Development of intermediate and high strain rate experimentation and material modeling
of viscoplastic metals

By

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of viscoplastic metals

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This work presents a combined theoretical-experimental study of strain rate behavior in metals. The method is to experimentally calibrate and validate an Internal State Variable (ISV) constitutive model with a wide range of strain rate sensitivity. Therefore, a practical apparatus and methodology for performing highly sought-after intermediate strain rate experimentation was created. For the first time in reported literature, the structure-property relations of Rolled Homogeneous Armor is quantified at the microscale and modeled with varying strain rates, temperatures, and stress states to capture plasticity and damage with a single set of constants that includes intermediate strain rates. A rolled homogeneous armor (RHA) was used as a material system to prove the methodology. In doing so, a newly implemented strain rate dependent nucleation parameter for RHA was implemented to transition the dominant damage mechanism from void growth to void nucleation as strain rate increased. The ISVs were utilized in finite element analysis for robust predictability of mechanical performance as well as predictability of microstructural evolution with regards to void size and number distribution. For intermediate strain rate experiments, robust load acquisition was
achieved using a novel serpentine transmittal bar that allowed for long stress waves to traverse a short bar system; this system eliminated load-ringing that plagues servo-hydraulic systems. A direct hydraulic loading apparatus was developed to provide uniform strain rates throughout intermediate rate tests to improve on the current limitations of the state-of-the-art. Key recommendations on the advancement of predictive modeling of dynamic materials, as well as performing advanced dynamic experimentation, are elucidated.
DEDICATION

To God, my wife, my family, and friends.
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CHAPTER I
INTRODUCTION

1.1 Dynamic Materials

Many engineering materials undergo deformation events that are fast. These fast events lead to so-called dynamics in materials. Strain rate and temperature variation causes extraordinary mechanical phenomena that is not accounted for if a researcher considers a static environment alone. When investigating over a wide range of dynamically deformed materials, new competing mechanisms that drive the material responses are revealed.
Figure 1.1 Fractured surfaces in four different cylindrical steel specimens

Note: Each row of images correspond to a tension test at a corresponding strain rate. Each column of images correspond to a single steel alloy [1]

Notice that in Figure 1.1, different strain rates have altered the appearance of the fractured surface in the selected tensile specimens. Each specimen column in Figure 1.1 are of the same material, the same plate, and even the same initial specimen geometry. The only boundary condition that changed in these experiments is the applied strain rate. Traversing six orders of magnitude in strain rate causes these fractures to appear very different. Indeed, strain rate dependencies can be profound. Figure 1.2 reveals the varying yield strength of the specimens previously shown in Figure 1.1. Also note that as the applied strain rate increased from 0.0002/s to 200/s, the central region (cup) decreased in size. Also, the outer region (cone) increased in size. Since the difference between the
cup-and-cone is when shearing fracture occurs, clearly these pictures indicate that as the strain rate increases, shearing fracture occurs sooner.

![Diagram of Yield Strength Variation](image)

Figure 1.2 Yield strength variation in four different steels at different applied strain rates.

Note: The trend shows that as strain rate increases, so does the material’s yield strength [1].

By now the picture becomes quite clear: designing engineered components that undergo dynamic plasticity must have some forethought regarding the applied strain rate. In other words, knowing the strain rate range of the operating conditions, as well as how that material will respond, is key to the dynamic component optimization.

Dynamics in components is not a new idea. Figure 1.3 shows that dynamic experiments date back as far as the early 1400s.
The first recorded experimental method for attaining dynamic mechanical information.

Note: The test illustration shown was intended for explanation of a cannon’s performance [2].

The purpose of the illustration in Figure 1.3 is to explain how the performance of a cannon and its explosive could be quantified: by measuring how far the cannon flew in the air if mounted on top of a stationary cannon ball apparatus. In this test, a component’s performance was the matter of concern. However, it would be more than 500 years before the first dynamic material response was measured. Figure 1.4 shows the first known dynamic material response graph, recorded in the late 1800s.
Figure 1.4  First known Dynamic and Static measures of Resistance graph of a material.

Note: The figure shows the static curve as a solid line and the dynamic curve as a dashed line [3].

Since then, many advances in the experimental nature of dynamics in materials have been achieved. Now we have expanded dynamics, captured the behavior in material models, and even designed materials specifically for dynamic performance.

The research in this dissertation attempts to further advance the acquisition of dynamics, as well as the prediction of dynamic deformation for viscoplastic metals. Two key aspects of this study are the development of experimental capabilities to garner material performance history, and to capture viscoplastic behavior over a wide range of these regimes. By examining mechanical and microstructural phenomena at different
strain rates, further understanding of dynamics in materials and their associated engineered components can be achieved.

1.2 Strain Rate Dependent Modeling

Modeling of material deformation began in the 1660s with Robert Hooke explaining the extension of a spring with respect to a load [5]. It would be another 200 years before a plasticity explanation was undertaken by Tresca in 1864. A good history of the fields that brings together plasticity from a physical standpoint is undertaken by Horstemeyer et al. in 2010 [6]. Observe the road map in Figure 1.5 that depicts this history.
Figure 1.5  Historical overview of the major contributions to our understanding of plasticity in materials.

Note: This history is presented here from the general perspective of unified creep/plasticity internal state variable modeling needs and requirements [5].
Notice in Figure 1.5 the road map section related to creep. This is where the first inclusion of strain rate dependence on plasticity was documented. Kocks [6], in 1970, included viscoplasticity in the yield locus while explaining a myriad of other phenomena from a microstructural perspective. Since this time, many material models capture strain rate sensitivity to improve predictability of deformation. Of these models, the plasticity model created by Johnson and Cook [7] for metals has been the most widely used strain rate dependent plasticity model for metals in recent history.

1.2.1 Johnson–Cook

The Johnson-Cook model has two principal elements: plasticity and damage. The plasticity model prescribes the dependency of plastic flow stress, $\bar{\sigma}$, on the equivalent plastic strain, $\bar{\varepsilon}$, equivalent plastic strain rate, $\dot{\varepsilon}$, and temperature:

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left( 1 - \hat{\theta}^m \right)$$

where $A$, $B$, $C$, and $m$ are constants; $n$ is strain hardening exponent; $\dot{\varepsilon}/\dot{\varepsilon}_0$ is the normalized equivalent plastic strain rate (typically normalized to a strain rate of 1.0 s$^{-1}$); and $\hat{\theta}^m$ is the homologous temperature defined as

$$\hat{\theta}^m = \frac{\theta - \theta_{amb}}{\theta_{mel}-\theta_{amb}}$$

where $\theta$ is the current temperature, $\theta_{mel}$ is the melting temperature, and $\theta_{amb}$ is the ambient/room temperature. The model assumes that the strength is isotropic and independent of mean stress.

The accumulation of plastic strain is covered by the Johnson-Cook plasticity model; the plastic failure strain is defined by the Johnson-Cook phenomenological damage model:
\[
\bar{\varepsilon}_f = \left( d_1 + d_2 \exp\left[ d_3 \frac{p}{\bar{\sigma}} \right] \right) \left[ 1 + d_4 \ln\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left( 1 - d_5 \dot{\theta}^m \right) \tag{1.3}
\]

where \( d_1 - d_5 \) are constants and \( p/\bar{\sigma} \) is the ratio of the pressure to the von Mises stress.

As far back as the work by Bamman [8] in the 1980s, many researchers have attempted to expand the capabilities of constitutive modeling of materials by including Internal State Variables (ISVs): variables that correspond to phenomena internal to the material. By this method, structural features such as a crack, void, particle, and/or grains are included as an evolving variable in the solution to these models. Indeed, physically based models have a unique advantage in dynamics due to their ability to resolve mechanical response as well as microstructural evolution during deformation. Because of this unique feature of physically based models, the work in this study expands on this type of constitutive model.

1.2.2 Internal State Variables (ISVs)

The plasticity–damage model used in this study consists of the equations listed below and follows the framework previously developed by Bammann et al. and Horstemeyer et al. [8–10].

From a continuum mechanics perspective, the observable variable being solved in terms of the internal state variables (bold represents a second rank tensor) is formed as

\[
\bar{\sigma} = \lambda (1 - \phi) \text{tr}(D^e)1 + 2\mu (1 - \phi)D^e - \left( \frac{\phi}{1-\phi} \right) \sigma \tag{1.4}
\]

with \( \sigma \) and \( \bar{\sigma} \) being the Cauchy stress and the co-rotational rate of the Cauchy stress, respectively. \( \phi \) is the internal fraction of the material that cannot sustain an elastic stress and is the damage. This damage can be in the form of a crack, void, debonded particle, or any other deleterious mechanism inside the material in question. \( \lambda \) and \( \mu \) are the elastic...
Lame constants related to Hooke’s Law. $1$ is the identity tensor. $D^e$ is the elastic rate of deformation tensor and is related to the plastic rate of deformation tensor $D^p$ by the applied boundary condition as:

$$D^e = D + D^p \tag{1.5}$$

Because the total deformation rate $D$ is defined by the finite element boundary condition, the ISV/Damage model framework seeks to solve $D^p$. Once the plastic rate of deformation is known, Equation 1.4 can then be solved.

The plastic rate of deformation tensor or inelastic flow rule, $D^p$, is given by the relationship:

$$D^p = f(T) \sinh \left( \frac{[\sigma' - \alpha] - [R + Y(T)](1 - \phi)}{V(T)(1 - \phi)} \right) \frac{\sigma' - \alpha}{\|\sigma' - \alpha\|} \tag{1.6}$$

where $\sigma'$ is the deviatoric part of Cauchy stress tensor defined by Equation 1.6. $R$ is the isotropic hardening and is related to the effect of global dislocation density. $\alpha$ is the kinematic hardening and is related to the effect of anisotropic dislocation density. $R$ and $\alpha$ can be elucidated separately using Bauschinger type testing [25]. $Y(T)$ is the static yield function, and $V(T)$ is the dynamic yield function. The function $f(T)$ sets the transition from static to dynamic yielding. The purpose of having $Y(T)$, $V(T)$, and $f(T)$ is to capture static and dynamic yielding with smooth transitions and accurate predictability.

Not only does yielding have static and dynamic properties, but so do the hardening rates. The co-rotational rate of the kinematic hardening $\dot{\alpha}$ and the material time derivative of isotropic hardening $\dot{R}$ are expressed in a hardening-recovery format as:

$$\dot{\alpha} = \{h(T)D^p - [r_d(T)]\|D^p\| + r_s(T)\|\alpha\|\} \left( \frac{GS_o}{GS} \right)^Z \tag{1.7}$$

$$\dot{R} = \{H(T)\|D^p\| - [R_d(T)]\|D^p\| + R_s(T)R^2 \} \left( \frac{GS_o}{GS} \right)^Z \tag{1.8}$$
where $G_{S_o}$, $G_S$, and $z$ parameters capture the microstructure effect of grain size that are based on Hall-Petch type dependencies [26, 27]. In Eq. 17 and 1.8, $r_d(T)$ and $R_d(T)$ are scalar functions of temperature that describe dynamic recovery; $r_s$ and $R_s(T)$ are scalar functions that describe static recovery; $h(T)$ and $H(T)$ represent the anisotropic and isotropic hardening modulus, respectively. By including the static and dynamic recovery terms, this ISV/Damage model unifies creep and plasticity by making use of the single mechanism driving the plastic deformation in most viscoplastic metals: the dislocation. The reader is again referred to the references for a full list of calibration constants.

To determine damage, defects are measured microscopically from materials in their undeformed and deformed states to garner the total evolution of damage mechanisms. This paradigm for defining damage using microstructural features is what gives the ISV/damage model the ability to provide more information in a simulation than simply stress and strain; now a simulation can output microstructural quantities.

The two components of damage progression used in most viscoplastic metals are void nucleation and growth from second phase particles and pores. In this regard, the material time derivative of damage, $\dot{\phi}$, is expressed as:

$$\dot{\phi} = (\phi_{\text{particles}} + \phi_{\text{pores}})c + (\phi_{\text{particles}} + \phi_{\text{pores}})\dot{c}$$  \hspace{1cm} (1.9)

where $\phi_{\text{particles}}$ represents void growth from particle debonding and fracture; and $\phi_{\text{pores}}$ represents void growth from pores. Parameter $c$ represents the void coalescence, or void interaction, due to internal stress fields that are generated when multiple defects are grown in close proximity. The form of Equation 1.2.3.6 provides a full interaction between particles and pores so that each damage mechanism, though independently monitored, has an equivalent total damage with linking effects.
The particle and pore based void growth rate and the void-coalescence rate equations are given as:

\[ \dot{\phi}_{\text{particles}} = \eta v + \eta \dot{v} \]  
(1.10)

\[ \dot{\phi}_{\text{pores}} = \left[ \frac{1}{(1 - \phi_{\text{pores}})^m} - (1 - \phi_{\text{pores}}) \right] \sinh \left( \frac{2V(T)}{Y(T)} - \frac{1}{2} \sigma_H \right) \sqrt{D^p} \]  
(1.11)

\[ \dot{c} = [cd_1 + cd_2 (\dot{\phi}_{\text{particles}})] \exp(C_{CT}T) \left( \frac{G_{SE}}{G_S} \right)^2 \]  
(1.12)

where \( \nu \) is the void growth; \( \eta \) is the void nucleation, and \( \sigma_H \) and \( \sigma_{vm} \) are the hydrostatic and von Mises stresses, respectively. The parameters \( cd_1 \) and \( cd_2 \) are related to first and second normalized nearest neighbor distance parameters to be measured by microstructure analysis measurements. \( C_{CT} \) is the void-coalescence temperature dependent parameter.

The void nucleation rate equation has been modified from its original version given the work by Tucker et al. (2010) and Whittington et al. (2014) with the inclusion of a multiplier of the effective stress to capture strain rate or other stress variation effects on the rate [11,12]. The void nucleation rate and void growth rate are given as:

\[ \dot{\eta} = |D^p|^{1/2} K_{IC} f^{1/3} \eta J_2 \left\{ a \left[ \frac{1}{27} - \frac{J_3^2}{J_2^3} \right] + b \frac{J_3}{J_2^{3/2}} + c \left[ \frac{I_1}{\sqrt{J_2}} \right] \right\} \exp\left( \frac{C_{\eta T}}{T} \right) \]  
(1.13)

\[ \dot{v} = \frac{\sqrt{3} R_0}{2(1-n)} \left[ \sinh \left( \sqrt{3}(1 - n) \frac{\sqrt{J_1}}{\sqrt{J_2}} \right) \right] |D^p| \]  
(1.14)

where \( d \) is the measured particle size; \( K_{IC} \) is the measured fracture toughness; \( f \) is the measured volume fraction of second phase particles; \( C_{\eta T} \) is the void nucleation temperature-dependent parameter; \( I_1, J_2, \) and \( J_3 \) are the independent stress invariants; \( n \) is the void growth constant; \( R_0 \) is the measured initial void radius. The operator including
the stress invariants and the constants $a$, $b$, and $c$ provides the model with a unique stress state dependence so that tension, compression, and torsion dependencies are independently determined.

The ISV/damage model has been successfully used to capture a wide range of strain rate dependent mechanical behavior of aluminum and steel alloys [11, 12]. Tools for calibrating the material model parameters and procedures for performing the necessary experimentation are widely available online [28] and the reader is encouraged to investigate the wider dynamic applicability of this and other closely related models.

1.3 Strain Rate Dependent Experiments

As previously discussed, dynamic experiments for materials have been elucidated nearly 100 years ago. The body of science in today’s age heavily researches material properties at quasi-static and high strain rates [14]. Because load frames are ubiquitous in deformation mechanics, this topic will not be discussed here. High strain rate experiments have become more widely utilized dynamic regime for experiments. In the high rate field, the most common experimental apparatus is the compression Split Hopkinson Pressure Bar (also known as a Kolsky Bar).

1.3.1 High Strain Rate Experimental Methods

The Split Hopkinson Pressure Bar (SHPB) is a common mechanism for determining the stress-strain behavior of materials at high strain rates. Figure 1.7 illustrates the SHPB mechanics. For a detailed description of the SHPB technique including the background and history, the reader is directed to the critical review by Gama et al. (2004) [13].
Figure 1.6  Typical Split Hopkinson Pressure Bar configuration. A striker bar is propelled by a pressurized Gas Gun.

Note: A striker bar is propelled by a pressurized Gas Gun. The Striker Bar then impacts the Incident Bar and propagates a wave that is recorded by Gage A. The wave then impact the Specimen and some of the energy is transmitted into the Transmitted Bar and is recorded by Gage B. The remaining energy from the impact is reflected and recorded by Gage A. The velocities, \( u_1 \) and \( u_2 \), are then calculated by one-dimensional wave mechanics equations using the recorded garnered by Gage A and Gage B [13].

The SHPB used in this work consists of interchangeable bars made from a maraging steel, 7075-T651 aluminum, or polycarbonate. Data analysis is performed using the MSU High Rate Software package developed in this study and explained in Appendix A. The basic equations to be solved for gather stress strain relations follow 1-D elastic wave propagation theory.

The velocities at the bar-specimen interfaces are calculated as:

\[
v_i(t) = -c_i(\epsilon_i(t) - \epsilon_r(t))
\]

\[
v_o(t) = -c_o\epsilon_t(t)
\]

where \( v_i \) is the velocity at the incident bar-specimen interface; \( t \) is time; \( c_i \) is the wave speed of the incident bar; \( \epsilon_i \) is the transported incident wave signal; \( \epsilon_r \) is the transported reflected wave signal; \( v_o \) is the velocity of the transmitted bar-specimen interface; \( c_o \) is the wave speed of the transmitted bar; \( \epsilon_t \) is the transported transmitted wave signal.
The forces at the bar-specimen interfaces are calculated as follows:

\[ F_i(t) = A_i E_i (\varepsilon_i(t) + \varepsilon_r(t)) \]  \hspace{1cm} (1.17)

\[ F_o(t) = A_o E_o \varepsilon(t) \]  \hspace{1cm} (1.18)

where \( F_i \) is the force at the incident-bar interface; \( A_i \) is the cross-sectional area of the incident bar; \( E_i \) is the elastic modulus of the incident bar; \( F_o \) is the force at the transmitted bar-specimen interface; \( A_o \) is the cross-sectional area of the transmitted bar; and \( E_o \) is the elastic modulus of the transmitted bar.

Once the velocities and forces are obtained, the nominal strain rate is calculated as follows:

\[ \dot{\varepsilon}_n(t) = \frac{v_i(t) - v_o(t)}{l_s} \]  \hspace{1cm} (1.19)

where \( \dot{\varepsilon}_n \) is the nominal strain rate and \( l_s \) is the initial length of the specimen. The nominal strain rate is integrated with respect to time to obtain the nominal strain:

\[ \dot{\varepsilon}_n(t) = \frac{v_i(t) - v_o(t)}{l_s} \]  \hspace{1cm} (1.20)

where \( \varepsilon_n \) is the nominal strain. The stress is calculated as follows:

\[ \sigma_n(t) = \frac{F(t)}{A_s} \]  \hspace{1cm} (1.21)

where \( \sigma_n(t) \) is the nominal stress; \( F(t) \) is the force imposed on the specimen; and \( A_s \) is the undeformed cross-sectional area of the specimen. With nominal stress strain relations, true stress strain relations can be made using constant volume assumption, known compressibility, or measurable means such as digital image correlation (DIC).

Generally, the SHPB can acquire stress strain relations for ductile metals in strain rates ranging from 500/s to 5000/s. Several factors influence the maximum strain rate including the pressure used to propel the striker bar and the length and diameter of the
specimen. The lower end strain rate capability of a SHPB is typically limited by the length of the bars and has been an area of research in recent years [25-28].

1.3.2 Intermediate Strain Rate Experimental Methods

Intermediate strain rates, ranging from 5/s to 500/s, have been under investigation for almost 50 years. Some major examples of intermediate strain rate events are car crashes, metal forming operations, sporting collisions, and natural disasters. Investigation of material and component performance metrics has been widely elucidated with many different niche equipment to garner the necessary data. Figure 1.8 shows a schematic illustrating the strain rate regimes for metals.

Figure 1.7 Strain rate regimes identified by material behavior and equipment used to achieve rate dependent deformation.

Note: Image taken from reference [14].
One reason for defining a regime between quasi-static and high strain rates is due to many material’s transitional dependencies. In quasi-static strain rates, materials may exhibit small strain rate dependent mechanical properties. At high strain rates, however, many materials exhibit large strain rate dependent mechanical properties that differ significantly from the low rate observations.

Figure 1.8  Yield strength of commercial cold rolled steel as a function of strain rate across three strain rate regimes and testing devices.

Note: Image taken from reference [15].

Figure 1.8 shows that the strain rate dependence of a steel alloy is less dramatic below 1/s as compared to the region between 1/s and 100/s. This makes this regime between 1/s and 100/s crucial in determining the shape of flow stress versus strain rate
for constitutive modeling and for strain rate dependent strength ratings. Due to these varying mechanical properties, design of intermediate strain rate systems have gained wide attention over the past several decades.

Modified servo-hydraulic systems are the most widely used systems for performing intermediate strain rate experiments. Several manufacturers have designed and built these systems and have achieved up to 10 m/s in ram speed to date.

One interesting result that limits the upper strain rates of these machines to approximately 50/s is the natural frequency of the load train used in the hydraulic ram system. Notice in Figure 1.9 that the stress strain curve becomes indistinguishable from the load ringing in the equipment with conventional gripping methods. Modification of these systems can improve the response.
Figure 1.9  Grip designs and associated stress strain curves for a servo hydraulic load frame at intermediate strain rates.

Note:  (a) Conventional grip, (b) modified grip, and (c) optimized grip and associated stress strain curves for a servo hydraulic load frame at intermediate strain rates [15]. The tensile dog-bone exhibits “load ringing” in the conventional and modified grip.

To improve the output data of modified servo hydraulic systems, curve fitting and filtering is performed to smooth the stress-strain data until the material response is revealed. Figure 1.10 shows the results from performing such filtering on the data. However, caution must be taken into account because this oscillating signal is not electrical noise or numerical artifacts. It is actually the material being subjected to high frequency loading.
Most intermediate strain rate experimentation using servo-hydraulic systems has been developed for tension testing. The specimen design for tension testing at intermediate strain rates is typically modified for monitoring load on the grip section, achieving uniform load early in the test, and reducing the overall load on the machine to help with strain rate uniformity. Appendix B shows a comprehensive list of flat tensile dog-bone designs used at a number of research laboratories around the globe.

Due to the wide usage of Split Hopkinson (Kolsky) Bar (SHPB) systems in research and industry for high strain rate experimentation, many laboratories have elected to modify their experimental setups to achieve intermediate strain rates. These
experiments are almost always compression, because compression SHPBs are more widely used and easier to implement.

To improve the lower strain rate capabilities of bar systems some researchers have built long Hopkinson or Split Hopkinson bars. Long bar systems allow for larger waves to traverse the system as compared to smaller bar system; long waves are necessary for achieving intermediate strain rates. These apparatuses can be on the order of 100–200 m in length and require infrastructure to handle the alignment of these systems over such a large distance. Figure 1.11 and 1.12 show two examples of these systems.
Figure 1.11  Long Hopkinson bar schematic (top) and image of long Hopkinson bar.

Note: Image taken from reference [27].
Each system shown in Figures 1.11 and 1.12 is designed for material deformation at the intermediate strain rates. These long bar systems provide the most robust load acquisition, as well as strain rate consistency, and are robust sources of intermediate strain rate data to date. However, these systems cannot be employed in many laboratories due to their large size.
Because the intermediate regime is important for a number of phenomena, the systems have played a key role in revealing interesting phenomena in materials in terms of mechanical test data and structure evolution. A full measure of the intermediate strain rates is important for the future of modeling viscoplastic metals, especially when the application involves intermediate phenomena.

1.4 Dissertation Structure

The work disclosed here expands the dynamic predictive capability of ISV plasticity-damage modeling, as well as the experiments used to calibrate the associated constitutive parameters for viscoplastic metals.

Chapter II presents an investigation of the mechanical response and damage evolution of Rolled Homogeneous Armor (RHA) steel at different temperatures, stress states, and strain rates. High strain rate experiments conducted via split-Hopkinson pressure bars showed increased strength and reduced failure strains as compared to low strain rates. Tension and torsion experiments revealed that torsional loading was more deleterious to ductility when comparing equivalent failure strains. As is typical of metals, the experiments showed that as the temperature increased to 300 °C from ambient conditions, the flow stress decreased, and the failure strains increased. Fractography was performed on selected tension and torsion post-mortem specimens to quantify the number density of nucleated voids and size distribution of voids from the experiments. For a RHA steel alloy, an ISV plasticity-damage model was used to capture the varying effects of temperature, strain rate, and stress state on plasticity and damage with a single set of parameters. Therefore, this ISV model for RHA steel can be used in finite element analysis (FEA) over a wide variety of dynamic boundary conditions.
Chapter III presents a new method for acquisition of load data at intermediate strain rates for tension and compression testing. A novel design of a serpentine Hopkinson transmitted bar allows for accurate and robust load acquisition at intermediate strain rates in a compact form. The new design produces repeatable stress-strain results without stress oscillations typical of a specially instrumented servo-hydraulic load frame; the design also produces data with a longer loading time than a conventional Kolsky/Hopkinson bar of the same length. The stress–strain response is presented for a 6061-T6 Al alloy in where low rate and high rate data from the literature bounded the intermediate bar's response.

Chapter IV completes the intermediate strain rate experimental needs by presenting a method for deforming materials at “near” constant strain rates. A direct action hydraulic loading system was developed for experiments in compression or tension. For robust intermediate strain rate experimentation, the loading apparatus was designed to persist with reasonable strain rate consistency throughout the duration of the experiment. And finally, the system is shown to be compact enough to fit into conventional labs, as well as ease of use so that many labs can acquire or build a similar system. The system is simple and is incorporated with a serpentine bar to monitor load so that the complete system performs robust intermediate strain rate experimentation. Tests on copper 101 were conducted to show the capability of the system.

Finally, Chapter V summarizes the results of this work and provides recommendations for future work with special considerations for expansion of dynamic experimentation.
1.5 References Cited

[1] Boyce, B.L., Dilmore, M.F., “The dynamic tensile behavior of tough, ultrahigh-strength steels at strain-rates from 0.0002s\(^{-1}\) to 200s\(^{-1}\),” International Journal of Impact Engineering 36 (2009)


[28] https://icme.hpc.msstate.edu
CHAPTER II
CAPTURING THE EFFECT OF TEMPERATURE, STRAIN RATE, AND STRESS STATE ON THE PLASTICITY AND FRACTURE OF ROLLED HOMOGENEOUS ARMOR (RHA) STEEL

2.1 Introduction

Armor steels have been used extensively for ballistic impact resistance of armored vehicles and structures as well as serving as a metric for measuring the power of anti-tank guns and in penetration studies for other potential armor materials [1]. The wide range of events for which rolled homogenous armor (RHA) is designed demands a simulation-based solution for design and optimization of RHA components in order to improve the safety of passengers exposed to unforeseen impacts. This research presents a single constitutive modeling approach for simulating RHA steel deformation and failure strains in a range of variable strain-rate, stress-state, and temperature environments such as in impact scenarios.

For impact event characterization, critical attention must be directed to the high strain-rate properties of the RHA. Several authors [1], [2] and [3] report increased yield strength with an increase in strain rate in RHA during split-Hopkinson pressure bar (Kolsky) experiments. However, the data are incomplete; no published high strain-rate testing of RHA in tension and very few published results of torsion testing have been reported [4]. Tucker et al. [5] showed that different stress states accommodate
deformation with differing strain-rate sensitivities in selected aluminum alloys. One question posed from the published literature is the dependency of strain-rate sensitivity of plasticity and failure of RHA on the stress state.

During these high strain-rate events, temperature rise can also become an important issue [6]. In the high-rate regime ($> 10^3 \text{ s}^{-1}$), energy dissipation into heat causes the temperature to rise in the material. One result is adiabatic shear bands (ASB) that can develop in local areas of the material and drive early fracture through these locally heated regions [3] and [4]. Even though impact events exist in areas where the critical components begin at ambient temperatures, the intermediate and final temperatures can be quite high. Therefore, some temperature dependence may also be necessary to accurately model the impact behavior of RHA.

The initial microstructure of RHA has a profound effect on the mechanical response. Weerasooriya and Moy [1] showed that the yield strength as well as its relationship with strain rate and temperature is affected by the varying microstructure in their RHA plates. In their study, they concluded that the thinner RHA plates had a higher strength and larger strain-rate sensitivity. Benck [7] also showed the same variation occurring in the stress–strain response of his RHA plates. Because RHA plates are quenched to produce small grains in order to increase strength, we can infer that the lower strength of thicker RHA plates is primarily due to the reduced cooling rates that induce larger grains. By changing the grain size in a material model, strength differentiation of several RHA plates of different thicknesses can be captured. In addition to grain size affecting strength, particle statistics can affect the failure of materials. Tucker et al. [5] showed that the initial volume fraction of particles affected the failure
strains of the different aluminum alloys considered in his study. The addition of real particle statistics with calibration to the evolution of damage can then be used to provide predictive modeling of RHA plates with different particle inclusions. Therefore, if a material model can allow for microstructural features to be adapted to a particular RHA component, these features can be used to adapt the RHA model to other components with different manufacturing histories.

To capture the deformation and failure of RHA, plasticity models, such as the constitutive material model developed by Johnson and Cook [8], have been used to describe deformation and failure of metals at varying strain rates and temperatures. However, models of this type lack the capability to provide deformation differentiation between loading paths, as well as failure criteria that can be related to observable quantities.

To provide a solution that captures a wider range of performance, a stress-state, strain-rate, and temperature dependent constitutive model must be utilized that can predict how RHA will deform and fail. The aforementioned ISV plasticity-damage model, derived from previous work of Bammann, Horstemeyer, and others [9], [10], [11] and [12], provides a basis for describing mechanical response under a wide range of input conditions. In this model, microscopic features from the material of interest are used to calibrate damage parameters, while the stress-strain relations of simply loaded experiments are used to calibrate plasticity parameters. These damage and plasticity parameters can be stress-state, strain-rate, and temperature dependent, giving a wider application range than other previously used models. Depending on the sensitivity of the
material response to these conditions, aspects of the model can be removed, allowing the specified model to be adapted and simplified to a designer's needs.

Recently, this material model was used to predict strain-rate sensitivity with respect to stress state in aluminum alloys [5]. The model was also used to predict stress-state dependence on temperature in steel [13]. Although the model has the capability to predict stress-state, strain-rate, and temperature dependence with a single set of constants, no study has been conducted in which a single material's deformation behavior is captured under all of these conditions.

In our study, we examine an RHA steel plate with regards to the stress state, strain rate, and temperature. By performing tension, compression, and torsion experiments at low- and high-strain rates, the stress-state strain-rate dependence on the mechanical response and failure of RHA can be presented. Mechanical tests at these strain rates at a higher temperature (300 °C) were then performed for information on the sensitivity of the conditions with respect to temperature. By quantifying the initial microstructure and then examining the fractured surface of each subsequent experiment, damage evolution can be used to understand how the RHA steel alloy would fail based on history rather than phenomenology. From the gathered information, an ISV plasticity-damage model was calibrated with a single set of material constants for the first time.

2.2 Experimental Procedure

As-received, 12.7-mm-thick RHA plate material, processed to Mil-A-12560H specification from the US Army Engineer Research and Development Center (ERDC), was utilized for experimentation and analysis. The RHA plate was examined for chemical composition in five different locations of the plate at a depth of 3 mm from the surface.
composition. Table 2.1 lists the average results that were consistent with all measurements. 10-mm specimens were cut out of three sections and polished for optical microscopy using Struers [14] polishing techniques and examined for the initial particle distribution using a Zeiss optical microscope. An image-analysis code was utilized for obtaining particle statistics on the size, area fraction, and nearest neighbor distance. The data from five different images were then imported into model calibration software, MSU DMG/fit [15, 28], which allows for semi-automated optimized calibration of material experimental results to the material model.

Table 2.1  
Average weight percent chemical composition of the RHA plate.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>0.226</td>
<td>0.224</td>
<td>1.27</td>
<td>0.0053</td>
<td>0.0022</td>
<td>0.055</td>
<td>0.099</td>
<td>0.477</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Note: Data were obtained from five different locations on the plate at a depth of 3 mm from the surface.

Specimens were extracted by conventional machining for use in mechanical testing. For low strain-rate tension and compression testing, an Instron 5869 load frame was utilized with a 50 kN load cell for obtaining load data and a 25 mm full-scale contact extensometer for obtaining strain data. The compression specimens were right cylinders 10 mm in diameter. For tension, flat dog-bone specimens with a gauge length of 5 mm, width of 2 mm, and thickness of 1 mm were selected to allow the same specimen geometry for high-rate tests. Tests were conducted at room temperature (20 °C) and at 300 °C, which used an Instron temperature-controlled environmental chamber. Three tests of each type were performed to obtain information about material/test uncertainty, and one specimen from each tension test was used for fracture studies.
Low strain-rate torsion tests were conducted on an MTS 858 biaxial load frame at room temperature. The axial load was held below 10 N to ensure torsional loading dominance for free-end torsion testing. Load-frame data were used for collection of the torque and angular displacements of the experiments. Because load-frame data were used for angular displacements, modulus correction during data processing was performed, assuming the fixtures remained entirely elastic during the test. The torsion testing was performed using thin-walled Lindholm specimens with gauge dimensions of 0.5 mm thickness, 7 mm average radius, and 3.2 mm in length. A sketch of the specimens used herein is in Tucker et al. [5].

The high strain-rate tests were conducted with a split-Hopkinson pressure bar (SHPB), direct tension Kolsky bar, and a direct torsion Kolsky bar for compression, tension, and torsion tests, respectively. Details about the experimental setup and procedures for these types of high strain-rate tests can be found in the literature [16]. In the SHPB, a 350 maraging steel bar system of 12.7 mm diameter was used with a 600 mm-long striker that delivered the impact energy to the system. Specimens were 10 mm diameter and 5 mm in length. The tension tests were conducted using 7075-T6 aluminum 12.7 mm-diameter bars with small 350 maraging steel grips to hold tension specimens, which were the same dimensions as the low strain-rate tests. Tension energy was stored by pre-strain in a section of the incident bar and was released using 7075-T6 aluminum breaker pins. Torsion tests were conducted on a 22.23 mm diameter 7075-T6 aluminum bar with Gilat high strain-rate thin-walled torsion specimens that were directly glued to the bars using high-strength epoxy provided by ResinLab [17]. The torsional energy was stored and released similarly to the tensile setup. A high strain-rate, 103 s⁻¹,
room-temperature experiment was performed on each machine; strain rate uniformity was controlled as feasibly possible. Representative fractured tension and torsion specimens from the high-rate tension test were kept for fractography studies.

Imaging of the failed tension and torsion specimens were performed on the fractured ends of the specimens, normal to the surface, using a Zeiss Supra 40 FEG-SEM. Specimens were placed in a vacuum storage vessel and removed for examination no later than one day after testing had occurred.

All experiments generated stress–strain curves, and selected curves that represented a three-specimen batch were imported into the MSU DMG/fit software for calibration of the ISV/damage model. Plasticity constants were selected that represented reasonable consistency with experimental curves with the minimum number of parameters necessary to provide accurate solutions.

2.3 Constitutive Model

The summarized internal state variable (ISV) plasticity/damage model and calibrated parameters are shown in Appendix A and Appendix B, which uses the same model framework as discussed in Tucker [5]. The material model was introduced by Bammann [18] and Bammann et al. [10], and later modified by Horstemeyer and Gokhale [11] and Horstemeyer et al. [12]. Here, the model remains unchanged with regards to plasticity and damage except for the nucleation rate. The nucleation rate is used with the modification made by Tucker et al. [5], which introduces strain-rate sensitivity by multiplying the original nucleation-rate equation by the deviatoric stress invariant, $J_2$. 


\[ \dot{\eta} = \| D^p \| \frac{a^{1/2}}{K_{IC} f^{3/2}} \eta J_2 V(T) \left\{ a \left[ \frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + b \frac{J_3}{J_2^{3/2}} + c \| I_1 \| \right\} \exp \left( \frac{C_{\eta T}}{T} \right) \] (2.1)

The nucleation rate \( \eta \) is dependent on physical parameters such as the fracture toughness, \( K_{IC} \), the volume fraction of particles, \( f \), and the particle diameter, \( d \). \( J_2 \) will increase at higher strain rates due to the plasticity model constant, \( C_3 \), described in detail in by Tucker et al. [5], and is scaled by the ratio of strain-rate sensitivity to yield stress \( V(T)/Y(T) \). The nucleation rate will also increase, thereby increasing the damage rate and subsequently reducing strain to failure at higher strain rates. The nucleation rate equation and the particle coalescence equation also have an Arrhenius-type temperature dependence scaled by \( C_{\eta T} \) and \( C_{CT} \), respectively. The nucleation equation has stress-state dependence scaled by \( a \), \( b \), and \( c \). The material constant, \( a \), is determined from torsion experiments, while \( b \) and \( c \) are determined from tension and compression experiments, respectively [12].

For elastic parameters, 4340-steel elastic constants were used from previously published data due to the similarity of 4340 steel and RHA.

2.4 Results and discussion

The optical micrographs (Figure 2.1) reveal that the hard carbide particles and grain-size distributions of RHA are typical of commercial RHA. Table 2.2 presents the average values of the necessary statistics needed for calibration of the model.
Figure 2.1 Optical micrograph image of RHA (rolled homogenous armor) steel showing hard carbide particles and grains.

Table 2.2 Average values of particle-size diameter, area fraction, and grain size for the as-received RHA plate.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Particle size (μm)</th>
<th>Particle area fraction</th>
<th>Grain size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value</td>
<td>3.5</td>
<td>0.00065</td>
<td>12</td>
</tr>
</tbody>
</table>

Note: Data were obtained from three different 10 mm-thick specimens that were analyzed with five images each.

Post-mortem samples from the tension and torsion tests were gathered and their fractured surfaces examined as described previously. When investigating the voids closely, larger voids showed evidence of particles trapped in their center. This observation is widely reported in literature [20] and is known to occur in ductile metals due to voids originating from the debonding of the metallic matrix from the particle inclusions. Figure 2.2 shows an example of a trapped void, sometimes referred to as a “birds nest”, in a room-temperature low-rate experiment. This observation is expected
and is necessary for determining the relevance of using the MSU ISV/damage model, which assumes ductile failure.

![Figure 2.2 Scanning electron microscopy (SEM) image of fractured RHA surface.](image)

Note: Scanning electron microscopy (SEM) image of fractured RHA surface from a low strain-rate (0.001 s−1), ambient temperature, tension test showing particles located in the surface voids. The image in (b) is an enlarged section from (a).

Figure 2.3 shows the stark difference in the fractured surfaces of the low strain-rate experiments and the high strain-rate experiment. Notice that the low-rate fractured surfaces exhibit a very rough, dimpled surface with deep voids. The high-rate surface, however, has many more voids than the lower-rate experiment, but these voids are smaller in size and depth than the low-rate experiments. The higher-temperature (300 °C) quasi-static tension test revealed larger voids than the room-temperature test. This shows that void growth increases with an increase in temperature. Also, the higher-temperature test showed less voids, meaning that nucleation of voids decreases with an increase in temperature. The void nucleation rate, defined as the rate of the number of voids created per unit of strain, must therefore increase with strain rate and decrease with temperature.
Figure 2.3  Scanning electron microscopy (SEM) image of fractured RHA surfaces.

Note:  (a) Scanning electron microscopy (SEM) image of fractured RHA surfaces from ambient-temperature, low strain-rate (0.001 s$^{-1}$) test, (b) a 300 °C low strain-rate (0.001 s$^{-1}$) test, and (c) an ambient temperature, high strain-rate (1000 s$^{-1}$) tension test

The fractured surfaces of the high-rate torsion experiments, shown in Figure 2.4, reveal a section that appeared ductile, and then a larger section that appeared brittle. The ductile section, known to be the initiation of fracture, is the section chosen for microstructure quantification.

Figure 2.4  Scanning electron microscopy (SEM) image of fractured RHA surfaces from a high strain-rate torsion test.

Note: Scanning electron microscopy (SEM) image of fractured RHA surfaces from a high strain-rate torsion test showing (a) ductile and brittle regions and (b) higher magnification of ductile region
A simulation of the damage parameters was conducted using the MSU Dmgfit software to see how well the model could capture the final-number density of voids (nucleation) gathered from the different strain-rate and higher-temperature fractured surfaces. Figure 2.5 shows the simulated nucleation results versus strain compared to the measured nucleation from the experimentally determined values of the fractured surfaces.

Figure 2.5  Comparison of the number density of voids and the model prediction of nucleation plotted versus strain.

Note: Comparison of the number density of voids, i.e., nucleation, on the fractured surface of the failed tension and torsion specimens, and the model prediction of nucleation plotted versus strain

The nucleation at the failure strains shows good agreement, with the exception of the high-rate case, between experiments and the model predictions. The model captures the stress-state dependent trends that exhibit more nucleation of voids in torsion than in tension for the experiments. Also, as temperature increased, the nucleation decreased in both the experiments and the model. While the model did show an increase in nucleation for the high-rate tension specimen, the model under predicts the nucleation seen in the
experiment. However, in torsion, the strain-rate dependence on void size in the experiments was not as strong as in tension, and therefore the model solution more closely predicted the final nucleation.

With the initial and final damage quantified and its evolution fitted to the model, the plasticity parameters were then calibrated by comparison to the stress–strain curves gathered from the experiments. The compression experimental results, shown in Figure 2.6, showed that for the low-rate tests, no hardening exists. In the high strain-rate tests, however, work hardening does exist revealing that the work-hardening rate is a function of applied strain rate. The overall yield strength of RHA also increases as strain-rate increases. The high-temperature tests showed little effect on the strain hardening behavior but did reduce the yield strength considerably. No failure was observed in the compression experiments to 60% true strain. The model predictions show excellent agreement with the compressive experimental data, as shown as the solid curves in Figure 2.6.
Figure 2.6  Compressive stress versus strain curves from experiments and the calibrated responses.  

Note: Compressive stress versus strain curves from experiments and the calibrated responses from the ISV/Damage model using the tabulated values in Appendix B.1  

Tension tests, shown in Figure 2.7, revealed similar strain-rate dependence on yielding as in compression. The high strain rate experimental oscillations were assumed to be a result from the stress wave interaction with the bars and specimen grips during experimentation and were not assumed to be a result from material. The failure strain level for the room-temperature low-rate experiments were less than that of the higher-temperature tests, which show that damage is temperature dependent. The high strain-rate experiment showed a significant reduction in strain to failure as well. Because the nucleation at high rate was not accurately captured, as shown previously in Figure 2.5, the strain to failure is over-predicted. The reduction in ductility from low strain rates to high strain rates is known to be a cause of nucleation strain-rate dependence [7]. A
different method for introducing strain-rate dependence in nucleation would be necessary to capture the much higher nucleation seen in the tension experiments. One way to capture nucleation more accurately could be performed by the addition of a power term to $J_2$. This would allow the dependence on $J_2$ to be scaled non-linearly, rather than a simple direct relationship as was used in this study.

Figure 2.7  Tension stress versus strain curves from experiments and the calibrated response.

Note: Tension stress versus strain curves from experiments and the calibrated response from the ISV/Damage model using the values from Appendices B.1 and B.2

The torsion experiments were all performed at room temperature. Figure 2.8 shows the results that exhibited similar yield-strength dependence on strain rate as the tension and compression experiments. The final strains for the torsion simulations over-predicted both experiments; ASB in RHA can exist in high strain-rate torsion tests and
have an effect on the perceived strain to failure [5]. However, the stress–strain response was captured relatively well for the torsion tests.

Figure 2.8  Torsion stress versus strain curves from experiments and the calibrated response.

Note: Torsion stress versus strain curves from experiments and the calibrated response from the ISV/Damage model using the tabulated values from Appendices B.1 and B.2

Figure 2.9 shows the room-temperature, quasi-static (0.001 s\(^{-1}\)) mechanical responses for the different stress states. This figure shows significant differences in mechanical properties. The torsion experiments failed at a much lower equivalent true strain than the tension experiments. The hardening rate-dependence on strain rate was lower than for tension and compression. Because no observable failure was seen in the compression tests, the damage in compression was assumed to be low. The model was able to scale the failure strain based on the stress-state dependent damage parameters \(a\),

44
$b$, and $c$, from Eq. (2.1), while the variation of the hardening rates between tension and torsion were captured by the plasticity parameters, shown in Appendix equations (A.1) and (A.3).

![Figure 2.9](image)

**Figure 2.9** Ambient temperature (25 °C) compression, tension, and torsion experimental and modeling true stress versus true strain curves at a strain rate of 0.001 $s^{-1}$.

### 2.5 Summary and Conclusions

RHA was investigated with regards to microstructure and mechanical response. An ISV plasticity/damage model was chosen to predict microstructural statistics and mechanical responses of the RHA plate due to the model’s ability to be used under a wide range of events. The RHA plate in this study was shown to have small particles that were assumed to be homogenously distributed throughout the part. Microstructure of the RHA
plate was quantified and used in the MSU ISV/Damage model to allow the model to be adapted for RHA plates of different initial particle and grain-size and distributions.

Mechanical experiments were conducted on the RHA plate for calibration of the material model. Tension, torsion, and compression experiments were conducted so that the dependence on flow stress and failure strain could be quantified and used as a metric for calibrating the material model with respect to stress state. The model was able to capture stress-state dependence on flow stress and failure strains reasonably well. Slight over-predictions of the failure strains were shown in the tension and torsion cases, but the trends between the stress states reflect the experimental trends. Strain-rate dependence of RHA was also investigated by performing low and high strain-rate experiments for each different stress state examined. RHA showed an increase in flow stress with an increase in strain rate for all stress states. Capturing of strain-rate dependence on stress state was performed well with the current material model. However, the nucleation at the final strain was under-predicted for the high-rate tension case.

The low strain-rate experiments were also conducted at different temperatures and were able to be predicted by the model. RHA exhibited higher elongation to failure and lower strength for the higher-temperature tests. Nucleation at the failure strains for each temperature was shown to be in good agreement between the model and the experiments.

Several conclusions to this study are apparent to the authors. RHA is notably strain-rate dependent on plasticity and damage based on the experiments reported. The failure strains of these experiments changed for the different loading conditions showing stress-state variation in damage. Temperature also provides a significant factor in the plasticity and damage of RHA. The material model used in this study captures these
effects reasonably well, but could use improvement in the strain-rate-dependent nucleation equation due to the under-prediction of nucleation rate in the high-rate tension experiment. Because impact scenarios can encompass stress-state, strain-rate, and temperature variations, these material characteristics should be captured in the chosen material model in order to accurately predict the deformation and failure of RHA.
2.6 References Cited


3.1 Introduction

The mechanical response of engineering materials is widely known to depend on the applied strain rate [1]. In high strain rate testing (500 s\(^{-1}\) to 5000 s\(^{-1}\)), the split Hopkinson pressure bar (SHPB) is widely used to gather the stress–strain behavior [1], [2], [3], [4], [5] and [6]. In these experiments, a single shock wave is imparted to the specimen and using one dimensional stress wave theory, stress–strain relations can be extracted from monitoring the bars. The drawback of SHPB testing is that the time duration of the test is limited to the length of the bars. To achieve strain rates in the intermediate strain rate regime (5 s\(^{-1}\) to 500 s\(^{-1}\)), the testing apparatus would become too large to fit in conventional laboratories. Nevertheless, some laboratories have created intermediate strain rate bar systems in the order of 30 m length to achieve intermediate strain rates [7] and [8]. Some researchers have modified conventional SHPBs to provide a long loading duration with hydraulic or other means with load acquisition using two or more strain gages on each bar to monitor the stress–strain relationship. In these systems, a multi-gage solution to the stress wave propagation allows stress–strain measurements to be captured after the stress wave has traversed the short transmitted bar multiple times [9] and [10]. This method, however, presents a new problem as the strain rate jumps at every
instance that the initial transmitted wave comes into contact with the specimen, and the reduced data may have many oscillations at intermediate strain rates.

Another approach to testing materials in the intermediate strain rate regime is to modify existing low strain rate testing equipment [11], [12], [13] and [14]. The desired loading rate of the specimen is realized by servo-hydraulics, while the sample grips and fixtures are modified to improve the load acquisition [11] and [12]. The most common goal in modifying the fixtures is to design the load train with a high natural frequency such that the test frame reaches equilibrium along with the specimen. The load then can be measured by a strain gage mounted on the fixture or grip section of the specimen or by using a small piezoelectric load washer [15]. Data from these test setups, with careful consideration, have been used to calculate stress–strain responses up to approximately 100 s\(^{-1}\) [11] and [12]. Shown in Figure 3.1 is a comparison of the as-received high rate testing apparatus from a manufacturer (Figure 3.1(a)) and the best case improvement to the system (Figure 3.1(c)). Although modified servo-hydraulics are typically rated for higher loading rates (10 m s\(^{-1}\)), at strain rates above 100 s\(^{-1}\) these systems become unreasonably difficult to acquire load data. Therefore, experimentalists are forced to perform data filtering and curve fitting techniques [12].
Figure 3.1  Tensile load ringing in three different modified servo-hydraulic specimen fixtures at three different natural frequencies.

Note: Tensile load ringing in three different modified servo-hydraulic specimen fixtures at three different natural frequencies: (a) 2500 Hz, (b) 4800 Hz, (c) 13 000 Hz. Reproduced with permission from [16].

With bar systems having a minimum strain rate limitation in the intermediate regime and modified servo-hydraulic systems having a maximum strain rate limitation also in this regime, improvements to one or both systems must be made to provide significant strain rate overlap between the testing practices. The objective of this paper is to provide an intermediate strain rate solution that acquires accurate load data without unreasonable difficulty in providing laboratories with a common of load acquisition method.

3.2 Materials and Methods

3.2.1 Bar System Methodology

As discussed in the introduction, the issue with bar testing at intermediate rates is due to the bar size constraint along with the wave speed. These constraints arise, because the stress wave propagates along the bar length, reflects off of the free end, and returns to the specimen [9]. Once the stress wave reaches the specimen, the energy applied to the specimen changes and can subsequently change the applied strain rate, commonly known
as a strain rate jump. Typical Hopkinson bar experiments are performed at such a high strain rate that the experiment is completed before the stress wave traverses the bar so as to eliminate this strain rate jump effect. Because of this size constraint, the Hopkinson bar has a lower strain rate limit for the bar setup. The minimum strain rate that can be achieved with a single continuous applied load in any bar system is described by the following:

\[
\sigma_n(t) = \frac{F(t)}{A_s}
\]  

where \( L \) is the length of the transmitted bar, \( c \) is the longitudinal wave speed of the bar material, and \( \varepsilon_{\text{max}} \) is the maximum strain incurred by the specimen. To reduce the minimum strain rate achievable in the test, the maximum strain could be reduced without changing the bar properties at all. However, reducing the maximum specimen strain preempts an experiment from achieving specimen failure. The longitudinal wave speed of the bar could be reduced by changing the bar material. However, materials with a significant reduction in wave speed, such as polymeric materials, also have a significant reduction in strength; this reduction in strength cannot be used for testing metals that are stronger than the bars themselves. The final parameter that is possible to change is the bar length. Changing the bar length can be performed only to the extent that a laboratory can accommodate such a testing apparatus. As previously mentioned, some researchers [7] and [8] have adopted this practice by increasing their length (~30 m). However, other laboratories would have to undergo infrastructure changes to acquire the ability to use these systems.

Packaging the bar in an economical way that allows conventional laboratories to perform intermediate strain rate tests would be optimal and that is the purpose of our
design. Typical laboratories that perform SHPB experiments can house a system of 6 m but need the capabilities of a longer transmitted bar (> 18 m) for smooth load acquisition durations in the intermediate strain rate range. The time duration of a bar with length of 18 m would be enough for testing nominal strain rates of about 70 s\(^{-1}\) for a specimens tested to 0.50 strain if a metallic bar (\(c = 5000 \text{ m s}^{-1}\)) was used. Because modified servo-hydraulic load-frames are capable of strain rates up to 100 s\(^{-1}\), our proposed technique provides enough overlap for complete testing throughout the intermediate strain rate regime if a laboratory had acquired both systems.

### 3.2.2 The serpentine bar approach

Figure 3.2 shows the structure of a serpentine bar that can provide increased time duration to achieve large strains. A serpentine bar has the advantage over a conventional long bar in that the stress wave, propagating from the sample, can be transferred into a series of tubes. These tubes are impedance matched to the original solid bar to eliminate the reflection due to the added tubes, and the joints are made small and stiff to reduce the joint reflections. Tubes have been used previously to trap the stress wave energy in “recovery” Hopkinson bar setups [17]. The recovery Hopkinson bar uses a tube that is located near a flange on the bar free end to admit bar movement before the stress wave enters the tube and is trapped from returning to the specimen. This process allows a precise amount of strain to be applied to the sample without repeated loading from the stress waves. This setup transmits the stress wave very well when designing the transfer flange is carefully considered. Here, we adapt this concept for increasing the stress wave duration possible in a given bar length, rather than trapping a shorter stress wave inside a detachable tube. The main difference with the serpentine bar setup is that a series of tubes
are rigidly connected at alternating ends of the bar. Figure 3.2 shows a serpentine bar with two attached tubes, which multiplies the effective length of the bar by a factor of three. As manufacturing techniques permit, any number of tubes can be attached to increase the effective length of the bar. Attaching a serpentine bar to a direct Hopkinson bar loading system (as the transmitted bar) or to the fixed end of a servo-hydraulic load frame, elimination of high frequency ringing with a long time duration can be achieved efficiently in a fairly short bar.

Figure 3.2 Structure and setup of our proposed serpentine transmitted bar loaded in compression.

Note: Structure and setup of our proposed serpentine transmitted bar loaded in compression, with two strain gage stations (blue), the specimen location (white), and bushings (red).

3.2.3 Prototype fabrication

A serpentine transmitted bar with a single attached tube, designed for compression testing, was selected to provide a direct comparison to a longer bar of equal effective length, detailed in Section 3.3. The serpentine bar was built using a 15 mm diameter rod of 1.5 m length with a 1 m long tube (giving an equivalent length of 2.5 m), both being the same grade 350 maraging steel. The gap between the tube and the rod was 1.5 mm and the tube was machined to match the cross sectional area of the solid rod. Joining the bars was performed using a gas-tungsten arc welding process without filler.
Threaded connections between the bars were also attempted, but the load did not transmit smoothly through the joint. Bronze rings were placed in the gaps in between the bar and tube at 300 mm intervals to ensure rigidity of the bar inside the tube. Two gage stations were placed near the specimen approximately 300 mm apart from each other with the closest strain gage 150 mm from the sample to provide load sampling and reflection monitoring. The entire bar was then mounted on a SHPB frame in a similar fashion to conventional Hopkinson bar mounting. Images of the fabricated serpentine bar are shown in Figure 3.3.

![Figure 3.3 Schematic of the serpentine bar.](image)

Note: Schematic of the serpentine bar (a and b). Front half of the two pass bar (c) and close-up of the welded joint at the far left of the serpentine bar (d).

The physical limitations of making a serpentine bar became clear during the fabrication of the prototype. If each tube would have the same characteristic impedance, i.e. cross sectional area, then the tube's thickness becomes very small as the number of
tubes increases. A practical limitation of two tubes for a 12 mm–15 mm diameter bar was observed during the project. However, larger diameter bars would possess the ability to have more attached tubes. A 25 mm diameter bar may admit four tubes.

3.3 Theory/Calculations

3.3.1 Dynamic joint behavior

When constructing the serpentine bar, the authors hypothesized that the welded joint may cause unwanted reflections of the stress wave that would propagate towards the specimen and subsequently produce unwanted specimen ringing. The stress wave position diagram, shown in Figure 3.4(a), shows the theoretical position versus time of the transmitted stress wave front, as well as an illustration of the gage positions in the bar. The tube is shown unfolded for viewing purposes. Using an experimentally determined bar wave speed of 4783 m s\(^{-1}\), a reflected wave from the welded joint would move past Gage A after 0.000 57 s of record time elapsed during impact. To investigate this notion, an experiment was constructed on the serpentine bar prototype in which a striker bar 0.6 m long was fired at the serpentine bar. The striker bar length was chosen to allow the initial wave to transmit through the joint and enter the attached tube so that any reflection from the joint could be monitored without interference. The striker, originally moving at 10 m s\(^{-1}\), was fired at the serpentine bar, which had a small 3 mm thick aluminum pulse shaper inserted between the two bars to eliminate dispersion effects [18].
Figure 3.4  Stress wave position diagram in the serpentine bar prototype.

Note: Stress wave position diagram in the serpentine bar prototype (a) and the experimental data gathered from Gage A (b) from an impact of a striker bar with pulse shaper. The serpentine bar illustration is shown with the attached tube in reverse direction for comparison to diagram.

Notice in Figure 3.4(b) that the stress wave generated is smooth in nature and ends at a time of approximately 0.000 47 s. After this time, the signal should remain null if no reflections from the joint occur. However, at 0.000 538 5 s, a small wave was detected which is negative (tension) first followed by a positive (compression) response. A single wave of this size is not likely to affect the specimen behavior; however, this wave could pose a problem for data analysis. If the final design also has a reflection wave of this size, a second strain gage, Gage B, could be placed an appropriate distance away from Gage A, depicted in Figure 3.4(a), that can be used to provide more accurate accounting of the stress versus time by a two point strain methodology proposed by Zhao and Gary [9]. The form of the equations used to solve for the actual elastic strain in the serpentine bar near the specimen is the following:
\[ \varepsilon(t) = \begin{cases} 
\varepsilon_A \left( t - \frac{L_A}{c} \right) & \text{if } t < \frac{2(L - L_A)}{c} \\
\varepsilon_B \left( t - \frac{L_B}{c} \right) & \text{if } \frac{2(L - L_A)}{c} \leq t < \frac{(2L + L_B)}{c} \\
\varepsilon_C \left( t - \frac{L_A}{c} \right) & \text{if } t \geq \frac{(2L + L_B)}{c} 
\end{cases} \] (3.2)

where \( L, L_A, \) and \( L_B \) are the distances from the sample to the joint, Gage A, and Gage B, respectively. By providing an appropriate distance between Gage A and Gage B, the stress wave, free of the reflection from the joint, can be produced using the appropriate strain gage signal at the appropriate time. This will not remove the inflection due to the reflected wave bouncing from the specimens, since this is a real stress existing on the specimen bar interface. If the reflection for the final design does not show a significant reflection, Gage B is not needed and a single strain gage can be used to monitor the stress history similar to long bar systems [8].

3.4 Results/discussion

3.4.1 Intermediate strain rate experiment

To judge the robustness of the new serpentine bar in operation, an intermediate strain rate compression test was performed on a 6061-T6 aluminum specimen. For this experiment, a 2.5 m striker bar was used to force the reflections to exist during the experiment as will be done for the final design. A compression specimen was placed at the end of the bar and impacted by the long striker bar at the free end of the specimen at 2 m s\(^{-1}\) in a direct Hopkinson bar fashion. The striker bar velocity was chosen to give a nominal strain rate in the intermediate strain rate regime. The aluminum specimen was machined to a right cylinder of 12.7 mm diameter. A high elongation EP style strain gage was attached to the specimen to monitor strain. For monitoring the calculated loads,
the previously used transducer class strain gages were mounted to the bar at selected locations, shown in Figure 3.4(a). Figure 3.5 shows the raw data from the test.

![Figure 3.5](image)

Figure 3.5 Raw strain gage data from a direct compression test of 6061-T6 aluminum with a striker impact at 2 m s\(^{-1}\) using the serpentine bar.

Figure 3.5 exhibits the bar strain versus time as recorded from the two strain gages mounted on the bar. In Figure 3.5, the specimen gage record becomes static at approximately 0.001 s. This is the time at which the stress wave has traversed the entire bar length, including the tube, and has finally unloaded the specimen. At this time both Gages A and B now record significant drops, except for some ringing due to the stress wave.

The length and beginning time of the strain waves are slightly different in Gage B compared to Gage A due to the physical locations. As a strain gage distance from the specimen/serpentine bar interface increases, the length of the wave decreases due to the overlap between the initial and reflected wave. Notice the two inflections in the Gage A
and Gage B results during the specimen loading. The spikes in Gage B are separated by a larger distance than in Gage A due to Gage B being placed further from the specimen end of the bar. Gage A is at the proper distance away from the specimen where the small inflection is both seen, yet not self-interfering with its reflection. These inflections in the data appear to be a direct result of the joint. The inflection magnitudes decrease when compared to the previous test performed with the shorter striker. This is likely due to an increased rise time of the stress wave as compared to the previously performed test. Nevertheless, the signals show promise as compared to long bar and servo-hydraulic systems [7], [8], [9], [10], [11] and [12].

### 3.4.2 Verification experiment

To compare signals of the serpentine bar to that of a traditional long bar system, an experiment was conducted using a long bar of equal effective length to the serpentine bar. A 2.5 m solid bar was instrumented with a single strain gage in the same approximate distance from the specimen as Gage A in the serpentine bar arrangement. Stress in the specimen was calculated by gathering the transmitted bar strain gage data as a force measurement. This force in the specimen-bar interface is inferred from to the raw transmitted bar strain gage measurement by the relationship:

\[
F(t) = \varepsilon(t - L_g/c)EA
\]

where \(\varepsilon(t - L_g/c)\) is the transmitted bar strain gage record at some time \(t - L_g/c\); \(L_g\) is the distance from the transmitted bar strain gage to the specimen-bar interface; and \(c, E\) and \(A\) are the wave speed, elastic modulus and cross sectional area of bar, respectively.
Calculations for the serpentine bar test used the two point strain data reduction method shown in Equation 3.2 to quantify the bar's elastic strain at the specimen-bar interface and then directly inputted into Equation 3.3 to calculate the force. The strain gage on the specimen was used in both cases for direct strain measurements. True stress and true strain curves were then calculated assuming a constant volume and are shown in Figure 3.6.

Figure 3.6  Comparison of a compression stress–strain curves and strain rate–strain curves of the solid 2.5 m long bar (solid bar) and the new serpentine bar transmitted bar.

Note: (a) Comparison of a compression stress–strain curves and strain rate–strain curves of the solid 2.5 m long bar (solid bar) and the new serpentine bar (transmitted bar), and (b) comparison of the serpentine bar data with published compression data at a higher and lower strain rate for the same sample material with results from Tucker et al. [20] and Agarwal et al. [19] for a 6061-T6 aluminum alloy.

Figure 3.6 shows that the stress–strain behavior and strain rate–strain curves compare very well to each other for the two different testing configurations. The two point strain data reduction method employed for the serpentine bar experiments improved the stress–strain curve by removal of the first inflection in the data. A key aspect of the
serpentine bar experiment is that robust stress–strain data at intermediate strain rates is achieved without filtering or curve fitting due to the bar being free of ringing noise. Figure 3.6(b) also shows that the serpentine experimental data for a 6061 aluminum alloy compares well with other high and low strain rate data [19] and [20]. The direct Hopkinson bar experiment can induce a drastic strain rate drop that in turn caused the hardening rate drop. However, many of the researchers have worked diligently at providing constant strain rate experiments using hydraulic or other means [9] and [15].

3.4.3 Simulation

To understand the behavior of the reflection of the joint during the serpentine bar experiment, a simulation of the previous serpentine bar intermediate strain rate compression experiment on 6061-T6 aluminum was carried out in Abaqus/Explicit [21]. A quarter symmetric simulation was created with the specimen modeled using an internal state variable plasticity-damage model for 6061-T6, based on work from Refs. [22], [23] and [24]. For a complete description of the model used in this study, the reader is referred to the work on 6061-T6 by Tucker et al. [20]. The same material constants used by Tucker et al. [20] were implemented in this study using an Abaqus VUMAT. The quarter model of the bar was given elastic parameters of steel and the bar-tube joint was given a uniform thickness cross-section to allow for ease of meshing. Hexahedral quadratic elements were used throughout the model without considering dispersion and default damping was used. Bar elements were approximately 1.5 mm–2.0 mm, while the specimen elements were reduced to 0.75 mm–1.0 mm to better capture the plasticity in the specimen. The incident bar was constrained with an initial uniform velocity of 2 m s\(^{-1}\) with a 2 mm gap between the bar and the specimen. Just before impacting the
specimen, a separate step in Abaqus was created to remove the velocity constraint to allow free movement between the incident bar and the specimen. The two bars and the specimen were constrained at their centerline with respect for radial motion to ensure that all members remain parallel; all other movements were kept free, with the exception of the initial velocity constraint on the striker bar. The specimen/bar interface was kept frictionless.

Figure 3.7 shows the setup of the serpentine bar simulation with the specified elements and nodes used for history output. The history outputs from the specified nodes and elements were gathered from the simulation to provide comparison to the transmitted bar strain gage history output, with the actual Gage A output, previously shown in Figure 3.5, from the serpentine bar experiment on 6061-T6. To compare the two solutions, the transmitted bar strain gage, located near the actual position of Gage A in the real 6061-T6 experiment, was used to provide axial stress measurements in the specimen after manually calculating the force using Equation (3.5.2.1); however, the simulation stresses were garnered directly from the middle element, depicted in Figure 3.7. Displacement nodes on the specimen edges were used for calculating the specimen strain. The final results of the calculations are shown in Figure 3.8.
Figure 3.7  Quarter space finite element simulation model.

Note: Quarter space finite element simulation model using Abaqus Explicit and the associated data acquisition points near the specimen for comparison to a compression experiment. Nodes were used in specimen displacement calculations, and selected elements were used in specimen stress calculations.

Figure 3.8  Simulated stress–strain behavior comparing the specimen middle in the finite element simulation versus the experimental result using a single transmitted bar element near the actual Gage A location.
Notice in Figure 3.8 that the stress–strain behavior calculated from the bar strain gage shows a similar anomaly as was observed in the raw experimental data of Figure 3.5, whereas the calculation using the specimen stress element shows no anomaly. Therefore, the anomaly that is shown does not significantly affect the specimen loading. Figure 3.8 shows that the average stress compares well with the transmitted bar result. This non-uniformity in stress is inherent to high strain rate experiments [25]. Also notice that the specimen flow stress differs from experimentation, because we used a material model calibrated to another data-set from a previously published work [20].

Also revealed in Figure 3.8 is that oscillations exist in the simulations that were not observed in the experiments. This behavior is attributed to the artificial damping in the simulation. The results gathered in the serpentine simulation performed herein provide sufficient evidence that the methods proposed in the study provide a sufficient accuracy to be used for intermediate strain rate experiments.

3.5 Conclusions

The design of a serpentine, or folded, Kolsky/Hopkinson bar, is described that can produce useful stress–strain measurements in the intermediate strain rate regime. The device produces results in which stress oscillations that are typical of a specially instrumented servo-hydraulic load frame are not present and is able to reach lower strain rates and longer test times than Kolsky/Hopkinson bar devices of the same length. Experimental stress–strain results of 6061-T6 aluminum at a strain rate of \( \sim 300 \, \text{s}^{-1} \) on the device reproduce nearly exactly published conventional Kolsky/Hopkinson bar results [20]. An explicit dynamic finite element simulation of the experiment was presented that reflected the theoretical behavior of the test setup. This serpentine Hopkinson transmitted
bar design can be useful in providing longer recording times than conventional bars of the same effective length. This method may be employed for intermediate strain rate experiments in laboratories that cannot house a long bar system. Furthermore, this system may be employed when load ringing exists in experiments performed using modified servo-hydraulics systems.
3.6 References cited


CHAPTER IV
DIRECT HYDRAULIC LOADING SYSTEM FOR ACHIEVING CONSTANT STRAIN RATES IN THE INTERMEDIATE STRAIN RATE REGIME

4.1 Introduction

Dynamic tension and compression experiments tend to dominate literature in high strain rates [1]. However, there exists nearly an order of magnitude less dynamics journal articles that include intermediate strain rates. The authors agree that this issue is mainly due to a lack in appropriate testing methodologies, rather than the impact of this regime.

To date, Hopkinson and Kolsky bar systems have been the most widely used dynamic deformation experimental apparatuses in literature. Many researchers have investigated the nature of these tests, refined the appropriate analyses, and expanded its capability. Strain rate consistency has been a focus of recent research namely in pulse shaping efforts [1, 3]. The Hopkinson bar has been used to experiment on metals, polymers, composites, fibers, organics, ceramics, geomaterials, and still others [1, 3–5].

Recently, a resurgence of intermediate strain rate experiments in tension on automotive sheet steels has been undertaken [6]. This increase in literature has been accomplished for two reasons: automotive manufactures now require this information for crashworthiness metrics, and commercial systems are now available for tension testing at intermediate strain rates. Even with these systems in practice, there are two main limitations: robust load acquisition and strain rate uniformity.
Figure 4.1  Round robin test results from 10 different research laboratories showing tensile results on mild steel at 100/s target strain rate.

Note: Data in this study showed significant variability [6].

Notice that the results of the round robin study shown in Figure 4.11 vary greatly. The yield stress is shown to have a variation of up to 25%, and a failure strain variation up to 45%. Failure strain discrepancies are most likely due to the different specimen designs used. Some laboratories used elongated grip sections to help with ramp-up distances of their machines. Still other laboratories used short specimens to keep total speed of the machine within limits. Appendix B shows the specimen designs used in this study. Strength variations can be from two major sources: load ringing and strain rate variation.
In Chapter III, we showed how a conventional laboratory may acquire the ability to garner useful load data from intermediate strain rate experiments, whether by use of bar systems or servo-hydraulics. In that study, we showed that by adding concentric tubes with alternating joints around a solid bar, the stress wave traverses the bar with the same useful load duration as a much longer bar system that normally requires a specially designed laboratory. However, loading was accomplished using a striker bar in a direct Hopkinson bar configuration. In the Hopkinson bar experiment, the strain rate was highly non-uniform, and the strain rate during the total experiment varied between 200/s–400/s. For robust intermediate strain rate experimentation, the loading apparatus must be designed to persist with reasonable strain rate consistency throughout the duration of the experiment. A long pulse (>4 ms), is desirable for intermediate strain rate experimentation. And finally, the system should be compact enough to fit into conventional labs, and simple enough so that many labs can acquire or build a similar system.

4.2 Design

The design of the direct hydraulic loading system is based on previous direct tension Hopkinson bar systems [8]. In these systems, stored elastic energy in a long incident bar is released very quickly to produce a relatively long square pulse for high rate tension experiments. Figure 4.2 shows the clamping device used in these systems and the wave propagation through the bars.
Figure 4.2  Direct-tension split Hopkinson bar setup.

Note: Direct-tension split Hopkinson bar setup showing the Lagrange diagram (left) and clamp release schematic (right) [8]. The clamp setup is used in conjunction with an applied load to store elastic energy in the incident bar. Upon fracture of the fracture pin, this energy is released and the wave travels to the specimen in accordance with the Lagrange diagram. Analysis is similar to the SHPB wave analysis.

To provide a load pulse with a 4 ms length, stored hydraulic fluid was used to make use of the slow fluid wave speed (approx. 1000 m/s), impedance mismatch, and low effective elastic modulus (approximately 2 GPa). For load acquisition at intermediate strain rate experiments in this study, a 3.5 m long serpentine bar with two tube of equal length was used. The equivalent bar length was 10 m. This results in a stress wave duration of 4 ms with a nominal acoustic wave speed of 5000 m/s. Figures 4.4, 4.5, and 4.6 shows the hydraulic system and clamp, a close-up view of the strain gage and specimen placement at the loading end of the serpentine bar, and the full length of the intermediate strain rate system, respectively.
Figure 4.3 Setup of intermediate strain rate apparatus using serpentine bar and direct hydraulic setup.

Note: (1) The hydraulic pump used to store fluid potential energy, (2) Clamp used to release the stored energy quickly, (3) ram used to translate the energy into a displacement of the specimen, (4) the placement of the specimen, and (5) the strain gage on the Serpentine Bar used for monitoring load.
Figure 4.4  Close-up of strain gage and specimen location at end of Serpentine Bar.
In the Hopkinson and Kolsky bar experiments, the incident wave profile is of upmost importance because information about strain rate uniformity can be garnered from interpreting the curve shape and size. Typically, square pulses are used, because they provide a “near” constant load during the experiment. In our setup, we also attempt
to attain a square pulse. Figure 4.6 shows the incident wave load profile from a direct impact of the loading ram with the serpentine bar.

![Load profile of intermediate strain rate testing device by a direct hydraulic loading system without a specimen.](image)

An initial observation of Figure 4.6 reveals an initial spike in the load that quickly levels off at 1 ms. The initial spike is most likely due to the steel ram, shown in Figure 4.3, reaching equilibrium with the hydraulic system. The ram, which is 0.75 m long, must reach equilibrium with the hydraulic cylinder before the load provided by the cylinder is transferred to the serpentine bar. Although the length was not altered to confirm this, we hypothesizes that a shorter ram would reduce the time duration, and associated momentum in the initial spike. After 1 ms, the loading pulse is flat overall.
until 4 ms and is when the incident wave has returned to the specimen. Note that 4 ms is a full order of magnitude longer than conventional SHPB pulses, and is at the heart of this design. There is also a small high frequency oscillation with a period of approximately 100 μs. This oscillation could be from the piston in the cylinder that is 50 mm long. Removal of this oscillation could possibly be performed by adding a dampener in the ram near the specimen platen.

4.3 Preliminary Tests on Copper

To investigate the performance of the intermediate bar for experimentation, two experiments on copper 101 were performed in compression. The specimens were nominally 3 mm diameter and 3 mm long. The small specimen dimensions were chosen so as to be compared to another long bar system in a future study. An experiment with the same pressure input parameters were used to give a similar loading pulse as shown in Figure 4.6. The load in the specimen was taken directly from the serpentine bar, and strain was taken from a high speed camera at 20 kfps. 7 shows four images during one of the compression experiments.
Figure 4.7 Four images from compression of copper 101 at 137/s nominal strain rate.

Displacement in the specimen was taken by two points at each end of the specimen in contact with the platens. During the experiment, only 20–30 frames were present because after 2 ms, the specimen diameter was so large that the load in the ram was not high enough to deform the specimen any more. Figure 4.8 shows the interpolation of strain versus time as well as the stress record from the gage.
Figure 4.8  Stress record from the serpentine bar strain gage transducer and strain points from digital image correlation, as well as a strain interpolation between points versus time.

Note: Stress record from the serpentine bar strain gage transducer and strain points from digital image correlation, as well as a strain interpolation between points versus time for two copper 101 compression experiments. The top plot exhibits an average of 66/s while the bottom plot exhibits an experiment at 137/s. Note that a constant strain rate would indicative of a straight line, rather than a curve.

Notice in Figure 4.88 that some of the strain points in the video do not line up with the moving average interpolation in the video. This error in the video can be improved if more images are taken, and if speckle patterns are applied to the specimen
for better reference points. However, in the 137/s test, strain versus time in the plot in Figure 4.8 shows significant improvement over the Direct Hopkinson results shown in Chapter III.

With regards to the non-uniformity that still exists in the strain versus time plot in Figure 4.8, each subsystem can be investigated for its own contribution to the system performance. One contribution to the strain rate variation in the experiment is the constant load delivered to the specimen. As stated before, compression specimens increase their diameter, and therefore the load required to deform the specimen typically increases. Another reason, and probably the culprit of the initially high strain rate, is probably due to the long ram. Referring to Figure 4.6, the first 1 ms has a highly nonuniform spike in the loading curve, therefore, either reduction of the ram bar length, or a small separation distance between the specimen and the ram could provide even better strain rate consistency during the test. To check the robustness of the setup to provide stress-strain relations, Figure 4.9 shows the true stress-strain curves of the two experiments on copper 101.
Figure 4.9  Compressive true stress-strain curve of copper 101 tested on the intermediate bar used in this study.

Note: Strain rates are calculated as averages (negative indicates compression).

Although some strain rate variations exists, and that there were only 20–30 strain points for data collection, the stress-strain curves from the two experiments showed consistent trends. One notable point is that the stress-strain curves are free from load ringing that plagues compact intermediate strain rate equipment to date. Also, the experiment at 137/s showed significant plasticity during the experiment.

4.4 Conclusions

The direct hydraulic loading system was used to perform intermediate strain rate compression experiments in conjunction with a serpentine bar. The incident loading curve exhibited an initial spike, followed by a uniform load until 4 ms. Although the system enclosed did not provide absolute constant strain rate desired in the experiment, it does present a significant improvement over the method employed in Chapter III and considerations to improve on in the future could be achieved. By adding a damping filter
to remove high frequency oscillations, strain can be smoother during experiments. Also, by shortening the ram bar, the initial spike in the incident wave, can be reduced. These two improvements should be investigated and more experiments on copper 101 can be performed to compare to the data enclosed herein. Finally, more frames should be available during the experiment so that the strain data does not present sharp corners when calculating strain rate.

The experiments performed in this study also further show the benefits of using a serpentine bar as the load garnering device. The stress-strain relations showed smooth data without unwanted load ringing. The total system was 6 m, that is typical of a conventional Hopkinson or Kolsky setup. Experiments between 60/s and 140/s were conducted this way, and are typically hard to perform without long bar setups.
4.5 Reference Cited


CHAPTER V
SUMMARY AND RECOMMENDATIONS

5.1 Summary

The work disclosed herein advances the world of dynamics from both a modeling and an experimental perspective. Low, intermediate and high strain rate modeling and experimentation are basic elements in dynamic investigations and require complementary experimental and modeling efforts to fully understand dynamic material behavior.

To expand the dynamic experimentation at intermediate strain rates, a serpentine transmittal bar was created to provide the same robust load acquisition as long bar systems, but in a compact form factor necessary to be implemented in most laboratories that use modified servo-hydraulic load-frames, or conventional Hopkinson (Kolsky) bars. Load data free of ringing was achieved and is an important step in expanding the acquisition of intermediate strain rate data, especially at rates near Hopkinson (Kolsky) bar lower limits. We recommends that the serpentine bar be used to modify existing Hopkinson (Kolsky) bar systems to improve the lower strain rate limitation; also, modified servo-hydraulic load-frames may undergo retrofitting with a serpentine bar to improve the upper strain rate limitation of these systems.

In order to improve on the strain rate uniformity of the intermediate strain rate experiments, a direct hydraulic system was created to provide near constant strain rates during experiments. Using a fracture pin to instantly release stored energy in a hydraulic
cylinder allows this apparatus to deliver near constant load without long ramp-up
distances typical of other intermediate strain rate system. Having this capability to
provide constant strain rates during the intermediate rate deformation is a very important
success for experimental resources.

Material models with highly developed strain rate dependencies on stress state
and temperature should be implemented with a physical based approach in mind. To help
the dynamic community with the proper tools of achieving the goal of incorporating these
characteristics in dynamic modeling, strain rate dependent nucleation was implemented
in a well-known ISV plasticity-damage model for finite element analysis. By achieving
this end, a widely used constitutive model was employed to encompass stress state, strain
rate, and temperature dependencies on plasticity and damage with a single set of
parameters. Rolled Homogeneous Armor (RHA) was calibrated to this ISV model,
because of its use as a metric in ballistic flyer plate experiments, as well as its historical
significance in armor plating. This model can be used for various other metals especially
when designing components that undergo widely varying strain rates.

The key accomplishments of this work are the following:

- Developed and ISV plasticity-damage model for a Rolled Homogeneous
  Armor (RHA) steel alloy

- Implemented an updated strain rate dependent damage nucleation rate
  equation into Abaqus UMAT and VUMAT

- Provided underreported tension, torsion, and compression experimental
  data at varying temperatures and strain rates for RHA

- Provided underreported microstructural statistics of RHA pre and post
  mortem and related these statistic to damage in the material
• Designed and verified a compact load monitoring apparatus known as the “Serpentine Bar” to achieve the robust data acquisition for intermediate strain rates formerly acquired only in long test systems

• Designed and hydraulic loading apparatus known as the “Direct Hydraulic Loading System” for obtaining a uniform strain rate that is consistent during intermediate strain rate experimentation

• Disclosed information herein on a well-known online database at https://icme.hpc.msstate.edu/mediawiki/images/temp/f/ff/20141111152413!phpw5JmeI.pdf

Several specific items in this study can be further investigated to improve on the merits of this work and others, such as:

• Calibration of other steels and aluminum alloys to the ISV plasticity-damage modified strain rate nucleation model

• Component level FEA using the calibrated RHA model

• Full-field Digital Image Correlation (DIC) of intermediate and high strain rate experiments using high speed imaging for more accurate strain measurements and failure determination

• Full-field adiabatic thermal heating measurements using high speed infrared camera or other means to investigate the temperature effects on dynamic deformation

• High temperature capability in intermediate and high strain rate testing in tension, compression, and torsion for specific investigations such as metal forming operations

• Intermediate torsion serpentine bar system for expanding stress state dependence on dynamic strain rate experiments

For adiabatic thermal imaging, DIC, ISV/damage model calibration, and component level dynamic simulation, literature and methodologies are abundant and accessible to many researchers. For high temperature dynamic experiments and for intermediate strain rate torsion experiments, literature is scarce. Therefore, a discussion into these two future works is discussed below.
5.2 High Temperature Dynamic Experiments

For high temperature dynamic experiments, a few different niche solutions exist. Many dynamic, high temperature experiments are completed by placing a heated specimen into cool bars, and performing the experiment quickly afterwards; the hope is that the specimen hasn’t cooled, and that the bars have not been heated [2]. If the specimen is in contact with the bars for a long time, a temperature gradient exists in the bar and stress waves reflect off of the gradient induced impedance mismatch boundary. As discussed, many researchers have elected to solve this problem by quickly performing the test so the bars do not have a high thermal gradient. Some researchers have even developed equipment to load the specimen into contact with the bars in a fast operation [1]. However, quick specimen placement in the bars is not practical in many experiments, especially in tension and torsion tests where loading a specimen requires specialized grips.

In the 1960s, research was performed to provide a practical analytical solution to a Hopkinson Bar with a thermal gradient [2]. In this study, thermocouples were used to monitor the temperature profile of the bars at different distances. By assuming a certain number of impedance mismatch boundaries, a solution set of equations was created to solve for the stress strain relations in a high temperature experiment. Figure 5.1 illustrates the concept.
Figure 5.1  Temperature profile of pressure bar at different locations, and the assumed stress wave interaction along the bar system.

Note: Temperature profile of pressure bar at different locations (left), and the assumed stress wave interaction along the bar system (right) [3]. The solid line in the pressure profile curve is the assumed temperature distribution, while the dashed lines show positions of actual temperature measurement from thermocouples.

Another preferred solution to obtaining high temperature data from Hopkinson Bars is to choose a bar material that does not have a large impedance mismatch resulting from a thermal gradient. Since the reflections at an impedance mismatch boundary are a function of the bar impedances alone, materials with low impedance dependencies on temperature can be used to reasonably high temperatures without any complex solution equations or experimental setups. The impedance of an elastic bar is:

\[ z = \rho c A \]  

(5.1)

where \( \rho \) is the density, \( c \) is the wave speed, and \( A \) is the cross sectional area of the bar.

Knowing that \( c \) is related to the elastic modulus, we have:

\[ z = \sqrt{\rho E A} \]  

(5.2)

with \( E \) being the elastic modulus. For most materials, the change in \( E \) versus temperature is much more drastic than the change in \( \rho \). Therefore, a material that has a low change in elastic modulus versus temperature should have a low impedance dependency on
temperature. Table 5.1 shows the elastic modulus dependency on temperature for a few common materials used as bars and platens.

Table 5.1  Change in elastic modulus versus a change in temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>$dE/dT$ (%MPa/100 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>-3.88 %</td>
</tr>
<tr>
<td>Aluminum</td>
<td>-7.07 %</td>
</tr>
<tr>
<td>Inconel</td>
<td>-1.04 %</td>
</tr>
<tr>
<td>Tungsten Carbide</td>
<td>-0.61 %</td>
</tr>
</tbody>
</table>

Notice in Table 5.1 that for a 100 K degree change in the temperature there is a 7% reduction in the elastic modulus for aluminum and nearly a 4% change for steel. For aluminum and steel, the strength would decrease as the temperature increases as well. Therefore, aluminum and steel bars are not used in high temperature experiments exceeding 400 K and 600 K, respectively.

However, for tungsten carbide and Inconel, only small changes in the elastic modulus is observed at high temperatures, and much of the strength is retained in both materials up to 1300 K. This means that for most high temperature testing, bars made of tungsten carbide or Inconel would prove beneficial. We suggest the use of Inconel rather than tungsten carbide due to the availability of Inconel rods, the higher ductility of the material, and the lower overall elastic modulus. By selecting an Inconel rod as the rod of choice in a high temperature Hopkinson Bar setup, wave interactions through large thermal gradients would not pose a problem for analysis.
Once the wave interaction issue is solved in high temperature Hopkinson Bar experiments, the desired method to heat the specimen should also be investigated. Many different setups exist for specimen heating, such as resistive, induction, radiant and convection methods. Resistive heating uses electrical current that is subjected to the bars. By using a small specimen, the specimen acts like a resistor and will generate heat. This heat quantity is a function of the geometry and electrical resistivity of the specimen and has a benefit in heating very fast when used with metals. However, resistive heating does not work on electrical insulators, good conductors such as copper, and limits the overall size of the specimens to have a small diameter as compared to the bars.

Radiant methods use infrared energy projected from a heat lamp onto the specimen. The benefit of radiant methods are fast heating times, and they are noncontact. However, radiant methods have trouble in heating specimens uniformly, and are expensive systems at the present time.

Convection systems utilize a chamber that heats the atmosphere enclosing the specimen. These systems are used in many quasi-static load frames because they have the advantage of very uniform heating and are simple and inexpensive to implement. However these system may require hours of time to reach a desired specimen temperatures. Also, high speed videos of these experiments in a Hopkinson bar are very difficult, because the chamber typically has small or no windows for viewing.

Induction heaters utilize high frequency magnetic pulses to induce electrical current in metals. This method is noncontact and requires a few minutes of time to heat a specimen to desired temperature. Like resistive methods, induction heaters cannot heat an
electrical insulator directly. However, induction heating coils can be designed to heat the bars or platens near a specimen if the specimen is an electrical insulator.

Figure 5.2 shows a suggested induction coil setup for heating the bars on both sides of the specimen.

![Proposed induction coil setup for Hopkinson bar.](image)

The benefits of an induction coil setup as shown in Figure 5.2 is that the specimen would have a uniform temperature distribution and be open to be viewed by a high speed camera. Because the bars are being heated up, rather than the specimen, parameters for
controlling the temperature would be less problematic when performing experiments on different materials including low conductivity materials.

Once the heating method is chosen, the final measurement in the system is to measure the temperature throughout the experiment. This measurement is not paramount in many high temperature experiments, however, they play a key role in determining the effect of adiabatic heating: the temperature rise due to plastic work. The two dominant approaches to determine the temperature during a Hopkinson bar experiment are to attach a thermocouple or provide a noncontact pyrometer. In both of these systems the temperature at a single point is measured. The author’s opinion is that the research field will move towards full field thermal measuring as has been the trend in strain measurements via DIC. However, no high speed infrared camera exists with good resolution over 10 kfps. The main reason for this is because high speed cameras require significantly more light to excite the sensors. Infrared thermal imaging necessitates the capturing of light from only the specimen, and is normally a very low quantity. Therefore, the author hypothesizes that the invention of a high speed thermal infrared imaging camera with good resolution and frame rates above 50 kfps will be revolutionary to the dynamic materials community.

5.3 Torsion at Intermediate Strain Rates

Torsion experiments at intermediate strain rates are probably the most underutilized dynamic experimental regime in existence. Because, until recently, experiments have been so difficult to achieve at intermediate strain rates, tension and compression experiments have dominated the focus of research. Torsion tests, being more difficult experimentally, have not seen any attention at intermediate strain rates.
To provide insight into practical methods of torsion testing at intermediate strain rates, the author suggests a modification of the disclosed serpentine bar design to accommodate torsional loading. For tension and compression, impedance matching of the tubes to the initial solid rod was performed by equivalent cross sectional area of each tube. This procedure matches each tube’s impedance to the solid rod. However, in torsional loading this is not the case. Impedance in torsion is a function of the second moment of area, rather than simply the cross sectional area. By determining a Jacobian for the solid rod, and the associated concentric tubes, a new serpentine bar can be developed for torsional loading with the same material and welding procedures.

For torsional loading, direct hydraulic actuation can be accomplished similar to the disclosed direction tension and compression means. Because direct torsional Hopkinson bars have already been in existence for high strain rate experimentation, it follows that intermediate strain rate torsional experimentation may also be important for torsional stress strain relations. Instead of using a double acting hydraulic cylinder for tension, a rotational hydraulic cylinder can be used. This cylinder must have the correct size and pressure requirement for torsion (not known at this point in time). By combining this rotational hydraulic cylinder with the setup and new torsional serpentine bar, robust torsional intermediate strain rate experiments can be performed for the first time.

5.4 Final Thoughts

The work disclosed here shows that the implementation of an ISV plasticity-damage model with a strain rate dependent nucleation damage model and an intermediate strain rate experimental apparatus are important gains in the world of dynamics in materials. The materials and mechanics communities can significantly benefit from these
and other solutions that expand the range of dynamic investigative methods. Dynamic

events span a wide range of strain rates, stress states, and temperatures; being cautious of
dynamic information used in a model and the ability of a model to capture these dynamic
effects are paramount to the future of viscoplastic metals.
5.5 Reference Cited


APPENDIX A

MSU HIGH RATE SOFTWARE MANUAL
A.1  Introduction

The MSU High Rate Software has the ability to provide data analysis for
custom conventional Split Hopkinson Pressure Bar (SHPB) testing as well as Direct Kolsky Bar
testing. The executable was created for use by researchers who do not have access to the
LabView software. However, the VI software, use in conjunction with LabView, can
tailored to fit a researcher's needs.

The current software was created for Windows 7 and cannot be guaranteed to
work on other operating systems. If using other operating systems, one needs to update
the VI for that system.

A.2  Installing and running the executables

Installing software on CAVS computers requires administration privileges. To get
the required privileges, contact Admin. Describe the software you want to download, and
they will give you access to it.

To run the executable, the free LabView 2011 runtime engine must be
downloaded from LabView at the following:
http://joule.ni.com/nidu/cds/view/p/id/2534/lang/en. The page is shown in Figure A.1.
However, clicking on the “Standard Download” will take you to a page where your information is required before downloading. A direct link to the .exe can be found here:


After the LabView 2011 runtime engine is installed, the executable can then be run. There are no licensing agreements with the MSU software.
The executable can be run from the CAVS network at this location: //samba-cavs.hpc.msstate.edu/cmd/data1/common/MSUHighRateSoftware/DataProcessing/MSUJHBTDDataProcessing.exe. If prompted with a security warning dialog box, click “Run” to continue opening the software.

The software should then open and work correctly. If not, try reinstalling the runtime engine.

A.3 Using the software

A.3.1 Settings

After opening the software, the user will be prompted with the Advance Settings window shown in Figure A.2. This window can also be accessed from the settings icon located in the main window.

![Figure A.2 Settings window.](image-url)
Here, the operator chooses whether the test to be analyzed will be performed with a 2 gage setup or a 3 gage setup. A 2 gage setup is typically used in SHPB testing while Direct Kolsky Bar tests typically use 3 gages. Also, the operator chooses whether the test was uniaxial (tension/compression) or torsion. The analysis for tension and compression are the same; therefore, there is no distinction between the two types of tests.

- Click on the Mode tab to choose tension/compression or torsion analysis mode.
- Click on the Gages tab and choose 2 Gages or 3 Gages for the correct test setup.
- Click the Continue tab.

A.3.2 Main Window

After the Settings window is completed, the operator will view the main window shown in Fig. 3. The “Main Window” shows all of the steps to the data processing (Settings, Parameters, Select Data, Select Waves, Correct, Shift) as well as the files that the waves are taken from (Gage 1/A, Gage 2/B, Gage 3/C). A graph in the Main Window shows the raw data once it is imported into the software.
Below is an explanation of what each button on the main window does:

- **Stop ( )** Stops the program from running. Push this button when you need to reanalyze your data. For instance, if you analyze your data and something does not seem correct, push this button to stop the analysis, then push the start button ( ) to begin a new session.

- **Start ( )** Starts the program analysis loop. If the stop button ( ) is pushed, you must push the start button ( ) to run the program.

- **Open File 1 ( )** Opens the test data for the incident (input) bar.

- **Open File 2 ( )** Opens the test data for the transmitted (output) bar if in the 2 Gage Setup. If in the 3 Gage Setup, it will open the second gage data from the incident (input) bar.
- Open File 3 ( ) Opens the test data for the transmitted (output) bar for the 3 Gage Setup only.

- Exit ( ) Exits the software. You can also exit the software by pushing ( ) and then closing the window.

- Settings ( ) Step 1 to the analysis. Here you can select the analysis mode and number of gages.

- Parameters ( ) Step 2 to the analysis. Here you can input all of the necessary setup information for the analysis to correctly analyze the test.

- Select Data ( ) Step 3 to the analysis. Here you can crop out all of the unnecessary test data.

- Select Waves ( ) Step 4 to the analysis. Here you can select which parts of the data correspond to each wave.

- Correct ( ) Step 5 (optional) to the analysis. Here dispersion of the waves is taken into consideration.

- Shift ( ) Step 6 to the analysis. Here the waves are transported to the sample for fine tuning of the analysis. If using the 3 Gage Setup, the true reflected signal in the incident (input) bar is reconstructed.

- Skip Dispersion ( ) Highlight this tab if you want to skip dispersion correction (Step 5).

- Pre-Adjust Shift Waves ( ) This option is only available in 3 gage mode.
A.3.3 Importing Raw Data

In the Main Window, the operator will open the files with the raw strain gage transducer data in the Open File # tabs, with one file for each gage (e.g. for Gage 1, ). The test data must be numerical text data of a single column with no heading. If this is not the conventional test data format for the user's test setup, import the data into Microsoft Excel or another spreadsheet program to be formatted to the required format. When using a 2 Gage setup, the Open File 3 tab cannot be used, because the setup does not require 3 gages. After the files are open, then the operator will begin the analysis.

When the Open File 1 icon ( ) is clicked, the screen shown in Figure A.4 should result. It is likely that the raw data does not have the correct file extensions of 0.1, 0.2, 0.3, or 0.4. Therefore use the All File Type to see the input files in the data loading dialog box.
Click the Open File 1 icon ( ) and select the text file containing the raw data for the incident wave on the incident bar. If the file is not shown, select All Files(*.*) in the Files of type selection menu. If the files still do not appear, examine the folder path to see if you are in the correct directory. When this step is completed, the graph should show your raw data as shown in Figure A.5(a).

Repeat previous step, except instead of clicking the Open File 1 icon ( ), click on the Open File 2 icon ( ) to open the transmitted wave signal (if in 2 gage setup) or the second gage on the incident bar (if in 3 gage setup). If you are analyzing a 3 gage setup, also repeat with the Open File 3 icon ( ). If the Open File 3 icons does not allow you to open a file, click the Stop button ( ) and then click the Start icon ( ) and restart with Importing Raw Data section, but making sure to select 3 Gage Setup. Then proceed with all following steps.
Now that the necessary test data has been opened, the operator can proceed with analyzing the data. Look at the raw data before proceeding to make sure that the data was properly imported. The data from the incident wave (Gage 1/A) should show up in blue while the data from the transmitted signal (Gage 2/B) should show up in red. If in 3 gage setup, the second incident bar gage data (Gage 2/B) will be red while the transmitted signal (Gage 3/C) will be green.

A.3.4 Parameters

The Parameters Window ( ) is used for inputting all of the necessary information into the software for analysis. Be careful when inputting data and make sure that all of the units are appropriate. Inputting wrong values can have profound effects on the analysis of the data.
Open the parameters window by clicking on the Parameters ( ) icon. Figure A.6 shows the Parameters Window.

Input the values described below.

- **Frequency** Here you will input the frequency at which data was sampled during the test.
- **Strain to Volt Factor** (For A, B, & C) Here you will input the conversion factor from the raw test data voltage to a corresponding strain in the bar. This value must be known prior to the test by calibration of the bars.
- **Distance from Sample** (For A, B, & C) Here you will input the distance from the sample (end of the corresponding bar) to the respective gage.
- **Bar Speed** (Incident, Transmitted) Here you will input the speed that the waves travel in the bar. This should be calculated experimentally prior to the test.
- **Bar Diameter** (Incident, Transmitted) Here you will input the diameter of the bars.
- **Bar Density** (Incident, Transmitted) Here you will input the bar density. This should be measured experimentally.

- **Poisson's Ratio** (Incident, Transmitted) Here you will input the Poisson’s ratio for the bars.

- **Incident Bar Elastic Modulus** (Optional) Here you can input a known elastic modulus for calculation of force. Otherwise, the elastic modulus will be calculated by the density and wave speed. 
  \[ E = \rho c^2 \]
  where \( E \) is the elastic modulus, \( \rho \) is the density, and \( c \) is the wave speed.

- **User Defined Constants** (Optional) Here you can enter the dispersion constants for your bars. For elastic bars, use Table A.1 values for a corresponding Poisson's ratio. Or fit the constants experimentally (very tough to do). If no dispersion correction is being used, there is no need to input user defined parameters. See Table 1 for the dispersion values.

### Table A.1: Nonlinear fitting parameters of Bancroft's dispersion data.

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
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<td>12.208</td>
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<td>2.9774</td>
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<tr>
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<td>0.31</td>
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<td>14.602</td>
<td>19.809</td>
<td>-5.0851</td>
<td>1.9895</td>
</tr>
</tbody>
</table>
The graph in the Main window should now show be scaled to strain and time (shown in Figure A.7), rather than voltage and data point (shown in Figure A.5).

![Newly scaled graph after the parameters have been applied.](image)

**Figure A.7** Newly scaled graph after the parameters have been applied.

### A.3.5 Select Data

The Select Data window is used for cropping the unnecessary test data from the analysis. By using the green cursor (top graph of Figure A.8) the beginning of the useful data can be shown in the bottom graph of Figure A.8. The orange cursor is used to select the end of the useful data.
Open the Select Data window by clicking on the Select Data icon ( ).

Move the green cursor in the top data graph to the beginning of the incident wave (Gage 1/A) data. Be careful not to cut off necessary data; it is better to have more data than less.

Figure A.8  Select Data Window
• After the data in the bottom window appears to account for all of the necessary data, but doesn't have too much unusable data, click the Continue icon.

After the Select Data step is completed, the graph in the main window will be reduced to show only the data left over. Notice the graph appearance in Figure A.9 compared to Figure A.5.

![Figure A.9](image-url) Newly scaled graph after the parameters have been applied.

### A.3.6 Select Waves

The Select Waves window ( ) is used to differentiate between which waves are the incident, the reflected, and the transmitted waves. In the 2 Gage Setup, the incident and reflected waves are captured in Gage 1/A data. Select Waves will separate
the Gage 1/A data into two signals. In the 3 Gage Setup, the reflected signal is captured on Gage2/A, however, the incident wave is also captured in Gage 2/A.

Figure A.10  Select Waves window for a 2 Gage Setup.

- Open the Select Waves window by clicking on the Select Waves icon (Select Data). Once opened, a window should appear like Figure A.10. The Select Waves window functionality is similar to the Select Data functionality window in the sense that a green and orange cursor will be used to crop the data used in the calculations. However, here the data for each wave needs to be separated. To do this, the operator must understand what parts of the wave correspond to each wave. Figure A.10 shows the correct portions of the waves highlighted for a 2 Gage Setup.

- Drag the green cursor, in the upper left graph, to the beginning of the incident wave and the orange cursor to the end of the incident wave (between the incident and reflected waves).

- Perform previous point for the upper right graph; only this time drag the green cursor to the beginning of the reflected signal, and the orange cursor to the end of the reflected signal.
• Perform previous point again for the lower graph; only this time drag the green cursor to the beginning of the transmitted wave, and the orange cursor to the end of the transmitted wave. If the signals appear to be rearranged (if the transmitted signal or incident signal is in the wrong graph) simply click in the file path tab above the misrepresented graph and change the path.

• After the correct portions of the waves are contained between the two cursors (green at the beginning and orange at the end), click the Continue tab.

After the Select Waves step is completed, the main window should be updated, with a new legend for the graph differentiating the incident, reflected, and transmitted signals. Notice Figure A.11.

Figure A.11  Main window appearance after the Select Waves step has been completed.
A.3.7 Dispersion

Dispersion correction changes the waves' shape due to the fact that shock waves do not retain their shape as they propagate through material. This step is optional because, in many cases, dispersion can be neglected. This dispersion option is not allowed in torsion tests, however, due to the nature of the wave propagation.

- Either click on the Correct icon or on the Skip Dispersion icon in order to account or neglect dispersion, respectively.

If dispersion is accounted for, then the Main window graph will be updated to include the dispersed waves so that the operator can view the original and dispersed signals as shown in Figure A.12.

![Figure A.12 Updated Main window after dispersion correction was considered.](image)
A.3.8 Shift Waves

The shift waves window, in a 2 Gage Setup, is used to fine tune the position of the waves such that all of the waves begin at the appropriate time. In a 3 Gage Setup, an extra step within the Shift Waves window is used to remove the incident wave from the reflected wave in the Gage 2/B signal. This window is found from the Shift icon ( ). The method for 2 gages is described first:

- Open the Shift Waves window by clicking on the Shift icon. After the Shift Waves window is opened, the window should appear like Figure A.14. Notice that in the Shift Waves that the transmitted signal is does not begin at the same time as the incident and reflected signals. This is because in the Parameters section the Gage distance for Gage 2/B was not exactly correct. The correct gage distance must be measured experimentally, not by simply measuring the distances with a measuring tape, but by analyzing the signals with no sample in between the bars.

- To adjust the waves such that they rise from the same point in time, click on the Wave Select tab to select the wave which you want to adjust. Then use the red cursor in the bottom graph to adjust that wave’s position. If it is hard to tell if the waves line up correctly or not, the waves can be flipped by clicking on the Flip Wave tab. Be careful that the Maintain Flip for Processing tab is not highlighted or the analysis will change the sign of the signal. Figure A.13 shows the details of performing the actions.

- Options in the Shift Wave window
  - **Negate Strain:** Negates Strain values in calculation
  - **Max Size:** Uses the maximum size array in the calculation
  - **Elastic Constant Method:** Option to use the elastic modulus from the Parameters window for calculation of stresses and strains instead of the modulus determined from the wave speed and density.
  - **Use Data Subset:** Uses the minimum or maximum subset for data processing.
  - **Maintain Flip for Processing:** If highlighted, then the flipping of waves in the window will change their sign in the calculations for stress and strain.
Click Continue once all of the waves are shown at their appropriate positions. Once the previous 3 points are completed, the Results window appears as shown in Figure A.15. The results in Figure A.15 show two graphs. The top graph shows the force and velocity vs. time. This allows the operator to get an idea of the strain rate vs. displacement of the sample. The bottom graph shows the incident and transmitted forces vs. time. This graph is necessary for the operator to see if the specimen reached equilibrium early in the test. In the case of Figure A.15, the incident force vs. time had many large oscillations which can be removed with techniques such as pulse shaping.

After the data is viewed and acceptable, click on the Save As tab to save the data. The data that will be saved is the incident and transmitted forces and displacements. The operator can then interpret the data however he/she would like. Typically, the transmitted bar force or the average force is used as the total force of the specimen, and the difference between the bar displacements are used for the displacement of the sample. All other calculations (strain, stress, strain rate, etc.) are done by the operator. Data filtering is not done in this software but can be performed readily in other software such as Matlab, MathCad, and Excel. Data filtering is not recommend as a means of increasing data quality, but does recommend data filtering if necessary to compare to modeling results.

Figure A.13  Moving the incident and reflected waves to begin at the same point.
Figure A.14  Shift Waves window.
Figure A.15 Results window of a compression test with 2 Gage Setup.
APPENDIX B

INTERMEDIATE STRAIN RATE FLAT TENSILE DOGBONE SPECIMEN GEOMETRIES
Table B.1 Specimen designs for tension testing in literature.

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<td>[23]</td>
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Table B.2  Specimen designs for tension testing at different industrial facilities [24].

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<td>ThyssenKrupp Stahl</td>
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