sqrt{E_2} + \sqrt{E_1}} \quad (\text{B-8})$$

Using these equations we obtain the reflected and transmitted part of the pulse at each temperature step. Experimental check of these equations have been done using high temperature foil gauges mounted on a solid elastic pressure bar. Calculated and measured pulses agreed within 1% for temperatures below 490°C and within 3% for temperatures between 490 and 650°C [15]

The next step is to apply these last two equations to the standard equations for Hopkinson bars presented in Chapter 1 along with the following identities

$$\epsilon_R^\alpha = \epsilon_{R1}^\alpha - \epsilon_{R2}^\alpha - \epsilon_{R3}^\alpha \quad (B-9)$$

$$\epsilon_I^\beta = \epsilon_{I1}^\beta - \epsilon_{I2}^\beta - \epsilon_{I3}^\beta \quad (B-10)$$

This gives for the displacement at interface α ,

$$u^\alpha = C_0^\alpha \int_0^t (\epsilon_I^\alpha + \epsilon_R^\alpha - \epsilon^{\prime\alpha}) dt \quad (B-11)$$

The superposition of the terms in the integral must be done by adjusting the time base of each pulse using travel time between α and the gauge station

At interface β , the displacement is given by

$$u^\beta = C_0^\beta \int_0^t (\epsilon_I^\beta - \epsilon^{\prime\beta}) dt \quad (B-12)$$

If we assume the specimen to be centered in a furnace heating uniformly along its surface, which is the standard arrangement, C_0^α is assumed equal to C_0^β . Assuming also that the total stress is equal on both side of the specimen gives

$$\sigma_I^\alpha - \sigma_{R1}^\alpha + \sigma_{R2}^\alpha + \sigma_{R3}^\alpha - \sigma_{\alpha,\beta} = \sigma_{I1}^\beta - \sigma_{I2}^\beta - \sigma_{I3}^\beta + \sigma_{\alpha,\beta} \quad (B-13)$$

Using the equalities presented in (B-9) and (B-10) yields

$$\sigma_I^{\alpha} - \sigma_I^{\beta} - \sigma_{I,\alpha} = \sigma_I^{\beta} + \sigma_{I,\beta} \quad (B-14)$$

Dividing this equation by E_{α} , which is equal to E_{β} , based on the same assumptions as those above, the following equation is obtained for the strain values

$$\epsilon_I^{\alpha} - \epsilon_I^{\beta} - \epsilon'^{\alpha} = \epsilon_I^{\beta} + \epsilon''^{\beta} \quad (B-15)$$

Using equation (B-11) and solving for ϵ_K^{α} produces the following equation for the displacement at interface α

$$u^{\alpha} = C_n^{\alpha} \int_0^t (2\epsilon_I^{\alpha} - \epsilon_I^{\beta} - 2\epsilon'^{\alpha} - \epsilon''^{\beta}) dt \quad (B-16)$$

The nominal strain in the specimen is given by

$$\epsilon_s = \frac{u^{\alpha} - u^{\beta}}{L_0} \quad (B-17)$$

Substituting from equations (B-12) and (B-16) gives the following equation for the nominal strain in the specimen

$$\epsilon_s = \frac{2C_n^{\alpha}}{L_0} \int_0^t (\epsilon_I^{\alpha} - \epsilon_I^{\beta} - \epsilon'^{\alpha}) dt, \quad (B-18)$$

where ϵ_I^{α} and ϵ_I^{β} are obtained from the strain pulses ϵ_I and ϵ_T recorded at the incident and transmitter bar gauges but corrected in amplitude using equation (B-7) because of the transmission through the thermal gradient. ϵ'^{α} is a reflection pulse which can be determined from ϵ_I^{α} and ϵ_T^{β} . Time in equation (B-18) is measured from the instant the incident strain pulse reaches the specimen. If the equation (B-18) is not integrated, one obtains the strain rate.

The stress in the specimen is obtained from data on the face of the specimen in contact with the transmitter bar which is $\epsilon_1^{\beta} + \epsilon''^{\beta}$. The transmitter bar is considered to remain elastic during the experiment but we have to apply a correction for the fact that the gauge area of the specimen (A_s) is not the same as the area of the bar (A_b) so we obtain the following equation for the stress in the specimen

$$\sigma_s = E^{\beta} \frac{A_b}{A_s} (\epsilon_1^{\beta} + \epsilon''^{\beta}), \quad (\text{B-10})$$

where ϵ''^{β} can be determined from ϵ_1^{ϵ} and ϵ_1^{β}

Figure B 1 - View of the pulses generated during high temperature testing

Data reduction program for experiments at high strain rate and elevated temperatures

PROGRAM NICOLETH

C CONVERTS NICOLET BRIDGE VOLTAGE DATA INTO AXIAL STRAINS
C THEN DETERMINES SPECIMEN STRESS, STRAIN RATE, AND STRAIN.
C CALCULATES AVERAGE SPECIMEN STRESS BASED ON TRANSMITTED
C PULSE AND (INCIDENT+REFLECTED) PULSE
C CALCULATES STRAIN RATE BASED ON REFLECTED PULSE AND
C (INCIDENT-REFLECTED-TRANSMITTED) PULSE
C THIS PROGRAM USES THE COMPLETE BRIDGE EQUATION METHOD
C THE NUMBER OF SAMPLES IN THE FILE CAN BE UP TO 20000

CHARACTER*20 NAME0,NAME1,NAME2
CHARACTER*10 PRO
CHARACTER*72 JUNK
INTEGER L,INDEX1,INDEXR,NB,J,H,NEX,N,NG(2),NFG(2),ISEN
REAL CH1(2,20000), CH2(2,20000),GAGE(2,17),VE(2),VD
REAL L,D,ASPEC,F,FINC,FTRAN,V1,V2,TRUEERIT,DOFS
REAL EZINC,EZRE(2000),EZREFL,EZTRAN,SUM,EZRIT,EZRITE(2000)
REAL SAV(2000),STRAN(2000),SIR(2000)
REAL ESPEC,ESPECR,C,E,ABAR,YMIN,SL,SUM2,EERIT(2000)
REAL TMP(5),YOU(5),SVEL(5),RHO,DIS(5)
REAL ESAY(2000),ESTRAN(2000),ESIR(2000),EE(2000),F(4)
PARAMETER (PI=3.141592654, E=-2.0685E+05, C=-5121.2)
PARAMETER (ABAR=197.9326)
REAL TRUEDE,TRUEA

C ABAR IS IN mm²
C STRESSFS ARE IN MPa
C DATA FILES CAN HAVE UP TO 20000 SAMPLES
C UPPER TRIGGER LEVEL MUST BE 20 mV

PARAMETER (RHO=7886.9)
DIS(1)=55
DIS(2)=10
DIS(3)=5
DIS(4)=5
DIS(5)=5

C ASK IF THE TEST WAS DONE AT WHICH TEMPERATURE THE TEST WAS DONE
PRINT *, 'ENTER THE TEMPERATURE THE TEST WAS DONE AT '
PRINT *, ' (1) 250 DEG. C'
PRINT *, ' (2) 500 DEG. C'
PRINT *, ' (3) 750 DEG. C'
READ *,NTEX

TMP(1)=25.
IF (NTEX=2) 10,20,30

C CASE OF 250 DEGREES

10 TMP(2)=36.5

TMP(3)=69.6

TMP(4)=105.6

TMP(5)=185.0

GOTO 40

C CASE OF 500 DEGREES

20 TMP(2)=53.9

TMP(3)=122.4

TMP(4)=197.5

TMP(5)=366.5

GOTO 40

C CASE OF 750 DEGREES

30 TMP(2)=77.0

```

TMP(3) 211.6
TMP(4) 337.1
TMP(5) 559.2

C YOUNG'S MODULUS DATA FOR STEEL AT DIFFERENT TEMPERATURE
C  $E = -0.08036T + 210.42$  (E IS IN GPa, T IS IN DEG. CELSIUS)
C REF: GAROFALO
C CALCULATE THE SOUND VELOCITIES FOR THE GIVEN TEMPERATURES

40 DO 50 I=1,5
    YOU(I) = 210.42 - 0.08036 * TMP(I)
    SVEL(I) = SQRT(YOU(I) * 1000000000 / RHO)
50 CONTINUE
C ASK HOW MANY POINTS IN THE FILE
PRINT *, 'ENTER THE NUMBER OF POINTS IN YOUR FILES: '
READ *, NB

C ASK FOR THE STRIKER LENGTH
PRINT *, 'ENTER THE STRIKER LENGTH IN INCHES: '
READ *, SL
DT = 2 * SL * 2.54 / C * 10000

C ASK FOR DISTANCE FROM END OF BAR TO STRAIN GAGE
PRINT *, 'ENTER DISTANCE FROM END OF BAR TO GAGE IN CM: '
READ *, DG
DT2 = 2 * (DG - DIS(1)) / SVEL(1) + 2 * DIS(2) / SVEL(2) + 2 * DIS(3) / SVEL(3)
DT2 = (DT2 + 2 * DIS(4) / SVEL(4) + 2 * DIS(5) / SVEL(5)) * 10000

C ASK FOR TRIGGER VALUE
PRINT *, 'ENTER TRIGGER VALUE IN MV: '
READ *, TR

C READ DATA FROM FILES INTO ARRAYS

PRINT *, 'ENTER FILE NAME FOR CHANNEL 1: '
READ (*,900), NAME1
PRINT *, 'ENTER FILE NAME FOR CHANNEL 2: '
READ (*,900), NAME2
OPEN (UNIT=43, FILE=NAME1, STATUS='OLD')
OPEN (UNIT=44, FILE=NAME2, STATUS='OLD')

DO 60 I=1,13
    READ (43,FMT=900) JUNK
    READ (44,FMT=900) JUNK
60 CONTINUE

DO 70 I=1,NB
    READ (43,FMT=910) CH1(1,I),CH1(2,I)
    READ (44,FMT=910) CH2(1,I),CH2(2,I)
70 CONTINUE

CLOSE (43)
CLOSE (44)

C ACQUIRE SPECIMEN STATISTICS

PRINT *, 'ENTER GAUGE LENGTH OF SPECIMEN (mm): '
READ *, L

PRINT *, 'ENTER GAUGE DIAMETER OF SPECIMEN (mm): '
READ *, D

ASPEC = PI/4.0 * D * D

C GET THE BRIDGE DATA

PRINT *, 'ENTER THE NAME OF THE FILE WITH THE BRIDGES DATA: '
READ (*,900), NAME0
OPEN (UNIT=42, FILE=NAME0, STATUS='OLD')

```

```

      DO 80 I=1,5
      READ (42,FMT=900) JUNK
80    CONTINUE

      DO 120 I=1,2
      DO 90 J=1,6
      READ (42,FMT=915) PRO,GAGE(I,J)
90    CONTINUE

C CALCULATE REQUIRED DATA

C CHECK FOR THE NUMBER OF AND TYPE OF STRAIN GAUGES
      IF (GAGE(1,4).EQ.0.0) THEN
          NG(I)=1
          NFG(I)=1
          GOTO 100
      END IF

      IF (GAGE(1,4).LT.3.0) THEN
          NG(I)=2
          NFG(I)=2
          GOTO 110
      END IF

      NG(I)=2
      NFG(I)=1
      GAGE(1,7)=GAGE(1,1)+GAGE(1,5)
      GAGE(1,8)=GAGE(1,2)+GAGE(1,6)
      GAGE(1,9)=GAGE(1,1)*GAGE(1,2)-GAGE(1,5)*GAGE(1,6)
      GAGE(1,10)=GAGE(1,1)*GAGE(1,2)*(GAGE(1,3)+GAGE(1,4))
      GAGE(1,11)=GAGE(1,1)*GAGE(1,2)*GAGE(1,3)*GAGE(1,4)
      GAGE(1,12)=GAGE(1,7)*GAGE(1,8)
      GAGE(1,13)=(GAGE(1,1)*GAGE(1,3)*GAGE(1,8))+(GAGE(1,2)*GAGE(1,4)*GAGE(1,7))
      GOTO 110

100   GAGE(1,7)=GAGE(1,1)*GAGE(1,2)+GAGE(1,1)*GAGE(1,6)+GAGE(1,5)*GAGE(1,2)
      GAGE(1,7)=GAGE(1,7)+GAGE(1,5)*GAGE(1,6)
      GAGE(1,8)=GAGE(1,1)*GAGE(1,2)-GAGE(1,5)*GAGE(1,6)
      GAGE(1,9)=GAGE(1,1)*GAGE(1,2)*GAGE(1,3)
      GAGE(1,10)=(GAGE(1,2)+GAGE(1,6))*GAGE(1,3)

C ACQUIRE TEST RUN EXCITATION VOLTAGES

110  WRITE (*,930) I
      READ *, VE(I)

120  CONTINUE
      CLOSE (42)

C CALCULATE STRAINS FROM VOLTAGES
      DO 160 I=1,NB
      DO 150 J=1,2
      IF (J-1) 130,130,140
130   VD=CH1(2,I)*1000
      CALL VOLSTR(VD,J,NG,NFG,VE,GAGE)
      CH1(2,I)=VD
      GOTO 150
140   VD=CH2(2,I)*1700
      CALL VOLSTR( ,D,J,NG,NFG,VE,GAGE)
      CH2(2,I)=VD
150  CONTINUE
160  CONTINUE

      PRINT *, 'OFFSET DISTANCE BETWEEN INC. AND TRANS. GAGES IN CM: '
      READ *, DOFS
      DT2A = DT2 + DOFS/SVEL(1)*10000

C OPEN OUTPUT FILES

```



```

OPEN (UNIT =296, FILE = 'inc.exp', STATUS = 'NEW')
OPEN (UNIT =297, FILE = 'tran.exp', STATUS = 'NEW')
OPEN (UNIT =298, FILE = 'crate.exp', STATUS = 'NEW')
OPEN (UNIT =299, FILE = 's.tran.exp', STATUS = 'NEW')
OPEN (UNIT =300, FILE = 'ez inc.exp', STATUS = 'NEW')
OPEN (UNIT =301, FILE = 'ez incal.exp', STATUS = 'NEW')
OPEN (UNIT =302, FILE = 'ez tran.exp', STATUS = 'NEW')
OPEN (UNIT =303, FILE = 'ez tranbe.exp', STATUS = 'NEW')
OPEN (UNIT =304, FILE = 'ez.ref.exp', STATUS = 'NEW')

C GET STARTING INDICES FOR PULSES
C DEFINITION OF FACTOR TO START LOOKING FOR FIRST MAXIMUM TAKING
C THE TYPE AND NUMBER OF GAGES INTO ACCOUNT

C DEFINITION OF FACTOR TO LOOK FOR PULSE BEGINNING
FAC1=(GAGE(1,3)+GAGE(1,4))/(157*2)*0.5
J=1
CALL VOLSTR(FAC1,J,NG,NFG,VE,GAGE)
FACR=-(GAGE(1,3)+GAGE(1,4))/(157*2)*0.75
J=1
CALL VOLSTR(FACR,J,NG,NFG,VE,GAGE)
FACT=(GAGE(2,3)+GAGE(2,4))/(157*2)*0.5
J=2
CALL VOLSTR(FACT,J,NG,NFG,VE,GAGE)

C INCIDENT PULSE
J=1
CALL VOLSTR(TR,J,NG,NFG,VE,GAGE)
DO 170 I=1,NB
IF (CH1(2,I).GE.TR) THEN
NPOS=I
NPOS2=NPOS
GOTO 180
END IF
170 CONTINUE

C SLOPE AND INTERCEPT CALCULATION FROM DATA NEAR THE TRIGGER POINT
180 SUMXY=0.0
SUMX2=0.0
SUMY=0.0
DO 190 I=(NPOS-5),(NPOS+5)
SUMXY = SUMXY + CH1(1,I) * CH1(2,I)
SUMX2 = SUMX2 + CH1(1,I)**2
SUMY = SUMY + CH1(2,I)
190 CONTINUE
SLOPE = SUMXY/SUMX2
SINT = SUMY/10.0
XORI = -SINT/SLOPE

DO 200 I=1,NB
IF (CH1(1,I).GE.XORI) THEN
NPOS=I-1
GOTO 210
END IF
200 CONTINUE
210 DO 220 I=NPOS,1,-1
IF (CH1(2,I).LE.FAC1) THEN
INDEXI=I
GOTO 230
ENDIF
220 CONTINUE

C TRANSMITTED PULSE
C FIRST GUESS AT STARTING POINT FOR TRANSMITTED PULSE
230 INDENT=INDEXI*INT((DT2A)/0.2)
IF (CH2(2,INDENT) - FACT) 240,260,260
240 DO 250 I=INDENT,(INDENT+2000)
IF (CH2(2,I).GE.FACT) THEN

```

```

        INDEXT=1
        GOTO 280
    END IF
250  CONTINUE
260  DO 270 I=INDEXT,(INDEXT-2000),-1
        IF (CH2(2,I) LT.FACT) THEN
            INDEXT=I
            GOTO 280
        END IF
270  CONTINUE

C  PUT THE EXPERIMENTAL STRAIN RESULTS IN FILES
280  DO 290 I=1,NB
        WRITE (296,FMT=920) ((I-1-NPOS2)*0.2),CH1(2,I)
        WRITE (297,FMT=920) ((I-1-NPOS2)*0.2),CH2(2,I)
290  CONTINUE

330  NP2=INT(DT/0.2)+500

C  CASE OF INCIDENT PULSE
    DO 340 I=1,NP2
        EZINC=CH1(2,INDEXI+1)
        WRITE (300,FMT=920) (I*0.2),EZINC
340  CONTINUE

        ISEN=1
        DO 360 J=1,4
            DO 350 I=1,NP2
                EZINC=CH1(2,INDEXI+1)
                CALL MODPUL (EZINC,YOU(J+1),YOU(J),EZTINC,EZRINC,ISEN)
                CH1(2,INDEXI+1)=EZTINC
350  CONTINUE
360  CONTINUE
370  DO 380 I=1,NP2
                WRITE (301,FMT=920) (I*0.2), CH1(2,INDEXI+1)
380  CONTINUE

C  CASE OF TRANSMITTED PULSE
    DO 390 I=1,NP2
        EZTRAN=CH2(2,INDEXT+1)
        WRITE (302,FMT=920) (I*0.2),EZTRAN
390  CONTINUE

        ISEN=2
        DO 410 J=1,4
            DO 400 I=1,NP2
                EZTRAN=CH2(2,INDEXT+1)
                CALL MODPUL (EZTRAN,YOU(J),YOU(J+1),EZTTTRA,EZRTRA,ISEN)
                CH2(2,INDEXT+1)=EZTTTRA
400  CONTINUE
410  CONTINUE
420  DO 430 I=1,NP2
                WRITE (303,FMT=920) (I*0.2), CH2(2,INDEXT+1)
430  CONTINUE

C  CALCULATE SPECIMEN STRESS AND STRAIN RATE

440  NP2=INT(DT/0.2)+500
    DO 450 I=1,NP2
        EZINC=CH1(2,INDEXI+1)
        EZTRAN=CH2(2,INDEXT+1)
        EZRIT=-(EZINC-EZTRAN)
        EZRITE(I)=EZRIT

        ESPECRIT =-2*C*EZRIT/L*1000.0
        STRAN(I) = E*ABAR/ASPEC*EZTRAN

        WRITE (299,FMT=920) (I*0.2),STRAN(I)

```

```

        WRITE (298,FMT =920) (I*0.2),ESPECRIT
        WRITE (304,FMT =920) (I*0.2),EZRIT

450  CONTINUE

        DO 460 I =1,9
            CLOSE (295+I)
460  CONTINUE

C  CALCULATE ENGINEERING STRESS-STRAIN CURVES

C  OPENING FILES

        OPEN (UNIT =303, FILE ='s-e tran.exp', STATUS = 'NEW')

C  CALCULATE ENGINEERING STRESS AND ENGINEERING STRAIN

        SUM2 = 0.0

        DO 470 I=1,NP2-1

            ESTRAN(I) = (STRAN(I)+STRAN(I+1))/2.0
            SUM2 = SUM2 + (EZRITE(I)+EZRITE(I+1))/2.0*0.2E-6
            EERIT(I) =2.0*C*SUM2/L*1000.0

            WRITE (303,FMT=920) EERIT(I),ESTRAN(I)

470  CONTINUE

        CLOSE (303)

C  CALCULATE TRUE STRESS-STRAIN CURVES

C  OPEN FILES

        OPEN (UNIT =303, FILE='ts-e tran.exp', STATUS = 'NEW')

C  ACQUIRE SPECIMEN STATISTICS

        PRINT *, 'ENTER THE NUMBER FOR THE TYPE OF SAMPLE USED'
        PRINT *, ' (1) J-NOTCH WITH LARGE SHOULDERS (NJ1)'
        PRINT *, ' (2) J-NOTCH WITH SMALL SHOULDERS VER. A (NJ2)'
        PRINT *, ' (3) J-NOTCH WITH SMALL SHOULDERS VER. B (NJ3)'
        PRINT *, ' (4) C-NOTCH (NC1)'
        PRINT *, ' (5) UNIAXIAL LONG (UA1)'
        PRINT *, ' (6) UNIAXIAL SHORT (UB1)'
        PRINT *, ' (7) J-NOTCH FOR OFHC COPPER'
        READ (*,940) N

C  CONVERT EXPERIMENTAL STRESS-STRAIN DATA TO TRUE STRESS-STRAIN

        IF (N.EQ.1) THEN
            F(1)=281.21
            F(2)=-33.5737
            F(3)=8.21119
            F(4)=-0.00167224
        ELSE IF (N.EQ.2) THEN
            F(1)=277.821
            F(2)=-32.2096
            F(3)=8.0921
            F(4)=-0.00157984
        ELSE IF (N.EQ.3) THEN
            F(1)=161.568
            F(2)=-20.4753
            F(3)=6.24717
            F(4)=-0.000785055
        ELSE IF (N.EQ.4) THEN
            F(1)=-14.0082

```

```

      F(2)=15.8193
      F(3)=5.36873
      F(4)=-0.000462324
    ELSE IF (N.EQ.5) THEN
      F(1)=12.246
      F(2)=-0.617301
      F(3)=1.3607
      F(4)=-0.00087
    ELSE IF (N.EQ.6) THEN
      F(1)=5.4252
      F(2)=1.391
      F(3)=1.09353
      F(4)=-0.000115
    ELSE IF (N.EQ.7) THEN
      F(1)=-466.842
      F(2)=134.834
      F(3)=-1.61527
      F(4)=-0.00293152
    END IF

    DO 480 I=1,NP2-1
      TRUEERIT=F(1)*EERIT(I)**3 + F(2)*EERIT(I)**2 + F(3)*EERIT(I)
      I + F(4)
      TRUEARIT=ASPEC/EXP(TRUEERIT)
      TSTRANRIT=ESTRAN(I)*ASPEC/TRUEARIT

      WRITE (303,FMT-920) TRUEERIT,TSTRANRIT

480  CONTINUE

C  CLOSE FILES
    CLOSE (303)

    PRINT *, 'DONE'

900  FORMAT (A)
910  FORMAT (F14.7,F14.7)
915  FORMAT (A10,F10.5)
920  FORMAT (F20.10,F20.10)
930  FORMAT ('ENTER EXCITATION VOLTAGE FOR CHANNEL',I2,' IN MV: ')
940  FORMAT (I2)

    END

C *****
    SUBROUTINE VOLSTR(VAL,J,NG,NFG,VE,GAGE)

    DIMENSION NG(*),NFG(*),VE(*),GAGE(2,*)
    INTEGER J

    NCH=1
    IF (J.EQ.2) THEN
      NCH=2
    ENDIF

    IF (NG(NCH).EQ.1) GOTO 220
    IF (NFG(NCH).EQ.2) GOTO 230

    GAGE(NCH,15)=GAGE(NCH,11)*(VAL-VE(NCH))
    GAGE(NCH,16)=GAGE(NCH,13)*VAL-GAGE(NCH,10)*VE(NCH)
    GAGE(NCH,17)=GAGE(NCH,12)*VAL-GAGE(NCH,9)*VE(NCH)

    BET=SQRT((GAGE(NCH,16)**2)-(4*GAGE(NCH,15)*GAGE(NCH,17)))
    RAC1=(-GAGE(NCH,16)+BET)/(2*GAGE(NCH,15))
    RAC2=(-GAGE(NCH,16)-BET)/(2*GAGE(NCH,15))

C  CHOOSING OF THE ADEQUATE ROOT
    IF (ABS(RAC1).LT.ABS(RAC2)) THEN
      VAL=RAC1

```

```

      ELSE
      VAL=RAC2
      ENDIF
      GOTO 240

220   VAL=((GAGE(NCH,7)*VAL)-(GAGE(NCH,8)*VE(NCH)))/((GAGE(NCH,9)*VE(NCH)-(GAGE(NCH,10)*VAL))
      GOTO 240

230   GF=1/((1/GAGE(NCH,3))+(1/GAGE(NCH,4)))
      STR=VAL/(VE(NCH)*GF)

240   RETURN
      END

C *****
      SUBROUTINE MODPUL(VOLD,YNG1,YNG2,VNEWT,VNEWR,ISW)

      REAL FCT1,FCT2,VOLD,YNG1,YNG2,VNEWT,VNEWR
      INTEGER ISW

      FCT1=(2*YNG1)/(YNG2+SQRT(YNG1*YNG2))
      FCT2=(SQRT(YNG2)-SQRT(YNG1))/(SQRT(YNG2)+SQRT(YNG1))

      IF (ISW.EQ.1) THEN
        VNEWT=FCT1*VOLD
        VNEWR=FCT2*VOLD
      ELSE
        VNEWT=VOLD/FCT1
        VNEWR=FCT2*VNEWT
      END IF

      RETURN
      END

```

APPENDIX C

PROGRAM TO COMPUTE DATA FOR

BRIDGMAN FACTOR AND STRAIN CONVERSION

PROGRAM BRIDGMAN

C CONVERTS THE DATA OBTAINED FROM SIMULATION FOR MAXIMUM
C PRINCIPAL STRESSES, VON MISES STRESS, PRESSURE, EFFECTIVE PLASTIC
C STRAIN IN FILES TO GET BRIDGMAN FACTOR

```

REAL ALDAT(100,25,5),BJUNK,MAXPRSTR,SIGEFFV,FORC33,FORCEF
REAL TRIAXIAL,EFPLSTR,RADIUS,DIASTR,EPTOT,AVMAPRS,AVEFSTR,AVEPLST
INTEGER I,J,K,NEL,NSTAT,NOD
CHARACTER*72 JUNK
CHARACTER*1 N1FIL,FILPRO1
CHARACTER*2 NFIL,FILPRO
CHARACTER*5 FILNAM
CHARACTER*7 ALFIL
PARAMETER (PI=3.141592654, E=2.0685E+05, C=5121.2)

```

C GET THE DESIRED TIME

```

PRINT *, 'ENTER THE NUMBER OF THE DESIRED PLOT STATE:'
READ (*,915) NSTAT

```

C LOOP TO READ THE ORION DATA AND PUT IN A BIG ARRAY

```

OPEN (UNIT=43,FILE='bridg.dat',STATUS='OLD')
PRINT *, 'ENTER THE NUMBER OF ELEMENTS DUMPED (Up to 20):'
READ (*,915) NEL
PRINT *, 'ENTER THE NUMBER OF NODES DUMPED (Up to 21):'
READ (*,915) NOD

DO 60 K=1,4
  DO 50 J=1,NEL
    DO 30 I=1,9
      READ (43,FMT=900) JUNK
30    CONTINUE
    DO 40 I=1,91
      READ (43,FMT=910) BJUNK,ALDAT(I,J,K)
40    CONTINUE
50    CONTINUE
60    CONTINUE
    DO 75 J=1,NOD
      DO 65 I=1,9
        READ (43,FMT=900) JUNK
65    CONTINUE
      DO 70 I=1,91
        READ (43,FMT=910) BJUNK,ALDAT(I,J,5)
70    CONTINUE
75    CONTINUE
CLOSE (43)

```

C LOOP TO CREATE THE FILE FOR MAXIMUM PRINCIPAL STRESS VS RADIUS

```

FILNAM='s33rd'
IF (NSTAT.LT.10) THEN
  WRITE (N1FIL,920) NSTAT
  READ (N1FIL,922) FILPRO1
  WRITE (ALFIL,924) FILNAM,FILPRO1
ELSE
  WRITE (NFIL,926) NSTAT
  READ (NFIL,930) FILPRO
  WRITE (ALFIL,940) FILNAM,FILPRO
ENDIF
C OPEN THE FILE

OPEN (UNIT=297,FILE=ALFIL,STATUS='NEW')
FORC33=0.0
DO 80 J=1,NEL
  I=NSTAT
  MAXPRSTR=ALDAT(I,J,1)

```

```

      RADIUS=(ALDAT(I,J,5)+ALDAT(I,(J+1),5))/2
      WRITE (297,FMT=950) RADIUS,MAXPRSTR
      FORC33=FORC33+MAXPRSTR*PI*((ALDAT(I,(J+1),5)**2)-(ALDAT(I,J,5)**2))
80    CONTINUE
      CLOSE (297)

```

C LOOP TO CREATE THE FILE FOR EFFECTIVE STRESS VS RADIUS

```

      FILNAM='sefird'
      IF (NSTAT.LT.10) THEN
        WRITE (N1FIL,920) NSTAT
        READ (N1FIL,922) FILPRO1
        WRITE (ALFIL,924) FILNAM,FILPRO1
      ELSE
        WRITE (NFIL,926) NSTAT
        READ (NFIL,930) FILPRO
        WRITE (ALFIL,940) FILNAM,FILPRO
      ENDIF
C OPEN THE FILE

      OPEN (UNIT=297,FILE=ALFIL,STATUS='NEW')
      FORCEF=0.0
DO 90 J=1,NEL
      I=NSTAT
      SIGEFFV=ALDAT(I,J,2)
      RADIUS=(ALDAT(I,J,5)+ALDAT(I,(J+1),5))/2
      WRITE (297,FMT=950) RADIUS,SIGEFFV
      FORCEF=FORCEF+SIGEFFV*PI*((ALDAT(I,(J+1),5)**2)-(ALDAT(I,J,5)**2))
90    CONTINUE
      CLOSE (297)

```

C LOOP TO CREATE THE FILE FOR TRIAXIALITY VS RADIUS

```

      FILNAM='trird'
      IF (NSTAT.LT.10) THEN
        WRITE (N1FIL,920) NSTAT
        READ (N1FIL,922) FILPRO1
        WRITE (ALFIL,924) FILNAM,FILPRO1
      ELSE
        WRITE (NFIL,926) NSTAT
        READ (NFIL,930) FILPRO
        WRITE (ALFIL,940) FILNAM,FILPRO
      ENDIF
C OPEN THE FILE

      OPEN (UNIT=297,FILE=ALFIL,STATUS='NEW')
DO 100 J=1,NEL
      I=NSTAT
      TRIAXIAL=-(ALDAT(I,J,3))/ALDAT(I,J,2)
      RADIUS=(ALDAT(I,J,5)+ALDAT(I,(J+1),5))/2
      WRITE (297,FMT=950) RADIUS,TRIAXIAL
100    CONTINUE
      CLOSE (297)

```

C LOOP TO CREATE THE FILE FOR EFFECTIVE PLASTIC STRAIN VS RADIUS

```

      FILNAM='epsrd'
      IF (NSTAT.LT.10) THEN
        WRITE (N1FIL,920) NSTAT
        READ (N1FIL,922) FILPRO1
        WRITE (ALFIL,924) FILNAM,FILPRO1
      ELSE
        WRITE (NFIL,926) NSTAT
        READ (NFIL,930) FILPRO
        WRITE (ALFIL,940) FILNAM,FILPRO
      ENDIF
C OPEN THE FILE

```



```

      OPEN(UNIT=297,FILE=ALFIL,STATUS='NEW')
      EPTOT=0.0
100 110 J=1,NEL
      I=NSTAT
      LEPLSTR=ALDAT(I,J,4)
      RADIUS=(ALDAT(I,J,5)+ALDAT(I,J+1,5))/2
      WRITE(297,UNIT=950)RADIUS,LEPLSTR
      EPTOT=EPTOT+LEPLSTR*PI*(ALDAT(I,J+1,5)**2)-(ALDAT(I,J,5)**2)
110  CONTINUE
      CLOSE(297)

C PART OF PROGRAM TO CALCULATE DIAMETRAL STRAIN, AVERAGE MAXIMUM PRINCIPAL
C STRESS, AVERAGE EFFECTIVE STRESS, AVERAGE EFFECTIVE PLASTIC STRAIN
      DIASTR=2*LOG(ALDAT(1,NOD,5)/ALDAT(NSTAT,NOD,5))
      WRITE(*,960)DIASTR
      AVMAPRS=FORC33(PI*ALDAT(NSTAT,NOD,5)**2)
      WRITE(*,970)AVMAPRS
      AVEFSTR=FORCEF(PI*ALDAT(NSTAT,NOD,5)**2)
      WRITE(*,980)AVEFSTR
      AVEPLST=EPTOT/(PI*ALDAT(NSTAT,NOD,5)**2)
      WRITE(*,990)AVEPLST
      PRINT*, 'DONE'

900  FORMAT(A)
910  FORMAT(I20,16,F20,16)
915  FORMAT(I2)
920  FORMAT(I1)
922  FORMAT(A1)
924  FORMAT(A5,A1)
926  FORMAT(I2)
930  FORMAT(A2)
940  FORMAT(A5,A2)
950  FORMAT(F20,10,F20,10)
960  FORMAT('DIAMETRAL STRAIN ',F20,10)
970  FORMAT('AVERAGE MAXIMUM PLASTIC STRESS ',F20,10)
980  FORMAT('AVERAGE EFFECTIVE STRESS ',F20,10)
990  FORMAT('AVERAGE EFFECTIVE PLASTIC STRAIN ',F20,10)
      END

```

END

0|4-06-9|6

FIN