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Dynamic characteristics of metals under elevated temperatures

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DYNAMIC CHARACTERISTICS OF METALS
UNDER ELEVATED TEMPERATURES

by

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Bachelor of Science in Mechanical Engineering
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July 1994

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Mechanical Engineering
Department of Mechanical Engineering
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Graduate College
University of Nevada, Las Vegas
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The Dissertation prepared by

Hui Wang

Entitled

Dynamic Characteristics of Metals Under Elevated Temperatures

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ABSTRACT

Dynamic Characteristics of Metals Under Elevated Temperatures

by

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Metals such as Stainless Steel 316L, Titanium Grade 7, and Alloy C22 must withstand structural deformation caused by static, thermal, and impact loads. Among the most important characteristics for metals is their integrity in case of accidents, where it may be subject to dynamic loads under elevated temperatures. This thesis attempts to experimentally identify properties of the three above mentioned metals at elevated temperature [70°F-350°F] and under different strain rates [10^{-4}-10^{2} \text{ sec}^{-1}].

The thesis will investigate the effect of temperature and strain rate on the dynamic properties of the metals. First of all, candidate metals were introduced; Second of all, the two testing systems, namely MTS and Instron Dynatup 8250 testing machines, were identified; finally, evaluation of the candidate metals testing results and verification of these testing results using finite element analysis is performed. Results showed that yield and ultimate strength of the three candidate metals decreased with temperature. Results also showed that strain at failure increases with temperature for Titanium Grade 7 and
Alloy C22, but decreased for Stainless Steel 316L. Verification of these results using Finite Element Analysis had less than 10% error.
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CHAPTER 1

INTRODUCTION

1.1 Introduction

Metals usually show distinct characteristics under dynamic load at elevated temperature compared to static and quasi-static conditions, it is necessary to understand these properties of metals accurately, which is a prerequisite condition for designing mechanical systems. The focus of this thesis is to experimentally determine the mechanical properties of the three candidate metals under different dynamic load at elevated temperatures and to simulate the experiment computationally.

1.2 Background

With the development of the science of metals, the fact that metals show a different behaviour when they undergo dynamic loading is widely accepted. It is well known that there is a general tendency to increase the flow stress and decrease the metal toughness with an increased rate of loading. The engineering tension Test, a fundamental tool for evaluating the properties of the metals, is well developed. Hopkinson (3) and Mason applied tensile stress pulses to wires by means of a falling tup. Ginns, using a spring mechanism to apply a sudden load and a resistance-pressure gauge to measure the
stress, was one of the first to attempt the direct recording of a dynamic stress-strain curve. Later, Brown and Vincent, with a pendulum-type impact machine and using piezoelectric crystals to measure stress, obtained load-elongation curves directly on an oscilloscope screen. Fanning and Basset developed the technique of impact strain measurement by means of electrical resistance strain gauges; Warnock and Taylor developed a technique to produce dynamic stress-strain curve using a repeated impact method. At the same time Kolsky introduced the Split Hopkinson Pressure bar (SHPB) apparatus, which made it possible to reach strain rates between 100 and 1000 sec\(^{-1}\). Apart from Hopkinson and Mason, most investigators up to this time had ignored the effects of stress wave propagation in the specimen, assuming that the stress measured at the end of the specimen was equivalent to the stress throughout the specimen. Guest concluded that where impact velocities were sufficiently high, the propagation and reflection of stress waves within the test apparatus, if ignored, were likely to produce significant errors in the results. This was proven later, when Clark and Duwez applied the theory of plastic wave propagation to the results of earlier tensile tests. These early endeavors for development established the basis of understanding of metal properties under high strain rates. However, they did not provide a systematic approach of testing for the whole range of strain rates. We must emphasize that tensile testing at whole range of strain rate is quite inadequate for design application. Due to insufficient information of the behavior of different metals under dynamic load, static and quasi-static conditions, which are substituted for dynamic conditions, are usually used in the impact analysis, thereby resulting in inaccuracy, a significant error compared with the practical result.
1.3 Classification of Dynamic Tension Testing Machines

Mechanical properties such as strength and ductility can vary with the strain rate, the rate at which a specimen is deformed. This rate can have an important influence on the mechanical properties, particularly the flow stress of materials. Strain rate, which can be defined as the rate of strain, \( \varepsilon \), with respect to time, \( t \):

\[
\dot{\varepsilon} = \frac{de}{dt} \quad (1-1)
\]

Where \( \varepsilon \) can represent either engineering or true strains. The strain rate is measured in \( \text{sec}^{-1} \). The strain rate regimes, which play a key role in choosing the appropriate machine in impact experiment, are summarized in Table 1-1.

<table>
<thead>
<tr>
<th>Strain rate regime</th>
<th>Experimental techniques</th>
<th>Wave propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low rate: ( \varepsilon &lt; 0.1 \text{ sec}^{-1} )</td>
<td>Standard mechanical testing procedures</td>
<td>Not significant</td>
</tr>
<tr>
<td>Medium rate: ( 0.1 \text{ sec}^{-1} \leq \varepsilon \leq 200 \text{ sec}^{-1} )</td>
<td>Servo-hydraulic frames, cam plastometer, drop test</td>
<td>Influences Load measurement</td>
</tr>
<tr>
<td>High rate: ( 200 \text{ sec}^{-1} \leq \varepsilon \leq 10^5 \text{ sec}^{-1} )</td>
<td>Hopkinson pressure bar, Rod impact (Taylor) test</td>
<td>Affects uniform stress approximation Analysis required for interpretation of results</td>
</tr>
<tr>
<td>Very high rate: ( \varepsilon &gt; 10^5 \text{ sec}^{-1} )</td>
<td>Flyer plate impact</td>
<td>Critical</td>
</tr>
</tbody>
</table>
For low strain rate testing $\dot{\varepsilon} < 0.1 \text{ sec}^{-1}$, the tensile testing machine typically used is as shown in Figure 1-1. It consists of two heads (3) that are equipped with clamping mechanisms, which are used to fix a specimen (5). The driving mechanism could be mechanical (power screw) or hydraulic. Usually, the lower clamping head is attached to the base (4) while the upper head is attached to a sliding bar (2), which leads it along the guides (1).

![Figure 1-1 Tensile Testing Machine Setup [30]](image)

For the strain rate ranging from 0.1 sec$^{-1}$ to 200 sec$^{-1}$, drop weight or pendulum testing machines can be used to conduct testing within this range though wave
propagation has some effect on the load measurements. This testing machine is usually
used for puncture tests of plate specimens. A typical drop weight tower-testing machine
shown in Figure 1-2.

![General Drop Weight Tower Impact Machine Setup](image)

**Figure 1-2  General Drop Weight Tower Impact Machine Setup [30]**

A. Tup (1) that slides along guides (3), which is used for the impact
loadin of the specimens. The tup mass can be varied to meet
different conditions of impact loading.

B. The tup and an attached striker (2) are raised to the desirable
height and then released to impact the specimen. Load cells could
be positioned either in the stationary part or on the tup.
C. This type of testing equipment is used to measure several variables including maximum fracture load, amount of absorbed energy, displacement in the fracture zone and velocities of the striker.

High strain rates (\( \varepsilon > 200 \text{ sec}^{-1} \)) require a split Hopkinson pressure bar because propagation of stress waves can have significant effect on the measurement of loads at strain rate. The most typical setup of the equipment is shown in Figure 1-3.

![Figure 1-3 A Typical Split Hopkinson Pressure Bar](image)

The Typical Split Hopkinson Pressure bar consists of two elastic pressure bars that sandwich the sample between them. Typically, striker bar is propelled toward the input bar. When the striker bar hit the incident bar, an elastic compressive wave is generated with the incident bar. Strain gage A, located at the midpoint of the incident bar, can measure the time-dependent strain. At the incident bar and sample interface, the wave is partially reflected and partially transmitted into the specimen. The portion that is reflected travels back along the incident bar as a tensile wave, and the strain, is measure by strain gage A. compressive strain, associated with the portion of the wave that is
transmitted through the sample into the transmission bar, is measured by strain gage B, located at the midpoint of the transmission bar. When the specimen is deforming uniformly, the strain rate within the sample is directly proportional to the amplitude of the reflected wave. The stress within the sample is directly proportional to the amplitude of the transmitted wave. The former integrated to yield strain, and combined to give the dynamic stress strain curve.

The one-dimensional technique of Split Hopkinson Pressure bar is based on the assumptions described as follows:

1. Uniform axial stress distribution in the specimen
2. Uniaxial conditions in the specimen can be affected by the presence of frictional forces that can cause radical traction at the interfaces between the specimen and the pressure bar.

1.4 Elevated Temperature Testing

Elevated temperature tension tests are conducted with the same specimens and procedures as room temperature tension test except the items list below:

1. The specimens must be heated in an appropriate environmental chamber.
2. The test fixture must be sufficiently strong and corrosion resistant.
3. The strain measuring system must be usable at the test temperature.
1.4.1 Temperature control in elevated temperature testing

The actual temperature must be within a few degree variance of the desired temperature, and it shouldn’t fluctuate with time or vary along the gage length. Thermocouples, which monitor the temperature, are attached near each end and at the center of the gage length. Due to the dependence of plastic flow mechanisms and materials behavior on temperature, proper control of temperature and minimization of thermal gradients along the specimen gage length are important. For instance, specimen “hot spots” generally will be weaker than the remainder of the specimen and can become sites for localized deformation and premature failure, thus leading to inaccurate and misleading tensile data.

1.4.2 Material behavior under elevated temperature

Stainless Steel 316L is an austenitic chromium-nickel stainless steel containing molybdenum. This addition increases general corrosion resistance, improves resistance to pitting from chloride ion solution, and provides increased strength at elevated temperature. Table 1-2 describes the basic properties of Stainless Steel 316L at elevated temperature.

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>UTS (ksi)</th>
<th>0.2%YS (ksi)</th>
<th>Elongation% in 2” (50.8mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>81.0</td>
<td>35.0</td>
<td>51</td>
</tr>
<tr>
<td>600</td>
<td>78.0</td>
<td>31.0</td>
<td>48</td>
</tr>
<tr>
<td>800</td>
<td>76.0</td>
<td>27.5</td>
<td>47</td>
</tr>
<tr>
<td>1000</td>
<td>70.0</td>
<td>24.0</td>
<td>44</td>
</tr>
<tr>
<td>1200</td>
<td>57.0</td>
<td>21.0</td>
<td>40</td>
</tr>
<tr>
<td>1400</td>
<td>35.0</td>
<td>18.0</td>
<td>37</td>
</tr>
<tr>
<td>1600</td>
<td>24.0</td>
<td>16.0</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 1-2 Elevated Temperature Properties of Stainless Steel 316L
Grade 7 is unalloyed titanium with a nominal amount (0.12-0.15%) of palladium added. The strength limits for titanium alloy at elevated temperature are divided into two ranges. Up to 600°F, the strength of titanium is limited to the yield strength of the alloy, because there is virtually no effect of creep in that range. Beyond 600°F creep strength becomes the controlling factor. The Data are tabulated in Table 1-3:

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Minimum Strength (ksi)</th>
<th>Percent of R.T. Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.T.</td>
<td>40</td>
<td>100%</td>
</tr>
<tr>
<td>200</td>
<td>37</td>
<td>92%</td>
</tr>
<tr>
<td>300</td>
<td>32</td>
<td>80%</td>
</tr>
<tr>
<td>400</td>
<td>26</td>
<td>65%</td>
</tr>
</tbody>
</table>

Alloy C22 is a Ni-Cr-Mo alloy that provides good resistance to pitting, crevice corrosion and stress corrosion cracking. The combination of Cr, Ni, Mo, and W provides very good resistance to oxidizing and reducing environments. This alloy poses high strength, good ductility, excellent welding and forming characteristics.

1.5 Objective of the Research

Though a wide range of strain rate testing has been conducted for many years, there are no well-documented data on different materials similar to those of mechanical properties under quasi-static loading at elevated temperatures. Search of references for mechanical properties for candidate materials such as, Stainless Steel 316L, Titanium Alloy Grade 7, and Alloy C22 obtained under low and medium strain rate under elevated temperatures rated failed.
The goal of this project is to create an alternative technique for determination of material properties under low and moderate strain rates at elevated temperatures. The scope of the research is focused on determination of the following mechanical properties of above listed materials:

1. Yield Strength
2. Ultimate Strength
3. Strain at Yield stress
4. Strain at Ultimate stress
5. Total elongation
6. Reduction of Area
CHAPTER 2

TESTING MACHINES, FIXTURES AND MATERIALS

2.1 Introduction

In this chapter, two tensile testing machines, namely Instron Dynatup 8250 and MTS testing machine, are introduced in detail. Also, the fixtures of the two testing machines are briefly introduced. Finally, mechanical and chemical properties for the metals are identified.

2.2 Specimen for MTS and Instron Dynatup Testing Machine

The geometric dimension of the specimen is presented in Figure 2-1:

![Figure 2-1 Geometry of the Specimen](image)

Figure 2-1  Geometry of the Specimen
2.3 Description of the Equipment

2.3.1 Description of the Instron Dynatup Impact Testing Machine

The Instron Dynatup 8250 is a drop weight type of impact testing system. It consists of a number of elements that are shown in Figure 2-2. The primary components of the Instron Dynatup 8250 impact testing machine, include a weight (1), load cell (2), striker (3), tup guides (4), brakes (5), environmental chamber (6), control panel (7), computer with data acquisition system (8), specimen support fixture (9), “flag” that is used to start the data collecting process (10) and a stationary trigger mechanism (11) that sets a signal to data acquisition board once the “flag” passes through it.

![Diagram of Instron Dynatup 8250 Impact Testing Machine Components.](image)

Figure 2-2  Instron Dynatup 8250 Impact Testing Machine Components.
Maximum and minimum values of velocities and energies for each of the main working modes of the Instron Dynatup 8250 impact test machine are presented in Table 2-1. View of the installed machine is presented in Figure 2-3.

Table 2-1  Characteristics of Instron Dynatup Testing Machine

<table>
<thead>
<tr>
<th>Working Parameters</th>
<th>Gravity-Driven</th>
<th>Pneumatically-Assisted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Impact Energy (lbf in)</td>
<td>6.00</td>
<td>2,688.00</td>
</tr>
<tr>
<td>Impact Velocity (in/sec)</td>
<td>24.00</td>
<td>144.00</td>
</tr>
</tbody>
</table>

Figure 2-3  Instron Dynatup 8250 Impact Testing Machine.

The Instron Dynatup environmental chamber allows for the physical testing of materials in either a high or low temperature environment. The unit features a removable
side panel that houses the blower, heating, and cooling systems as well as all electrical connections that run to the remote control unit. A microprocessor-based controller controls the temperature within the chamber. It has two output controls for both types of heating. Heating of the chamber is accomplished by means of a 1.3 kW open coil heater since it provided a quick response to controller demands. The chamber is also provided with an expendable gas cooling system, which utilizes either liquid nitrogen or liquid carbon dioxide. The temperature range is $-100^\circ\text{F}$ to $350^\circ\text{F}$.

![Diagram of Eurotherm 808 Controller of Instron Test Machine]

Figure 2-4  Eurotherm 808 Controller of Instron Test Machine

The light against OP1 will light up if it is heating and OP2 lights up if it is cooling. The lower four buttons are to enable the heating or cooling. FAN is used for
circulation of air within the chamber. ENABLE is used to start the heating or cooling process.

This machine uses a load cell calibrated to the load of 5000 lbf. The data measured by the load cell is collected by the data acquisition system. The Instron Dynatup drop weight testing machine incorporates 930-I data acquisition software. This software allows creation of custom test setup, test reports and export data files. The software that records 4096 data points within the given time frame of the experiment allows quickly obtaining curves of load, time, velocity, or deflections right after the test. Using the set-up procedure, a number of different tests can be arranged. The tests can be conducted in gravity mode and using a pneumatic assist. The former allows increasing velocity of the tup to 528 in/sec. Selection of the mode as well as selection of automatic tup return to the pre-selected height is done with the help of control panel shown in Figure 2-5. The Control panel is also used to lunch the tup to run the impact test.

There are a few options for triggering the mechanism of data collection. One of the most convenient options is the 'Flag trigger mode'. This type of data collection triggering initiates data collection process when the second leading edge of the double-edged 'flag', shown in the Figure 2-6, passes through the 'Velocity Detector', shown in Figure 2-7. This option of data collection initiation allows not only starting the data acquisition system right before the collision of striker and the specimen but also allows obtaining velocity of the tup prior to the impact, which in turn is used to calculate the displacement and energy.
Figure 2-5  Control Panel of Instron Dynatup Testing Machine

Figure 2-6  Instron Dynatup 8250: Close Up View of the ‘flag’
A built-in security system prevents running the equipment with an open access door. Safety “H” bar is used when installing and uninstalling the specimens.

Despite of the availability of many convenient features, this impact machine could not be used for the impact tensile testing of cylindrical specimen without certain modifications. Original design of the machine and the clamping fixture that was provided by the manufacture was designed for puncture test of plate type specimens. This fixture could not be used for the tensile testing. An original fixture was designed and fabricated to meet all the requirements of the testing in the environmental chamber for this project.

2.3.1.1 Instron Dynatup Environmental Fixture

Steel 4130 Annealed material is chosen for Instron Dynatup fixture. The mechanical properties of this material are presented in the Table 2-2. The Instron Dynatup Fixture is shown in Figure 2-8.
Table 2-2  Fixture Material Characteristics

<table>
<thead>
<tr>
<th>Fixture Material</th>
<th>Stress values (psi)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Stress (Su)</td>
<td>Yield Stress (Sy)</td>
<td>Young’s Modulus (E)</td>
</tr>
<tr>
<td>Steel 4130 Annealed</td>
<td>$81.2 \times 10^3$</td>
<td>$52.2 \times 10^3$</td>
<td>$29.00 \times 10^6$</td>
</tr>
</tbody>
</table>

Fig 2-8 Exploded View of Instron Dynatup fixture

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2.3.2 Description of the MTS Tensile Testing Machine

MTS tensile testing equipment is used for carrying out tensile and torsion tests of materials. The MTS testing system is composed of a number of integrated systems, as shown in Figure 2-9. It includes a load frame (1), a load unit control panel (POD) (3), grip supply (4), temperature controller (6), strain gage conditioner (5), computer (2), control box (7), hydraulic service manifold (8), hydraulic pump (9) and an environmental chamber (10).

The hydraulic grip supply is used to apply gripping pressure to the specimen during a test. Loading and unloading a specimen is accomplished with the four knobs on top. A dial indicator inside the cabinet displays the current gripping pressure. The pressure is controlled by a combination of air and hydraulic fluid. The maximum gripping pressure (6500 psi) of this supply unit can easily crush many soft materials. It is necessary to check the desirable gripping pressure before installing the specimen. View of the installed machine is shown in Figure 2-10.

The top of the grip supply is shown schematically in Figure 2-11. The four knobs shown are used to operate the grips. The two knobs on the right are used to open and close the lower grips. The two knobs on the left are used to open and close the upper grip.

The MTS Control Unit houses all the electronic signal conditioners and controllers for the hydraulic components. It is the piece of hardware that links the computer, testing machine, grips, and hydraulic supply altogether. The Hydraulic Service Manifold regulates supply to the actuator and grip supply unit. The Hydraulic Pump represents the pump and the reservoir for the hydraulic system.
Figure 2-9  MTS Tensile System Components

Figure 2-10  MTS Tensile System
The hydraulic wedge grips hold a set of customized blocks for mounting threaded specimen samples. Figure 2-12 shows major components of the MTS load frame, which includes an adjustable crosshead (1), Axial/Torsional Load Transducers (2), Wedge Grips (3), Crosshead Controls (4), LVDT (5), ADT (6), Linear Actuator (7), Rotary Actuator (8) and Environmental Chamber (9). Load Frame Specifications of the MTS Tensile/Torsion material testing system are presented in the Table 2-5.

![Figure 2-11 Hydraulic Grip Supply Controls](image-url)
Each actuator has two control modes. The linear actuator can be controlled by force or displacement. These controls can be operated automatically by the computer or manually by using the POD. The rotary actuator can be controlled by torque or angle. These controls can also be operated automatically by the computer or manually by using the POD. The POD elements are shown in Figure 2-13.
The Load Unit Control Panel shown in Figure 2-13 includes the following components: emergency stop button (1), Display (2 windows) which are toggled on/off with the “Next Pane” button (2), display controls (3), test controls, which are duplicated on the computer screen, interlocks (4), Interlocks (5), power control for main pump (6),
power control for service manifold (7), linear actuator control (8), and rotary actuator control (9).

The MTS high temperature environmental chamber (Figure 2-14) with model no. 652.02 is designed for low-cycle fatigue, fatigue rack growth, and fracture toughness testing at temperatures from 200 °C up to 1000 °C. The furnace is configured with two independent heating zones to improve the temperature gradient across the test specimen. A viewing window is available to monitor the specimen during the test. Technological parameters of this chamber are listed in Table 2-3.

Figure 2-14 MTS Environmental Chamber
Table 2-3 Specifications of MTS Environmental Chamber (Model No. 652.02)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temperature</td>
<td>1000°C</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>200°C</td>
</tr>
<tr>
<td>Control point stability</td>
<td>+/- 1°C</td>
</tr>
<tr>
<td>Overall Height</td>
<td>260mm (10.25 in)</td>
</tr>
<tr>
<td>Hot zone height</td>
<td>210mm (8.25 inches)</td>
</tr>
<tr>
<td>Hot zone width</td>
<td>125mm (5 inches)</td>
</tr>
<tr>
<td>Hot zone depth</td>
<td>125mm (5 inches)</td>
</tr>
<tr>
<td>Number of zones</td>
<td>2</td>
</tr>
</tbody>
</table>

2.3.2.1 MTS Environmental Fixture

Steel 1045 Annealed material is chosen for MTS fixture. The mechanical properties of this material are presented in the Table 2-3. The assembly of MTS fixture is shown in figure 2-15.

Table 2-3 Fixture Material Characteristics

<table>
<thead>
<tr>
<th>Fixture Material</th>
<th>Stress values (psi)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Stress (Su)</td>
<td>Yield Stress (Sy)</td>
</tr>
<tr>
<td>Steel 1045 Annealed</td>
<td>$108.9 \times 10^3$</td>
<td>$74.84 \times 10^3$</td>
</tr>
</tbody>
</table>

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2.3.3 Candidate Materials

This project studies three candidate metals, namely Alloy C22, Stainless Steel 316L and Titanium Grade 7. Typical chemical composition of the materials is tabulated in the Tables 2-4 through 2-6. The data is obtained from the manufacturer’s specification in purchasing sheet (Lab Testing Company).
<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.0004</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.004</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.03</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.16</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.96</td>
</tr>
<tr>
<td>Tungsten</td>
<td>2.94</td>
</tr>
<tr>
<td>Iron</td>
<td>3.87</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>13.30</td>
</tr>
<tr>
<td>Chromium</td>
<td>21.40</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.011</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.24</td>
</tr>
<tr>
<td>Nickel</td>
<td>Balance</td>
</tr>
</tbody>
</table>
Table 2-5  Chemical Composition of Stainless Steel 316L

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.023</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.026</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.027</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.049</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.42</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.52</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.09</td>
</tr>
<tr>
<td>Chromium</td>
<td>17.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>10.46</td>
</tr>
<tr>
<td>Copper</td>
<td>0.38</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.13</td>
</tr>
<tr>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>
Table 2-6 Chemical Composition of Titanium Grade 7

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>-</td>
</tr>
<tr>
<td>Vanadium</td>
<td>-</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>-</td>
</tr>
<tr>
<td>Nickel</td>
<td>-</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.0045</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>&lt;0.010</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.01</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.17</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.1</td>
</tr>
<tr>
<td>Iron</td>
<td>0.05</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Mechanical properties of these materials are provided in Table 2-7. From the references for Alloy C22, Stainless Steel 316L, Titanium Grade 7, the modulus of elasticity of the materials is obtained. Other mechanical properties are obtained from manufacturer's technological parameters.
Table 2-7  Mechanical Properties of Selected Metals

<table>
<thead>
<tr>
<th>Material/Properties</th>
<th>Titanium Grade 7</th>
<th>Stainless Steel 316L</th>
<th>Alloy C22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (ksi)</td>
<td>46.70</td>
<td>86.30</td>
<td>47.00</td>
</tr>
<tr>
<td>Ultimate Strength (ksi)</td>
<td>68.60</td>
<td>101.40</td>
<td>108.0</td>
</tr>
<tr>
<td>Strain at Fracture (%)</td>
<td>35.90</td>
<td>42.00</td>
<td>66.00</td>
</tr>
<tr>
<td>Young's Modulus (ksi)</td>
<td>$15.00 \times 10^3$</td>
<td>$29.00 \times 10^3$</td>
<td>$30.00 \times 10^3$</td>
</tr>
</tbody>
</table>

NOTE: DATA PROVIDED BY LAB TESTING COMPANY
CHAPTER 3

DATA MANIPULATION PROCEDURE

3.1 Introduction

This chapter presents a procedure for manipulation of the data acquired from Instron Dynatup and MTS testing machine respectively. The procedure is used to transfer the raw data files from the data acquisition software of Instron Dynatup and MTS machine to the processed data files including mechanical properties of the materials according to the QA procedures.

3.2 Measurement of the Specimen

After the completion of the test, the broken specimen is taken out from the fixture and then the two part fragments are mated along the fracture surface in a soft medium such as modeling compound or molding clay. The reconnected specimen is used to measure two dimensions: total length of the specimen and the smallest final diameter of the specimen near the fracture surface. Upon obtaining these measurements allow us to calculate the total elongation and reduction of area of the specimen are calculated using equations (3-1) and (3-2) respectively.
\[ \varepsilon_f = \frac{l_f - l_o}{l_o} \cdot 100\% \] (3-1)

Where \( l_o \) and \( l_f \) stand for the original and the final gage lengths of the specimen.

\[ \delta_f = \frac{A_o - A_f}{A_o} \cdot 100\% \] (3-2)

Where \( A_o \) and \( A_f \) stand for the original and the final cross sectional areas of the specimen measured within the gage of the specimen.

3.3 Preliminary Data Processing

After completion of the experiment, the data file is transferred to Microsoft Excel for data analysis. The Instron Dynatup data files have the following columns of data (units): Load (Pounds), Deflection (inches), Time (milliseconds), Energy (Pound-feet) and Velocity (Feet/second). The MTS data files have the following columns of data (units): Time (millisecond), Displacement (inches), Load (Pounds).

The following steps are taken to verify accuracy of the data transfer process for both procedures:

1. All the cells containing measurements are highlighted and specified as “Number” entries in the ‘Format cell’ menu command.
2. Visual inspection of the exported file information is carried out.
3. Random individual entries in the imported file are compared with the same entries.
4. A number of curves, such as, load versus time, load versus displacement, velocity versus time, or energy versus time, are plotted in order to check the anomalies data by visual inspection.
5. Accurately transferred and checked data is then saved with the same unique identification number used for the tested specimen.

6. The row including the negative values of the load, displacement or time is eliminated except for the two rows located before and after the positive load measurement.

7. In the new spread sheet, a number of calculations are carried out to get some mechanical properties such as Engineering Strain, Stress, True Strain, Strain Rate and Average Strain Rate.

8. A stress-strain curve is plotted based on the above calculation using Ms-Excel. A typical stress-strain curve includes two regions, one is the elastic region, the almost-linear segment with large slope value, and the other is plasticity region, the reminder of data for the whole region.

3.4 Instron Dynatup and MTS Data Handling Steps

As mentioned in chapter 1, wave propagation plays a role in the impact testing. It has insignificant effect to load measurement for MTS, but for Instron Dynatup, it accompanies some noise that can lead an inaccuracy data. On the basis of this, different handling procedures are carried out for Instron and MTS machine.

3.4.1 Instron data handing steps

In order to eliminate the noise in the raw stress-strain curve, a program is written in Matlab software, which fits the elastic portion with a 6th order polynomial. In most of the cases, the stress-strain curves produced in Instron testing exhibit initial low stress bump. Some curves (Figure 3.1) had a bump near the first peak in the elasticity region of
the raw data; others (Figure 3.2) are smooth in the elastic region. The determination of the lower boundary of the yield strength is similar in both cases. But, the determination of upper boundary is slightly different as described below.

![Graph](image)

Figure 3-1 Raw Curve of Typical Titanium Specimen (#19TEn)

Yield strength of the specimen was determined by averaging lower and upper boundaries of the yield strength region. The determination of lower boundary of the yield strength is based on the stress-strain curve corresponding to the elastic region.
For the cases where the curve is smooth in the elastic region, the upper boundary was determined by averaging the values of the first two extreme averages in the plastic region. But for the cases where there is a bump near the first peak in the elastic region, the average of the maximum value of the bump and the first extreme average of the plastic region is the upper boundary of the yield strength.

Both procedures along with the plastic region data analysis are shown in Figure 3-3 and Figure 3-4.
Figure 3-3  Creation of the Composite Curve for the Intron Dynatup Test Results

Figure 3-4  Creation of the Composite Curve for the Intron Test Results
For both cases, the global maximum of the first derivative of the fitted curve corresponds to the point of the stress-strain curve with maximum slope value. The lower boundary of the yield strength region is shown in Figure 3-5. The Portion of the Engineering Stress-Strain Curve corresponding to elastic region is shown in Figure 3-6.

Figure 3-5  First Derivative of the Stress-Strain Portion #04TEn
Upon obtaining the yield strength, the corresponding yield strain was redefined using equation between stress ($\sigma$) and Young's modulus of elasticity ($E$):

$$
e = \frac{\sigma}{E}$$  \hspace{1cm} (3-3)

Thus strain at yield established a needed reference point for shifting the rest of the stress-strain curve and modifying the entire range of strain values.

1. The midpoints of the plastic region waves were determined by averaging each two consecutive extreme points.

2. Ultimate strength of the tested material was determined by selecting the maximum average from a number of values computed in step 2.
3.4.2 Composite curve

Upon completion of data handling process and determination of the yield strength and strain corresponding to it along with the average values in the plastic region, a composite curve was created (Figure 3-7). A composite curve for the Instron Dynatup test result consisted of three segments.

1. First segment is a straight line that starts from (0,0) and ends at (Sy/E, Sy)
2. Second segment of the curve is represented by the set of data points obtained by averaging the extreme points of the isolations.
3. Third segment of the curve consisted of the data points collected by the data acquisition software, which were added starting from the last average value and ending at the last relevant data point.

Figure 3-7  Composite Engineering Stress-Strain Curve (#04TEn)
3.4.3 Verification of the results

The results acquired by creating the composite curve using the data collected by the data acquisition software are verified with the actual elongation of the specimen.

3.5 MTS Data Handling Steps

The determination of yield stress was designed based on the stress-strain curve corresponding to the elastic region.

Using the curve representing second derivative of data presented in Figure 3-8, it was determined that the average of strain at the first local minimum and the second local maximum of the curve corresponded to the strain of the yield strength of the material. Figure 3-9.

![Second Derivative of the Stress/Strain Curve](image)

**Figure 3-8** Second Derivative of the Stress-Strain Portion #09MSEn

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Upon obtaining the yield strength the strain that corresponds to it was redefined using equation between stress and Young's modulus of elasticity we mentioned in equation (3-3):

Thus strain at yield established a needed reference point for shifting the rest of the stress-strain curve and modifying the entire range of strain values.

3.5.1 Composite curve

Upon completion of data handling process and determination of the yield strength and strain corresponding to it, a composite engineering stress-strain curve was created. A composite curve for the MTS test result consisted of two segments.
1. Segment was a straight line that started from \((0,0)\) and ended at \((\frac{Sy}{E}, Sy)\).

2. The data points starting from the yield strength and ending at the last relevant data point acquired by the data acquisition software represented second section of the curve.

Strain values were shifted by the value equal to the difference between strain at yield determined from the equation (3-7) and strain at yield acquired by data acquisition software of MTS testing machine. An example of the composite curve is shown in Figure 3-9.

![Composite Engineering Stress-Strain Curve](image)

**Figure 3-10** Composite Engineering Stress-Strain Curve # 09MSEn
3.5.2 Verification of the results

The results acquired by creating the composite curve are compared with the actual elongation of the specimen.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents test results obtained using the Instron Dynatup and MTS machine. All experiments were conducted according to the testing procedures described previously [refer to IP]. Also, Data manipulation is performed according to the data handling procedure presented [refer to APPENDIX I]. Three different metals were tested at a series of different strain rates and elevated temperatures. Results presented in this chapter show the change of mechanical properties of metals depending on the strain rate and temperature. Results of individual specimens are shown in APPENDIX III.
4.2 Stainless Steel 316L

Fifty-two tensile steel specimens were tested to acquire mechanical properties of this metal at a series of strain rates and elevated temperatures. The following figures summarize the experimental results obtained during testing.
Figure 4-1  Variation of Yield Strength with Strain Rate (Steel)

Figure 4-2  Variation of the Ultimate Strength with Strain Rate (Steel)
Figure 4-3  Variation of the $S_y/S_u$ ratio with Strain Rate (Steel)

Figure 4-4  Variation of the Reduction of Area with Strain Rate (Steel)
Figure 4-5  Variation of the Strain at Ultimate Strength with Strain Rate (Steel)

Figure 4-6  Variation of the Strain at Failure with Strain Rate (Steel)
4.3 Alloy C22

Fifty-two tensile Alloy C22 specimens were tested to acquire mechanical properties of this metal at a series of strain rates and elevated temperatures. The following figures summarize the results showing experimental results obtained during testing.
Figure 4-8  Variation of the Yield Strength with Strain Rate (Alloy C22)

Figure 4-9  Variation of the Ultimate Strength with Strain Rate (Alloy C22)
Figure 4-10  Variation of the $\frac{S_y}{S_u}$ Ratio with Strain Rate (Alloy C22)

Figure 4-11  Variation of the Reduction of Area with Strain Rate (Alloy C22)
Stain at Su Versus Strain Rate

\[ y = 0.4876x^{0.9481} \]

Figure 4-12 Variation of Strain at Ultimate Strength with Strain Rate (Alloy C22)

Strain at Failure Versus Strain Rate

\[ y = 0.7321x^{0.028} \]

Figure 4-13 Variation of the Strain at Failure with Strain Rate (Alloy C22)
4.4 Titanium Grade 7

Sixteen tensile Titanium specimens were tested to acquire mechanical properties of this metal at a series of strain rates and elevated temperatures. The following figures summarize the results showing experimental results obtained during testing.

Figure 4-14  Variation of the Strain Error with Strain Rate (Alloy C22)
Figure 4-15  Variation of Yield Strength with Strain Rate (Titanium Grade 7)

Figure 4-16  Variation of the Ultimate Strength with Strain Rate (Titanium Grade 7)
Figure 4-17 Variation of the $S_y/S_u$ ratio with Strain Rate (Titanium Grade 7)

Figure 4-18 Variation of the Reduction in Area with Strain Rate (Titanium Grade 7)

55
Figure 4-19  Variation of the Strain at Su with Strain Rate (Titanium Grade 7)

Figure 4-20  Variation of the Strain at Failure with Strain Rate (Titanium Grade 7)
CHAPTER 5

COMPUTATIONAL SIMULATION AND VERIFICATION

5.1 Introduction

The objectives of this chapter is to simulate testing of specimens by using commercial Finite Element Analysis software and then compare results of simulation with that of experiment using Instron Dynatup testing machine. First, previous work is introduced, and then validation of simulation is evaluated.

5.2 Introduction of Finite Element Modeling Package

Generally, a finite element process procedure includes the following three stages: Pre-processing includes creating geometry properties of the modeled object, defining element type and materials, defining mesh, and giving boundary conditions. Solution includes assigning loads, constraints and solving. Post-processing includes further process and viewing the results. In this project, ANSYS is being used as the pre-processor, LS-DYNA is used for solution, and HYPERVIEW and LS-POST are being used as the Post-processor.
5.3 Introduction of Previous Work by Sirisha Dusi

The following geometric model was defined: specimen, receiver, and complete_striker [with weight, load cell, load cell extension rod and striker] as shown in Figure 5-1. Specimen was defined as MAT 24 [34], Complete_striker was defined as MAT 20 [34], and the receiver was defined as MAT 3 [34]. The upper surface of the specimen is fixed and two contact relations were defined: one is the surface between the lower striker and the upper receiver, the other is the surface between the lower specimen and the upper receiver, initial velocity is applied to the complete_striker. Then the problem is successfully solved in LS-DYNA solver. Results shows the error is less than 10% compared to the result of the experiment.
5.4 Procedures of Finite Element Analysis

The following geometric model was defined in the new model: specimen, receiver, the complete load cell (with load cell, load cell extension rod, weights) and striker as shown in Figure 5-5.

5.4.1 Material characteristics

Specimen was defined as MAT_PIECEWISE_LINEAR_PLASTICITY in DYNA, which includes a true stress-true strain curve for the plastic region. The corresponding LS-DYNA card that is corresponding to eight points for plastic region is shown in Table 5-1, and Table 5-2 shows the basic material input for the specimen.

Table 5-1 Control Card For MAT_PIECEWISE_LINEAR_PLASTICITY

<table>
<thead>
<tr>
<th>Entry in Stress-Strain Curve</th>
<th>0.0</th>
<th>0.0455</th>
<th>0.3844</th>
<th>0.4170</th>
<th>0.4528</th>
<th>0.4840</th>
<th>0.5050</th>
<th>0.5099</th>
</tr>
</thead>
<tbody>
<tr>
<td>96408.70,137301.46,229090.76,231603.38,224230.32,189373.92,128116.48,3793.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-2 Material Input for the Specimen (Units)

<table>
<thead>
<tr>
<th>Material</th>
<th>ID</th>
<th>Density (lb-sec^2/in^4)</th>
<th>Young’s modulus (lb/in^2)</th>
<th>Poisson’s Ratio</th>
<th>Yield Strength (lb/in^2)</th>
<th>Tangent modulus (lb/in^2)</th>
<th>Failure strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>2</td>
<td>0.414E-03</td>
<td>0.165E+08</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td>2</td>
<td>0.735E-03</td>
<td>0.29E+08</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alloy C22</td>
<td>2</td>
<td>0.805E-03</td>
<td>0.30E+08</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5-2 to Figure 5-4 show the LS-DYNA input and actual composite curve of Titanium Grade 7, Stainless Steel 316L and Alloy C22 materials obtained in experiment.
Figure 5-2  Comparison of Material Characteristic Curve for a Titanium Specimen.
Figure 5.3 Comparisons of the Material Characteristic Curves for a Steel Specimen
The receiver was defined as MAT_PLASTIC_KINEMATIC. Table 5-3 lists the material parameters for the receiver.

**Table 5-3 Material Input for the Receiver**

<table>
<thead>
<tr>
<th>ID</th>
<th>Density (lb·sec²/in⁴)</th>
<th>Young's modulus (lb/in²)</th>
<th>Poisson’s Ratio</th>
<th>Yield Strength (lb/in²)</th>
<th>Tangent modulus (lb/in²)</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.735E-03</td>
<td>0.29E+08</td>
<td>0.33</td>
<td>0.120E+09</td>
<td>0.200E+06</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(* Strain hardening exponent)

Complete_load cell and striker was also defined as a MAT_PLASTIC_KINEMATIC. Table 5-4 lists the material input for the Complete_load cell and striker.

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Table 5-4 Material Input for the Complete_load cell and the Striker

<table>
<thead>
<tr>
<th>ID</th>
<th>Density (lb-sec²/in⁴)</th>
<th>Young’s modulus (lb/in²)</th>
<th>Poisson’s Ratio</th>
<th>Yield Strength (lb/in²)</th>
<th>Tangent modulus (lb/in²)</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.735E-03</td>
<td>0.29E+08</td>
<td>0.33</td>
<td>0.120E+09</td>
<td>0.200E+09</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(* Strain hardening exponent)

5.4.2 Meshing

The complete_load cell was meshed with brick solid element; striker, receiver and specimen were meshed with a relatively coarse size. A more refined mesh in the gage section of the specimen was later created since this region experiences significant reduction of area during impact testing. The Specimen was meshed with 50 divisions over the gage length. Figure 5-5 shows the final meshing of the whole model.

Figure 5-5 Mesh of the whole model
5.4.3 Boundary conditions

1. The whole system is reduced to a quarter model using two planes of symmetry.

2. All degrees of freedom are fixed at the upper surface of the specimen.

3. Tied surface-to-surface contact boundary conditions between the specimen and the receiver. In these contact types, the slave nodes (specimen) are constrained to move with the master nodes (receiver).

4. Automatic surface-to-surface contact boundary condition between the striker and the receiver. It allows the transfer of loads from the slave nodes to the master nodes without penetration.

5. Automatic surface-to-surface contact boundary condition between the Complete_load cell and the receiver. The two surface nodes are selected using the DEFINE_BOX command. (See Figure 5-6)

6. Velocity profile to the complete_load cell. This profile for all the three metals is shown from Figure 5-7 through Figure 5-9.

7. Initial velocity of the striker, as obtained experimentally, was originally applied to the complete_load cell.
Figure 5-6  Contact Definitions in LS-Dyna
Figure 5-7  Velocity Profile of a Titanium Specimen (#05TEn) [23]
Figure 5-8  Velocity Profile of a Steel Specimen (#04SEn) [23]
Figure 5-9  Velocity Profile of an Alloy 22 Specimen (#02CEn)[23]
5.4.4 Post-processing

If the problem is successfully solved in LS-DYNA solver, results can be viewed in many software programs like HYPERVIEW, ANSYS, and LS-POST. The displacement contour shown is at the end of the simulation, which corresponds to the end of actual testing.

![Contour Stress (vonMises)](image)

Figure 5-10 Typical stress Contour of Titanium (#05TEn) Specimen

Figure 5-10 shows the Von-Mises stress contour of the Titanium specimen. Figure 5-11 shows comparison of the deformation of the Titanium specimen obtained experimentally and using LS-Dyna finite element analysis.
Figure 5-11 Typical displacement Contour of Titanium (#05TEn) Specimen
Figure 5-12  Displacement History for a Titanium Specimen (#05TEn)

The above analysis was done to the other two materials too, namely, Stainless Steel 316L and Alloy C22. The deformation of these materials, as compared with the experimental data is shown in Figure 5-13 and Figure 5-14.
Figure 5-13  Displacement History for a Steel Specimen (#04SEn)
Conçarisai of Displaceme
A Histoiy of Experinaerta! Data witii LS-Dyna Resuit fijr a AUoy 22 Specimen

Figure 5-14  Displacement History for an Alloy C22 Specimen (# 02CEn)

Table 5-5  Comparisons of Experimental Results with LS-Dyna Results

<table>
<thead>
<tr>
<th>Material</th>
<th>Height (in)</th>
<th>Measured Elongation at Failure (in)</th>
<th>Corresponding FEA Displacement (in)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium (# 05TEn)</td>
<td>3.0</td>
<td>0.1202</td>
<td>0.1298</td>
<td>7.98</td>
</tr>
<tr>
<td>Steel 316L (# 04SEn)</td>
<td>4.0</td>
<td>0.2146</td>
<td>0.2233</td>
<td>4.05</td>
</tr>
<tr>
<td>C22 Alloy (# 02CEn)</td>
<td>4.5</td>
<td>0.2205</td>
<td>0.2435</td>
<td>9.44</td>
</tr>
</tbody>
</table>

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5.5 Discussion and Verification

In the previous part of this chapter, we simulate the FEA model including three parts, namely Complete-striker, specimen and receiver. The specimen absorbs more energy that is transferred from the receiver, thus leading elongation and failure. To verify the validation of this model, we adopted the procedure as follows:

1. Keep the specimen only and delete the complete-striker and receiver in the geometry model.

2. Fix the upper surface of the quarter specimen; constrain the two surfaces that are perpendicular to each other. In the y-z plane, constrain the translation of x direction, rotation of x-y plane and x-z plane. Similarly, in the x-z plane, constrain the translation of y direction, rotation of x-y plane and y-z plane.

3. Apply initial velocity to the lower surface of the specimen.

Part of Corresponding control card:

(DEFINE_CURVE)
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
1
0.000E-03,-0.594E+02
0.108E-03,-0.593E+02
5.619E-03,-0.268E+02
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

(BOUNDARY_PRESCRIBED_MOTION_SET)
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*BOUNDARY_PRESCRIBED_MOTION_SET
5.2.0,1
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

Figure 5-15 shows the Von-Mises stress contour of the steel (# 04SEn). Figure 5-16 shows the displacement contour of the steel (# 04SEn).
The above analysis was done to the other two materials too, namely, Titanium Grade 7 and Alloy C22. (See Figure 5-17 to Figure 5-20)
Figure 5-17  Typical Von-Mises Stress Contour of Titanium (#05TEn) Specimen

Figure 5-18  Typical Displacement Contour of Titanium (#05TEn) Specimen
Figure 5-19  Typical Stress Contour of Alloy C22 (# 02CEn) Specimen

Figure 5-20  Typical Displacement Contour of Alloy C22 (# 02CEn) Specimen
<table>
<thead>
<tr>
<th>Material</th>
<th>Height (in)</th>
<th>Measured Elongation at Failure (in)</th>
<th>Corresponding FEA Displacement (in)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium (#05TEn)</td>
<td>3.0</td>
<td>0.1202</td>
<td>0.1291</td>
<td>7.4</td>
</tr>
<tr>
<td>Steel 316L (#04SEn)</td>
<td>4.0</td>
<td>0.2146</td>
<td>0.2265</td>
<td>5.5</td>
</tr>
<tr>
<td>C22 Alloy (#02CEn)</td>
<td>4.5</td>
<td>0.2205</td>
<td>0.2436</td>
<td>10.0</td>
</tr>
</tbody>
</table>

A same whole model is used to verify compression stress curve that travels in the load cell during the impact testing. Elements and nodes were picked by using control card, DATABASE_HISTORY_NODE, DATABASE_HISTORY_SOLID, DATABASE_NOD OUT, DATABASE_ELOUT, DATABASE_SECFORC [See Table 5-6]. The output results for the elements and nodes and the results are evaluated using LS-POST. The results are shown from Figure 5-21 to Figure 5-28.

Table 5-6  Part Control Cards for NODUT and ELOUUT

```
*DATABASE_HISTORY_NODE
$ DEFINE NODES THAT OUTPUT INTO NODOUT
$ ID1 ID2 ID3 ID4 ID5 ID6 ID7 ID8
$.>...1...>2...>3...>4...>5...>6...>7...>8
11156, 2522, 2172, 59591, 55188, 58833, 58907, 988
$
*DATABASE_CROSS_SECTION_PLANE
$.>...1...>2...>3...>4...>5...>6...>7...>8
$ PID XCY YCY ZCY XCH YCH ZCH
1, 0, 3,68345, 0, 0, 3,7733, 0
$XHEV YHEV ZHEV LENL LEM M ID ITYPE
0, 3,68345, 0,49911,0,49911, 0,62389

*DATABASE_HISTORY_SOLID
$ DEFINE ELEMENTS THAT OUTPUT INTO ELOUT
$ ID1 ID2 ID3 ID4 ID5 ID6 ID7 ID8
$.>...1...>2...>3...>4...>5...>6...>7...>8
861
6878
12675
22970
31130
44210
```
Figure 5-21 Elements of Titanium (#05TEn) Specimen

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Figure 5-22  LS-POST Results of Stress versus Time Curve for #05TEn

Figure 5-23  LS-POST Results of Stress Versus Time Curve I for #05TEn

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Figure 5-24  LS-POST Results of Stress versus Time Curve II for Element 861

Figure 5-25  LS-POST Results of Displacement for Node 2172
Figure 5-26  LS-POST Results of Force for Cross Section A

Figure 5-27  Energy for Titanium (# 05TEn)
A simple energy equation (Equation 5-1) is adopted to describe this model.

\[ E = \frac{1}{2} \times (m_w + m_{LC}) \times V^2 + (m_w + m_{LC}) \times g \times h = F_{av} \times \delta \]  

(5-1)

Where \( m_w \) is the weight mass, \( m_{LC} \) is the load cell mass, \( V \) is the impact velocity, \( g \) is the acceleration due to gravity, \( h \) is the drop height, \( \delta \) is the deformation of the test specimen, and \( F_{av} \) is the average deformation force of the specimen.

In the actual impact testing, the complete load cell is composed of different material properties, which have different natural frequencies, that is the reason the different number we got from the experiment and LS-Dyna analysis.
CHAPTER 6

RESULTS AND RECOMMANDATION

6.1 Results and Discussion

Tests were done at three different strain rates at Room, 175 °F and 350 °F temperatures for the three candidate metals using MTS and Instron Dynatup 8250 Testing Machine. The following observations are made with the results obtained.

Titanium had an increase in the yield and ultimate strength values with strain rate for all the three temperatures. The strain at failure values decreased with strain rate, but not significantly. There was a decrease in yield and ultimate strength values with temperature for all the strain rates at 175 °F and 350 °F, Especially for 350 °F. The strain at failure increased with temperature 350°F, but there was a decrease with temperature 175 °F.

Stainless Steel 316L, for all the three temperatures, had an increase in the yield and ultimate strength values with strain rate. The strain at failure values also increased with strain rate. There was a significant decrease in yield and ultimate strength values with temperature for all the strain rates especially from 175 °F to 350 °F. The strain at failure decreased with temperature for all the strain rates, but a significant decrease was observed from 175 °F to 350 °F.
Alloy C22, for all the three temperatures had an increase in the yield and ultimate strength values with strain rate. The strain at failure values decreased with strain rate. There was a significant decrease in yield and ultimate strength values with temperature for all the strain rates especially from 175 °F to 350 °F. The strain at failure increased with temperature for all the strain rates, but a significant increase was observed at 175 °F. The values practically didn't change between 175 °F and 350 °F.

Summarily, the yield and ultimate strength of the three materials decrease with temperature. Results also show that strain at failure increases with temperature for Titanium and Alloy C22 samples, but decreases with temperature for stainless steel 316L samples. This is just because when a metal is heated, the grains can grow larger and the metals became softer. This pattern is analogous to that of static tensile testing of similar materials and other related literature. Elevated temperature stress-strain curve are almost similar in appearance to those determined at room temperature. High temperature, thermally activated processes such as multiple slip cross slip allow the high local stresses relaxed, and strength is decreased. To some extent deformation under tensile condition is governed by crystal structure. Face-centered cubic materials generally inhibit a graduate change in strength. There are some other factors that can affect tensile behavior, such as Re-solutioning, precipitation and aging, it is very hard to predict easily because the factors may be occur in two-phase alloys during heating prior to testing and during the actual testing. These processes can produce a wide variety of responses in mechanical behavior depending on the materials.
The final displacement and the displacement history obtained from LS-Dyna were then compared with the experimental results. The difference between the experimental and FEA results for the three materials are within 10%.

6.2 Recommendation

The following recommendations can make the work more useful.

1. To use MTS and Instron Dynatup to test metals in a series of strain rate, thus obtaining the dynamic properties over a wide range of strain rates at elevated temperatures.

2. Draw an overall geometry model for Instron Dynatup machine and validate the results obtained experimentally.

3. Finally, using electron microscopy to photograph the dislocation of the broken specimen, explain and verify the result obtained from the experiment.
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