Plastic Deformation and Ductile Fracture of Ti-6Al-4V Under Various Loading Conditions

April 2014

Technical Thesis

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.
NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The U.S. Government does not endorse products or manufacturers. Trade or manufacturers’ names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This document represents the views of the author and does not represent the views of the FAA. The FAA assumes no liability for the contents or use thereof. The FAA has not edited or modified the contents of the reprint in any manner.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center’s Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).
A team consisting of The Ohio State University (OSU), The George Washington University (GWU) and National Aeronautics and Space Administration Glenn Research Center (NASA-GRC), and Federal Aviation Administration (FAA) Aircraft Catastrophic Failure Prevention Research Program collaborated to develop a new material model in LS-DYNA for metal failure. Plastic deformation and ductile fracture of Ti-6Al-4V plate stock is investigated under multiple loading conditions. The objective of this study is to generate experimental data that can be used for the development and calibration of constitutive and failure models for numerical simulations of dynamic events. Plastic deformation is investigated at various strain rates, orientations, temperatures, and stocks. The stress state dependence of ductile fracture is also investigated. Uniaxial tension, compression, and pure shear experiments are conducted at strain rates ranging from $1.0 \times 10^{-4} \text{s}^{-1}$ to 8000s$^{-1}$. Ductile fracture testing is conducted at various stress states, which are achieved with mechanical tests on various sample geometries subjected to various loading conditions. Testing is documented with an experimental technique that is introduced to measure full field strains using three dimensional digital image correlation at temperatures up to 800°C. This test setup has been designed to be a straightforward, repeatable, and accurate method for measuring strains at high temperatures.
Plastic Deformation and Ductile Fracture of Ti-6Al-4V under Various Loading Conditions

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

Jeremiah Thomas Hammer, B.S.

Graduate Program in Mechanical Engineering

The Ohio State University

2014

Master’s Examination Committee:

Dr. Amos Gilat, Advisor

Dr. Mark Walter
Abstract

Plastic deformation and ductile fracture of Ti-6Al-4V plate stock is investigated under multiple loading conditions. The objective of this study is to generate experimental data that can be used for the development and calibration of constitutive and failure models for numerical simulations of dynamic events. Plastic deformation is investigated at various strain rates, orientations, temperatures, and stocks. The stress state dependence of ductile fracture is also investigated.

Uniaxial tension, compression, and pure shear experiments are conducted at strain rates ranging from $1.0 \times 10^{-4}$s$^{-1}$ to 8000s$^{-1}$. Specimens are fabricated from several sheet and plate stocks with thicknesses of 2.29mm, 3.56mm, 6.35mm, and 12.7mm. Compression and tension tests are conducted with specimens oriented in several different directions. These data show significant strain rate sensitivity in tension, compression and shear. Both plates exhibit anisotropic plastic deformation behavior in tension and compression. The response of each of the plates are significantly different for yield stress, flow stress, hardening, failure, and anisotropic effects.

Ductile fracture testing is conducted at various stress states, which are achieved with mechanical tests on various sample geometries subjected to various loading conditions. Tension tests are conducted on thin flat specimens, wide flat specimens and axisymmetric specimens with varying notch radii. Thin walled tube specimens are subjected to combined axial-torsional loading for additional states of stress. The


results show that the stress triaxiality alone is unable to properly capture the failure characteristics of material. Digital image correlation is used to measure surface strains of the specimens. Parallel LS-DYNA simulations are used to determine the stress states and fracture strains. A fracture locus for Ti-6Al-4V is created in the stress triaxiality and Lode parameter stress space giving a more accurate description of the material fracture.

An experimental technique is introduced to measure full field strains using three dimensional digital image correlation at temperatures up to 800°C. This test setup has been designed to be a straightforward, repeatable, and accurate method for measuring strains at high temperatures. Design hurdles included thermal gradients of air, speckle pattern adhesion, viewing window image distortion, camera calibration, and infrared light pollution of the camera sensor. For validation, the coefficient of thermal expansion for Ti-6Al-4V up to 800°C is measured using the technique and compared to published values. Tests on Ti-6Al-4V were conducted in tension, compression, and torsion (shear). Experimentally measured coefficient of thermal expansion values correlate well with handbook values. The system performs well for each of the tests conducted here and gives substantially more data than standard methods.
This document is dedicated to my family and close friends.
Acknowledgments

Many people have helped me get to this point in my life and I would like to thank them. First and foremost I would like to thank my parents Bonnie and Peter Hammer, without their love and support through both smooth and rough times I do not think this would have been possible. Josh and Mary Moran have also been a constant source of support and friendship. There are countless other friends that have also been a source of inspiration.

My Advisor, Professor Amos Gilat, has been both inspiring and supportive. His advice during my time here has been invaluable and it has been a true pleasure to work with him. Dr. Jeremy Seidt has become a mentor both in and out of the laboratory as well as an esteemed colleague. During my time working on this project Jeremy has become a second advisor and I do not think the project would have had the same results without his guidance. Thanks also to Professor Mark Walter as my thesis defense committee member.

This research was funded by the Federal Aviation Administration with collaboration from National Aeronautics and Space Administration as well as George Washington University. Thanks to Don Altobelli, Bill Emmerling, and Chip Queitzsch from the FAA for all the support given to myself during this project. Thanks also to Paul Dubois, Steve Kan, and Doug Wang.
Thanks to Mike Pereira, Adam Howard, Kelly Carney, Chuck Ruggeri, and Brad Lerch of NASA Glenn Research Center for their support both during my master’s research and my time spent at the Glenn Research Center.

Thanks also to Casey Holycross, Matti Isakov, Bob Lowe, Chris Cooley, Tom Mattrka, Kevin Gardner, Emily Sequin, Zach Witeof, Mark Ryan, Michelle Wilson, Jarrod Smith, and Tim Liutkus. These students and researchers in the Mechanical and Aerospace Engineering Department at The Ohio State University have helped immensely with both technical discussions regarding the research and the friendship they provided. I also want to thank my friends and colleagues of Pi Tau Sigma.
Vita

2000 .......................... Frederick High School, Frederick, MD

2010 .......................... B.S. Mechanical Engineering,
                            The Ohio State University

2010-present .................. Graduate Research Associate,
                            Dynamic Mechanics of Materials
                            Laboratory,
                            Department of Mechanical and
                            Aerospace Engineering,
                            The Ohio State University

Publications:

of Ballistic Gelatin Impact Using an Instrumented Tube”, Proceedings of the 2012
SEM Annual Conference and Exposition on Experimental and Applied Mechanics,
Costa Mesa, CA, June, 2012

Hammer, J.T., Yatnalkar, R.S., Seidt, J.D., Gilat, A., “Plastic Deformation of Ti-
6Al-4V Plate over a Wide Range of Loading Conditions”, Proceedings of the 2012
SEM Annual Conference and Exposition on Experimental and Applied Mechanics,
Costa Mesa, CA, June, 2012

Hammer, J.T., Seidt, J.D., Gilat, A., “Strain Measurement at Temperatures up to
800°C Utilizing Digital Image Correlation”, Proceedings of the 2013 SEM Annual
Conference and Exposition on Experimental and Applied Mechanics, Lombard, IL,
June, 2013

Hammer, J.T., Seidt, J.D., Gilat, A., “Stress State Dependence on the Ductile Frac-
ture of Ti-6Al-4V”, Proceedings of the 2013 SEM Annual Conference and Exposition
on Experimental and Applied Mechanics, Lombard, IL, June, 2013

**Fields of Study**

Major Field: Mechanical Engineering, Experimental Mechanics, Dynamic Behavior of Materials, Plasticity, Computational Mechanics
Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Dedication</td>
<td>iv</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>Vita</td>
<td>vii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xiv</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xv</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation and Objectives for this Research Project</td>
<td>4</td>
</tr>
<tr>
<td>1.2 Literature Review</td>
<td>9</td>
</tr>
<tr>
<td>1.2.1 Plastic Deformation Behavior of Ti-6Al-4V</td>
<td>10</td>
</tr>
<tr>
<td>1.2.2 Ductile Fracture</td>
<td>12</td>
</tr>
<tr>
<td>2. Experimental Procedures and Techniques</td>
<td>15</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>15</td>
</tr>
<tr>
<td>2.2 Plastic Deformation of Ti-6Al-4V</td>
<td>16</td>
</tr>
<tr>
<td>2.2.1 Tension Experiments</td>
<td>20</td>
</tr>
<tr>
<td>2.2.2 Compression Experiments</td>
<td>21</td>
</tr>
<tr>
<td>2.2.3 Shear Experiments</td>
<td>22</td>
</tr>
<tr>
<td>2.2.4 Comparison of the Results from the Plastic Deformation Testing</td>
<td>24</td>
</tr>
<tr>
<td>2.3 Ductile Fracture of Ti-6Al-4V</td>
<td>25</td>
</tr>
<tr>
<td>2.3.1 Plane Stress Fracture Testing</td>
<td>29</td>
</tr>
<tr>
<td>2.3.2 Plane Strain Fracture Testing</td>
<td>31</td>
</tr>
</tbody>
</table>
2.3.3 Axisymmetric Fracture Testing ........................................... 34
2.3.4 Combined Loading Testing .................................................. 38
2.3.5 Fracture Parameter Determination ....................................... 41
2.4 Quasi-static Strain Rate Testing Techniques .............................. 44
2.5 High Strain Rate Testing Techniques ...................................... 48
  2.5.1 High Strain Rate Compression Testing ............................... 48
  2.5.2 High Strain Rate Tension Testing .................................... 53
  2.5.3 High Strain Rate Shear Testing ...................................... 59
2.6 Elevated and Low Temperature Testing Techniques ...................... 64
2.7 Digital Image Correlation .................................................. 67

3. Plastic Deformation of Ti-6Al-4V Experimental Results and Discussion . 71
  3.1 Experimental Results from the 2.29mm Plate Stock .................. 71
    3.1.1 Strain Rate Test Series Results .................................. 72
    3.1.2 Specimen Orientation Test Series Results ....................... 73
  3.2 Experimental Results from the 3.56mm Plate Stock .................. 74
    3.2.1 Strain Rate Test Series Results .................................. 74
    3.2.2 Specimen Orientation Test Series Results ....................... 75
  3.3 Experimental Results from the 6.35mm Plate Stock .................. 76
    3.3.1 Temperature Test Series Results .................................. 76
  3.4 Experimental Results from the 12.7mm Plate Stock ................... 77
    3.4.1 Strain Rate Test Series Results .................................. 78
    3.4.2 Specimen Orientation Test Series Results ....................... 80
    3.4.3 Temperature Test Series Results .................................. 81
  3.5 Comparison of the Various Plate Stocks Tested ...................... 83
    3.5.1 Tension Comparison ................................................ 83
    3.5.2 Compression Comparison .......................................... 88
  3.6 Johnson-Cook Plasticity Model Parameter Determination .............. 92
  3.7 Yield Criterion .......................................................... 96
  3.8 Conclusions .............................................................. 97

4. Ductile Fracture Experimental Results and Construction of the Fracture Locus for Ti-6Al-4V ..................................................... 100
  4.1 Plane Stress Experiments ............................................... 100
  4.2 Axisymmetric Experiments ............................................... 101
  4.3 Plane Strain Experiments ............................................... 102
  4.4 Combined Loading Experiments ......................................... 104
  4.5 Fracture Point Determination and Locus Creation ..................... 106
  4.6 Johnson-Cook Fracture Parameter Determination ....................... 111
  4.7 Conclusions for the Ti-6Al-4V Fracture Testing ....................... 115
5. Summary and Conclusions of the Ti-6Al-4V Testing ................................. 117
   5.1 Plastic Deformation Experimental Conclusions ............................... 117
   5.2 Ductile Fracture Experimental Conclusions .................................. 119
   5.3 Overall Project Conclusions ...................................................... 121

6. Strain Measurements at Temperatures up to 800°C utilizing Digital Image Correlation ................................................................. 122
   6.1 Introduction .................................................................................. 122
     6.1.1 Literature Review .................................................................... 123
   6.2 Experimental Setup ....................................................................... 125
   6.3 Validation of Measurement System ................................................ 129
     6.3.1 Optical Validation ................................................................... 129
     6.3.2 Coefficient of Thermal Expansion Validation Testing .............. 129
   6.4 Experimental Methods and Results of the Various Loading Conditions at High-temperatures ......................................................... 133
     6.4.1 Tension Measurement Techniques and Results ....................... 133
     6.4.2 Compression Measurement Techniques and Results ............... 137
     6.4.3 Torsion Measurement Techniques and Results ...................... 140
   6.5 Summary and Conclusions ............................................................... 143

Appendices ......................................................................................... 144

A. Experimental Results from the Ti-6Al-4V Plastic Deformation Test Series 144
   A.1 Tension Test Series ................................................................. 145
     A.1.1 Tension Strain Rate Dependent Test Series for the 2.29mm Plate Stock ................................................................. 145
     A.1.2 Tension Orientation Dependent Test Series for the 2.29mm Plate Stock ................................................................. 146
     A.1.3 Tension Strain Rate Dependent Test Series for the 3.56mm Plate Stock ................................................................. 147
     A.1.4 Tension Orientation Dependent Test Series for the 3.56mm Plate Stock ................................................................. 148
     A.1.5 Tension Temperature Dependent Test Series for the 6.35mm Plate Stock ................................................................. 149
     A.1.6 Tension Strain Rate Dependent Test Series for the 12.7mm Plate Stock ................................................................. 151

xi
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.3 Plane Strain Test Series</td>
<td>202</td>
</tr>
<tr>
<td>D.4 Combined Loading Test Series</td>
<td>205</td>
</tr>
<tr>
<td>E. Additional Views of the Fracture Locus for Ti-6Al-4V</td>
<td>209</td>
</tr>
<tr>
<td>Bibliography</td>
<td>212</td>
</tr>
</tbody>
</table>
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Material composition of the various plate stocks tested</td>
<td>8</td>
</tr>
<tr>
<td>1.2</td>
<td>Johnson-Cook constitutive parameters for Ti-6Al-4V</td>
<td>11</td>
</tr>
<tr>
<td>2.1</td>
<td>Experimental outline for the plastic deformation testing of Ti-6Al-4V</td>
<td>17</td>
</tr>
<tr>
<td>2.2</td>
<td>Experimental outline for the plane stress fracture testing</td>
<td>30</td>
</tr>
<tr>
<td>2.3</td>
<td>Experimental outline for the plane strain fracture testing</td>
<td>33</td>
</tr>
<tr>
<td>2.4</td>
<td>Experimental outline for the axisymmetric fracture testing</td>
<td>37</td>
</tr>
<tr>
<td>2.5</td>
<td>Experimental outline for the combined loading fracture testing</td>
<td>40</td>
</tr>
<tr>
<td>4.1</td>
<td>Results of the ductile fracture of Ti-6Al-4V testing</td>
<td>109</td>
</tr>
<tr>
<td>4.2</td>
<td>Comparison of Ti-6Al-4V Johnson-Cook constitutive parameters found in the literature to those determined for plate 4</td>
<td>116</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Uncontained engine debris incidents (a) MD-88 Flight 1288 compressor fan disk failure and subsequent fuselage damage, (b) Fan blade failure from United Airlines Flight 232 incident, (c) Damage to GE-CF6 turbofan engine following disk failure from American Airlines Flight 767, (d) Fuselage damage following disk failure from American Airlines Flight 767</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Virtual and physical testing of blade-off events for turbofan engines (a) Finite element mesh of a turbofan engine, (b) Finite element results of a turbofan engine under loading, (c) Experimental testing of a catastrophic blade-off event</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>Specimen manufacturing orientation for the 2.29mm, 3.56mm, and 6.35mm plate stocks</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Specimen manufacturing orientations for the 12.7mm plate stock</td>
<td>19</td>
</tr>
<tr>
<td>2.3</td>
<td>Plane stress smooth specimen used in plastic deformation testing</td>
<td>20</td>
</tr>
<tr>
<td>2.4</td>
<td>Compression specimen used in plastic deformation testing</td>
<td>21</td>
</tr>
<tr>
<td>2.5</td>
<td>Torsion specimen used in plastic deformation testing</td>
<td>22</td>
</tr>
<tr>
<td>2.6</td>
<td>Geometric representation of the shear stress calculation</td>
<td>23</td>
</tr>
<tr>
<td>2.7</td>
<td>Comparison of stress strain calculation types for the different loading conditions</td>
<td>25</td>
</tr>
<tr>
<td>2.8</td>
<td>Fracture specimen manufacturing orientations for the 12.7mm plate stock</td>
<td>26</td>
</tr>
</tbody>
</table>
2.9 Points of interest for: (a) plane stress, (b) axisymmetric and (c) plane strain specimens .............................................................. 28

2.10 State of stress in the plane stress tension specimen ................... 31

2.11 State of strain at the center of the plane strain fracture specimen . . 31

2.12 State of stress in the axisymmetric fracture specimen .................. 34

2.13 Sketch of Bridgman’s analysis of a necked axisymmetric sample . . 35

2.14 State of stress within a combined loading specimen ..................... 39

2.15 Stress state parameters for the combined loading specimens at differing stress component ratios .................................................. 41

2.16 Strain comparison from an experimental axisymmetric notched specimen and parallel simulation ...................................................... 43

2.17 Example of history from an experimental plane stress smooth specimen and a parallel simulation ...................................................... 44

2.18 Instron 1321 servo-hydraulic biaxial load frame equipped with hydraulic wedge grips ................................................................. 45

2.19 Test setup used for the quasi-static compression tests .................... 47

2.20 Compression Kolsky bar located in the DMML ............................ 49

2.21 Schematic representation of the compression Kolsky bar ............... 50

2.22 Typical wave data from a compression Kolsky bar experiment on Ti-6Al-4V ................................................................. 52

2.23 Reduced wave data from a compression Kolsky bar experiment on Ti-6Al-4V ................................................................. 52

2.24 Tungsten carbide inserts used with the compression Kolsky bar . . . 53

2.25 Schematic representation of the direct tension Kolsky bar ............... 54
2.26 Direct tension (left) and torsion (right) Kolsky bars located at the DMML ............... 55
2.27 Kolsky bar clamp used in pre-loading for the tension and torsion bars ............. 56
2.28 Typical wave data from a tension Kolsky bar experiment on Ti-6Al-4V .......... 57
2.29 Reduced wave data from a tension Kolsky bar experiment on Ti-6Al-4V ........ 58
2.30 High strain rate specimen with adapters (a)before and (b)following testing ............... 59
2.31 Comparison of the grip sections between the low and high strain rate shear specimens ............... 61
2.32 Schematic representation of the stored-torsion Kolsky bar ................... 62
2.33 Typical wave data from a torsion Kolsky bar experiment on Ti-6Al-4V ........ 63
2.34 Reduced wave data from a torsion Kolsky bar experiment on Ti-6Al-4V ........ 64
2.35 Cryogenic chamber and test setup for tension and compression testing of Ti-6Al-4V (a)Cryogenic testing chamber, (b)Tension and compression setup ............... 66
2.36 Gripping fixture used for cryogenic torsional testing of Ti-6Al-4V (a)Fixture drawing, (b)Test setup ............... 66
2.37 DIC data from a combined loading test with Vic-3D (a)2D image with speckle pattern, (b)3D visualization of specimen ............... 68
2.38 Strain measurement comparison between digital image correlation and the load frame measurement ............... 70
3.1 Tension strain rate dependence for plate 1 ............... 72
3.2 Compression strain rate dependence plate 1 ............... 73
3.3 Tension anisotropy data for plate 1 ............... 73
3.4 Tension strain rate dependence for plate 2 ........................................ 74
3.5 Compression strain rate dependence for plate 2 ................................. 75
3.6 Tension anisotropy data for plate 2 .................................................. 75
3.7 Tension temperature test series data for plate 3 .................................. 76
3.8 Compression temperature test series data for plate 3 ............................ 77
3.9 Tension strain rate test series data for plate 4 ..................................... 78
3.10 Compression strain rate test series data for plate 4 .............................. 79
3.11 Shear strain rate test series data for plate 4 ..................................... 79
3.12 Tension anisotropy data for plate 4 .................................................. 80
3.13 Compression anisotropy data for plate 4 .......................................... 81
3.14 Tension temperature dependence for plate 4 ..................................... 82
3.15 Compression temperature dependence for plate 4 ............................... 82
3.16 Shear temperature dependence for plate 4 ..................................... 83
3.17 Comparison of plate 1, 2, 3, and 4 in tension at a strain rate of 1.0s\(^{-1}\), at room temperature, specimens orientated in the rolled direction .... 84
3.18 Comparison of tension tests at various strain rates at room temperature in the rolled direction, (a)plate 1, (b)plate 2, (c)plate 3, (d)plate 4 ... 85
3.19 Comparison of tension tests at various fabrication orientations at room temperature and a strain rate of 1.0s\(^{-1}\), (a)Plate 1, (b)Plate 2, (c)Plate 3, (d)Plate 4 ......................................................... 87
3.20 Comparison of tension tests at various temperatures at a strain rate of 1.0s\(^{-1}\) from the rolled direction for plate 3 and 4 .............................. 88
3.21 Comparison of compression testing at various strain rates from the rolled direction for plates 3(a) and 4(b) ................................. 89

xviii
3.22 Comparison of plates 1, 2, 3, and 4 in compression at a strain rate of 1.0s\(^{-1}\) in the through thickness direction ........................................ 90

3.23 Comparison of plate 3(a) and 4(b) in compression at various fabrication orientations at room temperature and a strain rate of 1.0s\(^{-1}\) ............. 91

3.24 Comparison of plate 3 and 4 in compression at various temperatures in the rolled direction at 1.0s\(^{-1}\) ......................................................... 92

3.25 Comparison of several Johnson-Cook constitutive model parameters to plate 4 test data ................................................................. 93

3.26 Comparison of several Johnson-Cook constitutive model parameters to plate 4 tension strain rate data extracted at a strain of 5% at room temperature in the rolled direction ................................. 95

3.27 Comparison of several Johnson-Cook constitutive model parameters to plate 4 temperature data in tension at a strain rate of 1.0s\(^{-1}\) ............... 95

3.28 Plate 4 (a)asymmetry and (b)anisotropy test data ........................ 97

3.29 Strain rate dependence of various plate stocks of Ti-6Al-4V in tension, compression, and shear at strains of 5% ........................................ 98

3.30 Temperature dependence of various plate stocks of Ti-6Al-4V in multiple loading conditions .............................................................. 99

4.1 Plane stress tension results for various notch sizes of Ti-6Al-4V .... 101

4.2 Axisymmetric tension results for various notch sizes of Ti-6Al-4V .. 102

4.3 Plane strain tension results for various notch sizes of Ti-6Al-4V .... 103

4.4 DIC strain field data from plane strain specimens with various geometries104

4.5 Combined axial-torsional test results for various notch sizes of Ti-6Al-4V105

4.6 Time history of a tension-torsion experiment ............................. 106
4.7 Data from an experiment and parallel simulation of a plane stress specimen ................................. 108

4.8 Failure strain versus triaxiality(a) and Lode parameters(b) for each of the specimen geometries and loading conditions ................................. 110

4.9 Three dimensional view of the Ti-6Al-4V fracture locus ................................. 111

4.10 Johnson-Cook fracture strain predictions compared to experimental data: stress state sensitivity ................................. 113

4.11 Johnson-Cook fracture strain predictions compared to experimental data: Strain rate sensitivity ................................. 114

4.12 Johnson-Cook fracture temperature parameter determination ................................. 115

6.1 Furnace used with digital image correlation, (a)optical quartz window, (b)3D DIC system setup, (c)interior of furnace ................................. 126

6.2 Wavelengths of transmitted electromagnetic radiation through Tiffen hot mirror lenses ................................. 128

6.3 Image quality from room temperature to 900°C ................................. 129

6.4 Comparison of measured Ti-6Al-4V thermal expansion coefficients to previously published data ................................. 130

6.5 Measured data from a coefficient of thermal expansion test on Ti-6Al-4V ................................. 131

6.6 Projection error versus temperature for a coefficient of thermal expansion test on Ti-6Al-4V ................................. 132

6.7 Grip method and experimental setup for high temperature tension testing ................................. 134

6.8 Digital image quality of tension specimens at various temperatures ................................. 134

6.9 Axial strain measured with 3D digital image correlation just prior to failure at various temperatures and speckle pattern adhesion for tension ................................. 135

6.10 Comparisons of strain measurements for tension at 600°C ................................. 136

xx
6.11 Loading method and experimental setup for high temperature compression testing .................................................. 138

6.12 Digital images of compression specimens at various temperatures ................................................................. 138

6.13 Axial strain measured with 3D digital image correlation just prior to failure at various temperatures and speckle pattern adhesion for compression ................................................................. 139

6.14 Differences in the Strain Measurement Technique for Compression at 600°C ......................................................... 140

6.15 High temperature torsion tracking bracket setup and DIC results, (a) high temperature torsion test setup with tracking brackets, (b) tracking bracket DIC results for initial and deformed results ................................................................. 141

6.16 Differences in strain measurements for torsion at 400°C ................................................................. 143

A.1 Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, rolled direction .................. 145

A.2 Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 650s^{-1}$, room temperature, rolled direction .................. 145

A.3 Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, $45^\circ$ from rolled .................. 146

A.4 Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, transverse direction .................. 146

A.5 Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, rolled direction .................. 147

A.6 Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 600s^{-1}$, room temperature, rolled direction .................. 147

A.7 Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, $45^\circ$ from rolled .................. 148

A.8 Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, transverse direction .................. 148
A.9 Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $-50^\circ C$, rolled direction ................................................. 149

A.10 Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $200^\circ C$, rolled direction .................................................. 149

A.11 Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $400^\circ C$, rolled direction .................................................. 150

A.12 Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $600^\circ C$, rolled direction .................................................. 150

A.13 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0 \times 10^{-4}s^{-1}$, room temperature, rolled direction ........................................... 151

A.14 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0E - 2s^{-1}$, room temperature, rolled direction ........................................... 151

A.15 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, rolled direction ........................................... 152

A.16 Tension test data spread: 0.5” plate stock, $\dot{\epsilon} = 500s^{-1}$, room temperature, rolled direction ........................................... 152

A.17 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1500s^{-1}$, room temperature, rolled direction ........................................... 153

A.18 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, $45^\circ$ from rolled ........................................... 153

A.19 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, transverse direction ........................................... 154

A.20 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, $-45^\circ$ from rolled ........................................... 154

A.21 Tension test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $-50^\circ C$, rolled direction ........................................... 155
A.22 Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, 200°C, rolled direction ................................................................. 155

A.23 Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, 400°C, rolled direction ................................................................. 156

A.24 Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, 600°C, rolled direction ................................................................. 156

A.25 Compression test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, room temperature, rolled direction ................................................................. 157

A.26 Compression test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1500 \, s^{-1}$, room temperature, rolled direction ................................................................. 157

A.27 Compression test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, room temperature, rolled direction ................................................................. 158

A.28 Compression test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1500 \, s^{-1}$, room temperature, rolled direction ................................................................. 158

A.29 Compression test data spread: 6.35mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, −50°C, rolled direction ................................................................. 159

A.30 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \cdot 10^{-4} \, s^{-1}$, room temperature, rolled direction ................................................................. 159

A.31 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \cdot 10^{-2} \, s^{-1}$, room temperature, rolled direction ................................................................. 160

A.32 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \, s^{-1}$, room temperature, rolled direction ................................................................. 160

A.33 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1500 \, s^{-1}$, room temperature, rolled direction ................................................................. 161

A.34 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 4000 \, s^{-1}$, room temperature, rolled direction ................................................................. 161

A.35 Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 7000 \, s^{-1}$, room temperature, rolled direction ................................................................. 162
A.36 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, $45^\circ$ from rolled

A.37 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, transverse direction

A.38 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, $-45^\circ$ from rolled

A.39 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, through direction

A.40 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $-50^\circ$C, rolled direction

A.41 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $200^\circ$C, rolled direction

A.42 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $400^\circ$C, rolled direction

A.43 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $600^\circ$C, rolled direction

A.44 Compression test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0E - 4s^{-1}$, room temperature, rolled direction, Researcher Comparison and surface finish Tests

A.45 Compression test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, rolled direction, Alternate Geometry

A.46 Shear test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0E - 4s^{-1}$, room temperature, through direction

A.47 Shear test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0E - 2s^{-1}$, room temperature, through direction

A.48 Shear test data spread: 12.7mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, room temperature, through direction
A.49 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 500s^{-1}$, room temperature, through direction .................................................. 169

A.50 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1500s^{-1}$, room temperature, through direction .................................................. 169

A.51 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $-50^\circ C$, through direction .......................................................... 170

A.52 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $200^\circ C$, through direction .......................................................... 170

A.53 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $400^\circ C$, through direction .......................................................... 171

A.54 Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $600^\circ C$, through direction .......................................................... 171

B.1 Fracture test data spread: plane stress notched, notch=14.29mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........................................ 173

B.2 Fracture test data spread: plane stress notched, notch=4.76mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........................................ 173

B.3 Fracture test data spread: plane stress notched, notch=0.40mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........................................ 174

B.4 Fracture test data spread: axisymmetric smooth, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........................................ 174

B.5 Fracture test data spread: axisymmetric notched, notch=34.93mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction 175

B.6 Fracture test data spread: axisymmetric notched, notch=17.46mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction 175

B.7 Fracture test data spread: axisymmetric notched, notch=11.9mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........ 176

B.8 Fracture test data spread: axisymmetric notched, notch=6.75mm, 12.7mm plate stock, SR=1.0$^{-2}s^{-1}$, room temperature, rolled direction ........ 176
B.9 Fracture test data spread: axisymmetric notched, notch=3.18mm, 12.7mm plate stock, SR=1.0\(^{-2}\)s\(^{-1}\), room temperature, rolled direction . . . . . 177

B.10 Fracture test data spread: plane strain smooth, 12.7mm plate stock, SR=1.0\(^{-2}\)s\(^{-1}\), room temperature, rolled direction . . . . . . . . . . . 177

B.11 Fracture test data spread: plane strain notched, notch=12.7mm, 12.7mm plate stock, SR=1.0\(^{-2}\)s\(^{-1}\), room temperature, rolled direction . . . . . 178

B.12 Fracture test data spread: plane strain notched, notch=4.76mm, 12.7mm plate stock, SR=1.0\(^{-2}\)s\(^{-1}\), room temperature, rolled direction . . . . . 178

B.13 Combined loading force displacement data spread:, 12.7mm plate stock, \(\sigma/\tau=1.971\), room temperature, rolled direction . . . . . . . . . . . 179

B.14 Combined loading stress state parameter data spread:, 12.7mm plate stock, \(\sigma/\tau=0.847\), room temperature, rolled direction . . . . . . . . . . . . . 180

B.15 Combined loading stress state parameter data spread:, 12.7mm plate stock, \(\sigma/\tau=0.0\), room temperature, rolled direction . . . . . . . . . . . . . 181

B.16 Combined loading stress state parameter data spread:, 12.7mm plate stock, \(\sigma/\tau=-0.847\), room temperature, rolled direction . . . . . . . . . . . . . 182

C.1 Mesh for plane stress smooth specimen . . . . . . . . . . . . . . . . . 184

C.2 Mesh for plane stress specimen with a notch of 14.29mm . . . . . . . 184

C.3 Mesh for plane stress specimen with a notch of 4.76mm . . . . . . . . 185

C.4 Mesh for plane stress specimen with a notch of 0.40mm . . . . . . . . 185

C.5 Mesh for axisymmetric smooth Specimen (section view) . . . . . . . . 186

C.6 Mesh for axisymmetric specimen with a notch of 34.93mm (section view) 186

C.7 Mesh for axisymmetric specimen with a notch of 17.46mm (section view) 187

C.8 Mesh for axisymmetric specimen with a notch of 11.91mm (section view) 187
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.9</td>
<td>Mesh for axisymmetric specimen with a notch of 6.75mm (section view)</td>
</tr>
<tr>
<td>C.10</td>
<td>Mesh for axisymmetric specimen with a notch of 3.18mm (section view)</td>
</tr>
<tr>
<td>C.11</td>
<td>Mesh for plane strain smooth specimen</td>
</tr>
<tr>
<td>C.12</td>
<td>Mesh for plane strain specimen with a notch of 4.76mm</td>
</tr>
<tr>
<td>C.13</td>
<td>Mesh for plane strain specimen with a notch of 12.70mm</td>
</tr>
<tr>
<td>D.1</td>
<td>History comparison of simulated and experimental fracture data for the plane stress smooth specimen</td>
</tr>
<tr>
<td>D.2</td>
<td>History comparison of simulated and experimental fracture data for the plane stress large notch specimen R=14.29mm</td>
</tr>
<tr>
<td>D.3</td>
<td>History comparison of simulated and experimental fracture data for the plane stress medium notch specimen R=4.76mm</td>
</tr>
<tr>
<td>D.4</td>
<td>History comparison of simulated and experimental fracture data for the plane stress small notch specimen R=0.40mm</td>
</tr>
<tr>
<td>D.5</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric smooth specimen</td>
</tr>
<tr>
<td>D.6</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=34.93mm</td>
</tr>
<tr>
<td>D.7</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=17.46mm</td>
</tr>
<tr>
<td>D.8</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=11.91mm</td>
</tr>
<tr>
<td>D.9</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=6.75mm</td>
</tr>
<tr>
<td>D.10</td>
<td>History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=3.18mm</td>
</tr>
</tbody>
</table>
D.11 History comparison of simulated and experimental fracture data for the plane strain smooth .............................. 202
D.12 History comparison of simulated and experimental fracture data for the plane strain large notch R=12.7mm ......................... 203
D.13 History comparison of simulated and experimental fracture data for the plane strain small notch R=4.76mm ......................... 204
D.14 History of experimental fracture data for the combined loading $\sigma/\tau = 1.971$ ............................................. 205
D.15 History of experimental fracture data for the combined loading $\sigma/\tau = 0.847$ ............................................. 206
D.16 History of experimental fracture data for the combined loading $\sigma/\tau = 0.00207$ ............................................. 208
D.17 History of experimental fracture data for the combined loading $\sigma/\tau = -0.847$ ............................................. 208
E.1 Fracture locus for Ti-6Al-4V in the stress triaxiality - Lode parameter plane ............................................. 210
E.2 Fracture locus for Ti-6Al-4V in the stress triaxiality - failure strain plane ............................................. 210
E.3 Fracture locus for Ti-6Al-4V in the Lode parameter - failure strain plane ............................................. 211
E.4 Three dimensional view of the Ti-6Al-4V fracture locus ............................................. 211
Chapter 1: Introduction

Accurate material property data is required for the calibration of finite element material models if results from numerical simulations are to be dependable. Finite element simulations are a cost efficient way to test complex designs and have been implemented in many modern engineering design processes. Although most of these processes are concerned with a mechanical system’s elastic response there are many applications that require simulations of a system’s plastic deformation. Prior to yielding, the linear response of stress to strain is easily understood, is simply calculated, and has readily available material properties. Compared to plastic deformation this linear response is generally less affected by strain rate, temperature, and material anisotropy. Prior to yielding the material’s molecular bonds are stretching and no permanent damage has occurred. Post yield, the material no longer gives a linear response since these molecular bonds are releasing and reforming creating permanent damage[1]. These plastic deforming events are very complex and are more affected by temperature, strain rate, material anisotropy, residual stresses, and other factors.

Numerical codes, such as LS-DYNA[2] and ABAQUS[3], can be used to model materials under dynamic loading conditions at stress levels above yield. These applications require complex material models which are sensitive to the stress state, strain rate, and temperature. Since these models simulate deformation beyond yield,
plasticity research plays a significant role in the code development and in material characterization.

The Johnson-Cook material model [4, 5] is a commonly used material model which is capable of simulating plastic deformation and failure of materials subject to dynamic loading. The constitutive model accounts for different loading rates and temperatures and is given by

$$\sigma = [A + B\epsilon^n] \left[ 1 + C \ln \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_o} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right], \quad (1.1)$$

where, $\epsilon$ is the plastic strain, $\dot{\epsilon}_o$ is a reference strain rate (1.0s$^{-1}$), $T$ is the material testing temperature, $T_r$ is a reference temperature (295K), and $T_m$ is the melting temperature of the material. The Constants $A$, $B$, $n$, $C$, and $m$ are model parameters that need to be determined from experimental data. The first three parameters are found from a single mechanical test performed at the reference strain rate and temperature, when the second and third brackets are equal to one. The $C$ term is found from data taken at various strain rates and the reference temperature. The $m$ term is found from data at various temperatures and the reference strain rate. The strain at fracture of the material is given by

$$\varepsilon_p^f = [D_1 + D_2 e^{D_3 \sigma^*}] \left[ 1 + D_4 \ln \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_o} \right) \right] \left[ 1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right], \quad (1.2)$$

where, $\sigma^*$ is the stress triaxiality, and $D_1$, $D_2$, $D_3$, $D_4$, and $D_5$ are the model parameters of the specific material. The first three parameters are found experimentally by subjecting specimens to various loading conditions. Parameter $D_4$ is found by testing at various strain rates of a single triaxiality. The temperature dependent parameter, $D_5$, is determined with tests at different temperatures. The fracture model calculates
each element’s damage history by

\[ D = \sum \frac{\Delta \epsilon}{\epsilon_f}, \quad (1.3) \]

where, \( \Delta \epsilon \) is the incremental equivalent plastic strain and \( \epsilon_f \) is the equivalent plastic fracture strain. The element failure will occur when \( D = 1 \).

Although there are many plasticity and fracture models other than the one described here, they all require extensive experimental testing of the materials used. Since these material models require experimental data to determine their parameters, accurate mechanical measurements will be required for any material model. Generally, these models, including the analytical Johnson-Cook model, are formulated through the use curve fitting to the physical data.

The goal of this research is to generate a database of experimental data for Ti-6Al-4V to calibrate inputs for MAT224, a recently developed material model for LS-DYNA. This material model, known as the tabulated Johnson-Cook model, is more versatile than the analytical Johnson-Cook and other plasticity models because it uses tabulated stress strain curves at various strain rates and temperatures. Stress state dependence is incorporated by tabulating a fracture locus, or equivalent plastic strain versus one or more stress state variables. The ongoing goal of this project is to acquire and report data from a comprehensive test series in order for the team to generate the best possible material model.

Researchers from the Dynamic Mechanics of Materials Laboratory (DMML) at The Ohio State University (OSU) experimentally determine material behavior under these various conditions. In collaboration, researchers from the National Crash Analysis Center (NCAC) at George Washington University (GWU) are working to develop the material model, MAT224. Researchers from the National Aeronautics
and Space Administration (NASA) at the Glenn Research Center (GRC) perform ballistic impact testing, microstructural analysis, and LS-DYNA consulting. Members of the Federal Aviation Administration (FAA) provide programmatic oversight under the Uncontained Engine Debris Mitigation Program.

1.1 Motivation and Objectives for this Research Project

Jet engines are extremely complex mechanical systems, which like all mechanical systems are subject to failure. Due to the high potential for loss of life and equipment, much effort is put forth to minimize engine failures. Blade-off and disk failure events can be catastrophic to vehicle operation and therefore are subject to a high level of scrutiny. During these events, a mechanical failure causes parts, typically a blade or disk fragment, to be propelled outward from the engine. Since these machines are operating at high rotational velocities the energy released is extremely high and can cause significant damage to the engine and possibly the vehicle. Prior to an engine entering service it is rigorously tested experimentally. This issue is covered under Federal Aviation Administration (FAA) regulation 25.903 subsection (d) which states

\[(1) \text{Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case.}\]

Although governmental regulations are in place to avoid issues caused by uncontained engine debris, failures have occurred which causing serious damage or injury. An MD-88 experienced an uncontained rotor failure during takeoff rollout (Figure 1.1(a)). This incident caused significant damage to the rear of the fuselage, resulting in two fatalities and five injuries[6]. A fan disk failure shown in Figure 1.1(b) caused
the emergency landing of United Flight 232 after the uncontained debris severed three hydraulic lines running to the horizontal stabilizers resulting in 112 fatalities[7]. A disk failure on American Airlines flight 767 during a ground run can be seen in Figures 1.1(c) and 1.1(d)[8]. This disk exited the engine shroud, perforated the fuselage, and embedded into the number two engine. Fortunately, no injuries were sustained but the vehicle was decommissioned[8]. These are a small subset of instances that illustrate the consequences of uncontained engine debris.

Figure 1.1: Uncontained engine debris incidents (a)MD-88 Flight 1288 compressor fan disk failure and subsequent fuselage damage, (b)Fan blade failure from United Airlines Flight 232 incident, (c)Damage to GE-CF6 turbofan engine following disk failure from American Airlines Flight 767, (d)Fuselage damage following disk failure from American Airlines Flight 767
Many precautions are being taken by governmental bodies, airframe manufacturers, and powerplant manufacturers to address this significant threat. Each new engine design must be rigorously tested and certified prior to use. Advancements in computational mechanics allow researchers to simulate these events, see Figure 1.2(a) and 1.2(b)\[9\], giving valuable insight to a design. Virtual testing can be beneficial prior to physical testing which can be expensive and time consuming, see Figure 1.2(c)\[10\]. Although finite element models are becoming increasingly accurate, it is doubtful that this method will ever fully replace actual testing.

These events happen at high strain rates, elevated temperatures, and contain complex states of stress, therefore material models must be able to predict accurate behavior under these conditions. The model must be calibrated with physical testing conducted under similar conditions (high strain rates, high temperatures, and varying states of stress).

Titanium alloys are often used in the aerospace industry because of their high strength to weight ratio, excellent thermal properties, and resistance to corrosion\[11\]. Ti-6Al-4V accounts for 50% of all titanium alloys sold and is primarily used in aerospace applications. It is used in biomedical, automotive, and marine applications\[11\] as well. This study will determine the mechanical properties of Ti-6Al-4V under various loading conditions in order to develop more accurate material models. This stems from work initially started by Ravi Yatnalkar, who did extensive testing on a 6.35mm plate stock in the DMML at OSU\[12\]. The work presented here will cover limited tests on the identical plate tested by Yatnalkar as well as experiments on the additional three plates listed in Table 1.1. These tests are carried out in the DMML at OSU under the same project supervisors to maintain a consistent methodology.
Figure 1.2: Virtual and physical testing of blade-off events for turbofan engines (a) Finite element mesh of a turbofan engine, (b) Finite element results of a turbofan engine under loading, (c) Experimental testing of a catastrophic blade-off event
Although the plates are not all from the same sources they do have similar chemical makeups and are compliant with the same Aerospace Materials Standards (AMS), therefore the mechanical properties should be comparable. Great care is taken to ensure the specimens are from the correct plate stock so results are not corrupted. Results from the individual plate stocks as well as a comparison between the four are presented and discussed. These data are delivered to GWU for use in developing the LS-DYNA material model MAT224 for Ti-6Al-4V which will be used in the FAA’s ongoing Uncontained Engine Debris Mitigation Program.

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Plate Thick</th>
<th>Material Source</th>
<th>Ingot Source</th>
<th>Rolling Source</th>
<th>Chemical Makeup (wt%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.29mm</td>
<td>Tri-Tech</td>
<td>RTI</td>
<td>RMI Titanium</td>
<td>Al 6.74  V 4.07  Fe 0.16  O 0.151  C 0.003  N 0.006 bal</td>
</tr>
<tr>
<td>2</td>
<td>3.56mm</td>
<td>TIMET</td>
<td>TIMET</td>
<td>TIMET</td>
<td>Al 6.56  V 3.99  Fe 0.15  O 0.146  C 0.017  N 0.006 bal</td>
</tr>
<tr>
<td>3</td>
<td>6.35mm</td>
<td>RTI</td>
<td>Allegheny</td>
<td>Ludlum</td>
<td>Al 6.13  V 3.97  Fe 0.18  O 0.173  C 0.016  N 0.006 bal</td>
</tr>
<tr>
<td>4</td>
<td>12.7mm</td>
<td>Titanium Ind.</td>
<td>TIMET</td>
<td>TIMET</td>
<td>Al 6.64  V 4.04  Fe 0.13  O 0.190  C 0.011  N 0.006 bal</td>
</tr>
</tbody>
</table>

*Chemistry presented from measured values completed at NASA - Glenn Research Center

This study characterizes the plate’s strain rate and temperature dependence as well as its initial anisotropy with respect to plasticity. Stain rate dependence of the material is found by testing in tension, compression, and shear (torsion) at strain rates ranging from $1.0 \times 10^{-4}s^{-1}$ to $8.0 \times 10^{3}s^{-1}$. Temperature tests are conducted for tension, compression, and shear at temperatures ranging from $-50^\circ C$ to $600^\circ C$. 
Initial anisotropy in the plate is determined from tension and compression tests on specimens fabricated in several orientations.

Ductile fracture of the 12.7mm plate is studied in order to generate a fracture locus. This test series requires specimens with several different geometries which introduces several stress states. Multiple stress states are used so that the locus plot is sufficiently populated. Tension tests are conducted on specimens with geometries of plane stress (thin, flat), axisymmetric, and plane strain (wide). Other states of stress can be achieved through the testing of combined axial-torsional loading of thin walled tube specimens. Experimental results coupled with LS-DYNA simulations allow the state of stress at each fracture point to be recorded.

1.2 Literature Review

Some aspects of plastic deformation and the ductile fracture of Ti-6Al-4V have been investigated by other researchers. Plastic deformation has been previously evaluated for strain rate and temperature dependence[12, 13, 14, 15, 16, 17]. Anisotropic properties of the material have also been explored. Limited work has been performed on the fracture characteristics of Ti-6Al-4V as well[5, 18, 19, 20].

The outline of this research is modeled after the work done by Seidt[21] on aluminum 2024-T351. The work presented here along with the work completed by Seidt fall under the same body of work and have similar goals. Some aspects of the two works will be comparable including specimen geometries, test setups, test methods, and data analysis.
1.2.1 Plastic Deformation Behavior of Ti-6Al-4V

Many researchers have previously tested and analyzed Ti-6Al-4V for the plastic deformation properties under different loading conditions. Yatnalkar[12], investigated the strain rate dependence of Ti-6Al-4V under tension, compression, and torsion. Significant strain rate dependence was reported for all loading conditions studied with increases of 50, 56, and 77 percents for compression, tension, and torsion loading cases respectively, for strain rates ranging from $1.0 \times 10^{-4}s^{-1}$ to greater than $1300s^{-1}$. The work by Yatnalkar[12] also includes anisotropic data for tension and compression, finding flow stresses with variations of 13% and 14% respectively. Finally, Yatnalkar presented elevated temperature data for compression which showed a decrease of flow strength of 54% over a temperature range of $25^\circ C$ to $600^\circ C$. As a continuation of the program, this work continue tests with the same plate used by Yatnalkar to reduce external variables that may contaminate the data. Additional testing will be performed to determine properties for compression loading at $-50^\circ C$ as well as tension ranging from $-50^\circ C$ to $600^\circ C$. A direct comparison from Yatnalkar’s raw data will also be made here. Comparison of these plates is shown in Chapter 3.

Other researchers have determined the strain rate sensitivity of this material including Wulf[13], Follansbee, et al.[14], Lee, et al.[15], Lee, et al.[16], Lee, et al.[17]. Results from the work by Follansbee, et al.[14] showed a high strain-rate sensitivity of both the yield and flow stresses for several microstructures. The work by Wulf[13] displayed increasing bilinear strain rate dependence for Ti-6Al-4V in compression at strain rates of $3 \times 10^3s^{-1}$ to $3 \times 10^4s^{-1}$. Lee, et al.[15] presents Ti-6Al-4V data at strain rates of $0.02s^{-1}$, $0.1s^{-1}$, and $1.0s^{-1}$ at temperatures ranging from $25^\circ C$ to $500^\circ C$ in compression. The researchers found that yield strength increases with strain...
rate at similar temperatures but decreases with temperature at similar strain rates. They also observed that work hardening decreases as the temperature and strain rates increase. They attributed this to thermal softening which was present at the high temperature and strain rate tests. The former is due to the nature of the test but the latter develops the temperatures due to adiabatic heating during deformation. Another work by Lee, et al.[16] investigates the effects of temperature at high strain rates on Ti-6Al-4V with similar results. They also found that the work hardening of the material decreases considerably as the testing temperature and strain rate increase. Lee, et al.[17] also investigates the shear properties of Ti-6Al-4V at strain rates of $1.8 \times 10^3 \text{s}^{-1}$ to $2.8 \times 10^3 \text{s}^{-1}$ and temperatures of $-100^\circ \text{C}$ to $300^\circ \text{C}$. This work once again demonstrated the material has a significant temperature and strain rate dependence.

Multiple researchers have found Ti-6Al-4V material parameters for the Johnson-Cook constitutive model including Johnson et al.[22], Lesuer[22], Yatnalkar[12], and Milani et al.[23]. The results from these studies are presented in Table 1.2. A comparison of these parameters are shown with data in Chapter 3.

<table>
<thead>
<tr>
<th>Name</th>
<th>$A$ (MPa)</th>
<th>$B$ (MPa)</th>
<th>$C$</th>
<th>$m$</th>
<th>$n$</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$D_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johnson</td>
<td>862</td>
<td>331</td>
<td>0.012</td>
<td>0.8</td>
<td>0.34</td>
<td>-0.09</td>
<td>0.25</td>
<td>-0.5</td>
<td>0.014</td>
<td>3.87</td>
</tr>
<tr>
<td>Lesuer</td>
<td>1098</td>
<td>1092</td>
<td>0.014</td>
<td>1.1</td>
<td>0.93</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yatnalkar</td>
<td>1055</td>
<td>426</td>
<td>0.023</td>
<td>0.8</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Milani</td>
<td>1051</td>
<td>924</td>
<td>0.0025</td>
<td>0.98</td>
<td>0.52</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Although some of these experimental properties have been previously determined, this work is the first to include strain rate, temperature, and isotropic effects from a single plate. It is also the first to compare similar tests between multiple plate stocks. In this work, tension, compression, and shear tests are conducted on samples fabricated from the same plate. Previous works[12, 13, 14, 15, 16, 17], typically conduct only shear or tension tests, not all three. In addition to the plastic deformation testing, the fracture test series is conducted on the same stock. Data from this project is delivered to GWU for MAT224 development.

1.2.2 Ductile Fracture

Ductile fracture material characterization is valuable information for the analysis of failure and is needed for proper material modeling. Impact events often give rise to complex multiaxial stress states that include combinations of tension, compression, and shear. Many researchers[5, 18, 19, 20], have discovered that the state of stress can cause significant changes to the failure strain of a material undergoing complex loading conditions. Theories attribute this to void nucleation, coalescence, and eventually growth which then leads to complete failure. Rice and Tracey[18] showed that the growth of a void could be represented macroscopically by the triaxial stress, $\sigma^*$, and plastic strain. Bau and Wierzbicki[19] explored various specimen geometries and concluded that ductile fracture was strongly based on stress triaxiality. Stress triaxiality which is the ratio of mean stress, $\sigma_m$, to effective stress, $\sigma$, is defined as:

$$\sigma^* = \frac{\sigma_m}{\sigma},$$

where,

$$\sigma_m = \frac{1}{3} \sigma_{kk} = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}),$$
Barstowm and Falewakog[24] found that stress triaxiality of a specimen was insufficient to describe material fracture behavior, especially at low levels of triaxialility. The researchers also investigated Lode parameter which was found to be an important variable in the characterization of fracture and is given by

\[ \mu = \frac{-2\sigma_1 - \sigma_2 - \sigma_3}{\sigma_1 - \sigma_3}, \]  

where, \( \sigma_1, \sigma_2, \) and \( \sigma_3, \) are the principle stresses and \( \sigma_1 \geq \sigma_2 \geq \sigma_3. \) Xue [20] showed a plasticity damage model that utilizes both stress triaxiality and Lode parameter to describe the stress space of a specimen. The fracture model thus becomes a complex function of both stress triaxiality and Lode parameter in the form of

\[ \bar{\epsilon}_f^p = f (\sigma^*, \mu). \]

The goal of this portion of the work is to gain an understanding of the fracture characteristics of Ti-6Al-4V and ultimately utilize these parameters to create a fracture locus. The locus will be applied to plastic deformation results to form a material model used in the finite element calculations. To accurately represent the entire stress-space, multiple data points and thus multiple tests are required.

Johnson[22] determined the fracture model constants for Equation 1.2 seen in Table1.2. This model, however only takes into account stress triaxiality. In this work, both triaxiality and lode parameter are used to describe the material’s fracture
behavior. In addition, Johnson-Cook fracture model parameters are determined for tests conducted in this work. Johnson’s model and the new parameters are compared in Chapter 4.

Although similar tests have been previously preformed this work represents the most comprehensive database of plastic deformation and fracture data for Ti-6Al-4V. Ultimately, these data will be delivered to researchers at GWU and used to refine the MAT224 failure model.
Chapter 2: Experimental Procedures and Techniques

2.1 Introduction

This chapter presents experimental programs for plastic deformation and ductile fracture test series as well as the experimental techniques that are employed to conduct them. These test plans are presented with explanation for each of the tests. The quasi-static and dynamic testing methods and calculations are presented and discussed. Limited tests are performed on the 2.29mm and 3.56mm sheet stocks (plate 1 and 2 respectively) to show overall trends in the material characteristics. Strain rate characterization, anisotropic testing, and limited temperature testing has been performed previously on the 6.35mm plate (plate 3)[12]. On this same plate tests are completed in tension at high and low temperatures as well as in compression at low temperatures. Finally, a 12.7mm plate (plate 4) is studied in depth under similar conditions as plate 3 in addition to shear. Plate 4 is also tested to understand the fracture characteristics of the material.

A breakthrough in strain measurement called Digital Image Correlation (DIC) which is described in detail by Sutton, Orteu, and Schreier[25] is an optical method to measure full field strains of a deforming specimen. This method of measurement
provides good spatial resolution on the surface of a deforming specimen. This measurement technique is briefly discussed in this chapter.

This section also presents the mechanical methods used to test the material specimens. Several machines are used to conduct the tests outlined in this chapter. The DMML always strives to provide high quality data and therefore has developed original testing procedures. A new method, using DIC, is implemented in conjunction with this project. A method, first proposed and used in this work, to measure full field strains with DIC at elevated temperatures is discussed in detail in Chapter 6.

2.2 Plastic Deformation of Ti-6Al-4V

Plastic deformation of Ti-6Al-4V is investigated in the specific program presented in Table 2.1. Testing is preformed at several strain rates to gain an understanding of the strain rate dependence of the material. Anisotropic properties of the material are examined at several loading orientations. Lastly, the temperature dependence is investigated at several temperatures within the material’s operational range.

For plate stock 1 and 2, strain rate dependence is determined in tension at strain rates of $1.0 s^{-1}$ and $5.0 \times 10^2 s^{-1}$ and at rates of $1.0 s^{-1}$ and $1.5 \times 10^3 s^{-1}$ for compression. In addition to the rolled direction, tension tests are conducted at different orientations ($90^\circ$ and $45^\circ$) to determine its degree of anisotropy at a strain rate of $1.0 s^{-1}$. Due to size limitations, compression specimens are only fabricated from the through direction and therefore anisotropic tests cannot be conducted. Specimens are orientated in the directions illustrated in Figure 2.1. Results from these tests are presented in Chapter 3.
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Loading Mode</th>
<th>Testing Apparatus</th>
<th>Strain Rate (1/s)</th>
<th>Specimen Orientation</th>
<th>Temp (° C)</th>
<th>Plate Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tension</td>
<td>Hydraulic Load</td>
<td>1.00E-4</td>
<td>Rolled</td>
<td></td>
<td>3*,4</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Kolsky bar</td>
<td>5.00E2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>1.50E3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>45°From Rolled</td>
<td></td>
<td></td>
<td>1.2,3*,4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>Through</td>
<td></td>
<td></td>
<td>3*,4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>-45°From Rolled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Hydraulic Load</td>
<td>1.00E0</td>
<td>Rolled</td>
<td>200</td>
<td>3,4</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E0</td>
<td></td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td>Through</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td></td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Compression</td>
<td>Hydraulic Load</td>
<td>1.00E-4</td>
<td>Rolled</td>
<td></td>
<td>3**,4</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E-2</td>
<td></td>
<td></td>
<td>3*,4</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>1.00E0</td>
<td>Through</td>
<td></td>
<td>1,2</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Kolsky Bar</td>
<td>1.50E3</td>
<td>Rolled</td>
<td></td>
<td>3**,4</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>3.00E3</td>
<td></td>
<td></td>
<td>1,2</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>1.50E3</td>
<td>Through</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>45°From Rolled</td>
<td></td>
<td></td>
<td>3*,4</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Hydraulic Load</td>
<td>1.00E0</td>
<td>Rolling</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E0</td>
<td></td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td></td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td></td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>45°From Rolled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Torsion</td>
<td>Hydraulic Load</td>
<td>1.00E-4</td>
<td>Through</td>
<td>Room Temp</td>
<td>4</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>1.00E0</td>
<td>Through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>Kolsky bar</td>
<td>5.00E2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>1.50E3</td>
<td>Through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>Hydraulic Load</td>
<td>1.00E0</td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>Hydraulic Frame</td>
<td>1.00E0</td>
<td></td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td></td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
<td>1.00E0</td>
<td></td>
<td>-50</td>
<td></td>
</tr>
</tbody>
</table>

*Tests Completed by Ravi Yatnalkar[12]
**Tests Completed by Both Researchers
The 6.35mm plate, labeled plate 3, was extensively tested and presented by Yatnalkar[12] under the same project. This plate was tested in tension at strain rates of \(1.0 \times 10^{-4}s^{-1}\), \(1.0 \times 10^{-2}s^{-1}\), \(1.0s^{-1}\), \(5.0 \times 10^2s^{-1}\), and \(1.5 \times 10^3s^{-1}\). The plate was also tested in a range of orientations to check for anisotropic effects in the material at a strain rate of \(1.0s^{-1}\). In this work, tension testing at temperatures of \(-50^\circ C\), \(200^\circ C\), \(400^\circ C\), and \(600^\circ C\) are completed. Compression tests were previously completed at strain rates of \(1.0 \times 10^{-4}s^{-1}\), \(1.0 \times 10^{-2}s^{-1}\), \(1.0s^{-1}\), \(1.5 \times 10^3s^{-1}\), and \(3.0 \times 10^3s^{-1}\), elevated temperatures ranging from \(200^\circ C\) to \(600^\circ C\), and on specimens with various orientations. Compression tests are conducted here at \(-50^\circ C\) to complete the temperature test series for plate 3. Specimens for plate 3 were also fabricated in the directions shown in Figure 2.1. Results from these additional tests and a comparison to the other tests are presented in Chapter 3.
The 12.7mm plate, labeled plate 4, is tested in tension and shear at strain rates of $1.0 \times 10^{-4}s^{-1}$, $1.0 \times 10^{-2}s^{-1}$, $1.0s^{-1}$, $5.0 \times 10^2s^{-1}$, and $1.5 \times 10^3s^{-1}$. Compression tests are completed at strain rates of $1.0 \times 10^{-4}s^{-1}$, $1.0 \times 10^{-2}s^{-1}$, $1.0s^{-1}$, $1.5 \times 10^3s^{-1}$, $3.0 \times 10^3s^{-1}$, and $8.0 \times 10^3s^{-1}$. Tension anisotropic effects are investigated in the rolled, $45^\circ$ from rolled, transverse, and $-45^\circ$ from rolled directions at a strain rate of $1.0s^{-1}$. Compression anisotropy effects are determined from tests at these orientations in addition to the through direction. Tests are conducted in tension, compression, and shear at temperatures ranging from $-50^\circ C$ to $600^\circ C$ at a strain rate of $1.0s^{-1}$. Temperature specimens are made from the rolled direction for tension and compression and in the through direction for the torsion specimens. Fabrication directions are shown in Figure 2.2. This plate stock is also used to determine of the fracture characteristics of the material.
2.2.1 Tension Experiments

Plastic deformation tension tests are conducted on thin flat dog-bone specimens. The specimens have size constraints due to the nature of the high strain rate testing. The strain rate of a specimen in a Kolsky bar, which will be discussed later, is inversely proportional to the gage length. For consistency, specimen geometry for all strain rate, temperature, and orientation tests are conducted on the same specimen geometry, seen in Figure 2.3

![Figure 2.3: Plane stress smooth specimen used in plastic deformation testing](image)

The tension specimens have their profiles cut out and are sliced from the plate stock with the use of Electrical Discharge Machining (EDM). To ensure the base material is tested the specimens are precision ground to remove the EDM recast layer. Since the side of the gage section comparatively represents a much smaller area in comparison this is assumed to have a limited affect on the data and therefore not ground. Due to small variabilities in the specimen gage cross-section sizes, dimensions are measured and recorded prior to testing.

Force, $F$, and displacement, $\Delta L$, are recorded for all tension tests. Engineering stress, $\sigma_e$, and engineering strain, $\epsilon_e$, are calculated for these records. These are given
by,

\[ \sigma_e = \frac{F}{A}, \]  \hspace{1cm} (2.1)

and

\[ \epsilon_e = \frac{\Delta L}{l_g}, \]  \hspace{1cm} (2.2)

where, \( A \) is the cross sectional area of the specimen, and \( l_g \) is the initial specimen gage length.

### 2.2.2 Compression Experiments

Compression tests are conducted on a solid cylindrical specimen, as seen in Figure 2.4. The length to diameter ratio of the compression specimens is kept close to one to limit buckling during testing. If buckling occurs, a complex stress state exists and the test is no longer uniaxial.

![Compression specimen](image)

Figure 2.4: Compression specimen used in plastic deformation testing

Specimens are cut from the plate using conventional machining and turned to size on a lathe. In order to maintain uniaxial stress, the parallelism of the top and bottom of the specimen is controlled to within 0.025mm. Specimen dimensions are carefully measured and recorded prior to testing to monitor slight differences in fabrication.
Force and displacement are also recorded for the compression testing where the stress and strain will be negative. This negative value is consistent with compressive load and negative change in length.

2.2.3 Shear Experiments

Shear properties for Ti-6Al-4V are determined using of thin-walled torsion specimens shown in Figure 2.5. The specimens seen here are the high strain rate specimens which are glued into an adapter. The low strain rate specimens have a hexagonal gripping section so the screws, which are also placed in a hexagonal arrangement, align with the specimen. For strain rates of $1.0 \times 10^{-4}s^{-1}$ to $5.0 \times 10^{2}s^{-1}$ the gage length is 2.54mm. For the highest strain rates ($> 1.5 \times 10^{2}s^{-1}$) the gage length is reduced to 1.78mm since the strain rate is inversely proportional to gage length. The inside diameter and wall thickness dimensions are identical.

![Figure 2.5: Torsion specimen used in plastic deformation testing](image)

Shear stress, $\tau$, and shear strain, $\gamma$, and are given by
\[ \tau = \frac{T}{2\pi r_m^2 h} \tag{2.3} \]

and

\[ \gamma = \frac{\theta r_m}{L_s} \tag{2.4} \]

where, \( T \) is the measured torque, \( r_m \) is the mean radius, \( J \) is the polar moment of inertia, \( \theta \) is the angle of rotation, and \( L_s \) is the gage length of the specimen. A geometric representation of the shear specimen gage section is shown in Figure 2.6.

Shear displacements are calculated by tracking the relative motion of two points in space at the top and bottom of the specimen. As the points move during the test, the \( x \) and \( z \) displacements for both the top and bottom points are tabulated, shown in Figure 2.6. The angle of twist, \( \Delta \theta \), is calculated by taking the difference of the top
and bottom points. The angle is calculated by

\[
\Delta \theta = \arccos \left( \frac{(r_o - \Delta z)^2 + r_o^2 - \Delta x^2}{2r_o(r_o - \Delta z)} \right),
\]

(2.5)

where, \( r_o \) is the outside radius, \( \Delta z \) is the z displacement, \( \Delta x \) is the x displacement.

2.2.4 Comparison of the Results from the Plastic Deformation Testing

Tension and compression engineering stress-strain curves look very different as seen in Figure 2.7. These curves do not match in part because of transverse deformation. In tension, the cross-section of the sample reduces as it extends. In compression the cross-section of the sample increases as it is compressed. Engineering stress is simply the load divided by initial area. True, or logarithmic stress strain takes into account this positive or negative change in cross-sectional, making it a better metric to compare the two modes of loading. These values are given by

\[
\epsilon_t = \ln (1 + \epsilon_e),
\]

(2.6)

and

\[
\sigma_t = \sigma_e (1 + \epsilon_e),
\]

(2.7)

where, \( \epsilon_t \) is true strain, \( \epsilon_e \) is engineering strain, \( \sigma_t \) is true stress, and \( \sigma_e \) engineering strain. Once localization occurs these formulae are no longer valid because the deformation is no longer uniform.

Shear tests are compared here by calculating the effective stress and equivalent strain. Effective stress, \( \sigma_{eff} \), is found by substituting a pure shear stress state into Equation 1.6. The result is,

\[
\sigma_{eff} = \sqrt{3}\tau,
\]

(2.8)
Similarly the equivalent strain increment, $d\epsilon_{eff}$ is given as

$$d\epsilon_{eff} = \left( \frac{1}{2} d\epsilon_{ij} d\epsilon_{ij} \right)^{\frac{1}{2}} = \frac{d\gamma}{\sqrt{3}}, \quad (2.9)$$

where,

$$\epsilon_{ij} = \begin{bmatrix} 0 & \gamma/2 & 0 \\ \gamma/2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$ \quad (2.10)

These values can then be easily compared to the tension and compression effective stress-strain curves shown in Figure 2.7. Here we can see the elastic modulus in shear is now in agreement with the moduli for tension and compression. The stress levels in tension, compression, and shear do not match. This, however, is a property of Ti-6Al-4V plate and is exhibited in some other materials.

### 2.3 Ductile Fracture of Ti-6Al-4V

Ductile fracture testing is conducted on several different specimen types including plane stress (thin, flat specimens), plane strain (thick, flat specimens), axisymmetric
(round), and combined loading (thin walled tube). These specimens are all fabricated from plate 4. All specimens are fabricated with the loading direction parallel to the rolled direction shown in Figure 2.8.

Figure 2.8: Fracture specimen manufacturing orientations for the 12.7mm plate stock

All tests are conducted with a cross head velocity of 0.254mm/s which represents a strain rate close to $1.0 \times 10^{-2} \text{s}^{-1}$. Due to strain localization caused by different stress states the strain rate of the tension experiments will vary between tests. Combined loading tests undergo an increasing strain rate since the stress state is maintained in load and torque control.

The various stress states explored in this test series are used to construct a fracture locus. Several different geometries of the specimen types are used in order to effectively populate the locus used in the fracture model for MAT224. These various
specimens provide a range of values for both the triaxiality and Lode parameter. As seen in Figure 2.17, both the stress triaxiality and Lode parameter change throughout the test. In order to quantify the stress state, ultimately to create the fracture surface, representative values must be given to the stress state of the specimen. The stress state parameters presented here are weighted with the specimen plastic strain. The average stress triaxiality is given by

$$\bar{\sigma}^* = \frac{\int \sigma^* d\epsilon^p}{\epsilon^p_f}$$

With the average Lode parameter is given by

$$\bar{\mu} = \frac{\int \mu d\epsilon^p}{\epsilon^p_f}$$

Numerical simulations, which are completed with LS-DYNA, are used to design the specimens used in the fracture test series. Plane stress samples are designed such that the stress triaxiality ranges from 0.400 for a smooth gage section to 0.583 with a sharp notch. Plane strain samples have a thick gage section to achieve a state of plane strain in the center of the specimen. A thickness of 25.4mm was determined to yield plane strain conditions by other researchers[21]. Stress triaxialities of 0.470 and higher can be achieved with a smooth gage section and notches of varying radii. Axisymmetric samples are capable of obtaining stress triaxialities ranging from 0.369 for a smooth gage section to nearly hydrostatic tension ($\sigma_1 >> \sigma_2 = \sigma_3$ or $\sigma^* = 1$) for a sharp notch radius. Since the axisymmetric samples have the ability to bridge stress triaxiality values of both the plane stress and plane strain specimens, they will be used to compare similar stress states.

Simulations are run in LS-DYNA to design specimens with specific average stress triaxialities and Lode parameters. For all simulations, meshes are constructed such
that the element lengths are constant at 0.152mm/element. The resulting mesh density translates to 5 elements across the thickness of the plane stress samples, 32 elements across the minimum notch diameter of the axisymmetric samples, and 167 elements across the thickness of the plane strain samples. Hypermesh version 9.0 is used to create the meshes, which can be seen in Figure 2.9. The Johnson-Cook material model (MAT015) is used for these initial tests. The parameters used were those found by Lesure[22] and are tabulated in Table 1.2. Complete meshes for each of the specimens is presented in Appendix C.

![Figure 2.9: Points of interest for: (a) plane stress, (b) axisymmetric and (c) plane strain specimens](image)

The failure point of interest for each of the specimen types is taken from the center most point, as shown in Figure 2.9. This point of interest is used because
the void nucleation is assumed to begin here. Element aspect ratios near this point are nearly 1.0. For axisymmetric meshes the element aspect ratio increases moving radially outward from the center of the cross-section. This was deemed acceptable since stress state of interest lies on the axis of symmetry where the aspect ratio is nearly 1.0. Load is applied to the specimen by fixing one end and applying a constant-velocity actuator motion to the other.

2.3.1 Plane Stress Fracture Testing

Thin flat specimens are tested to approximate a state of stress where the out of plane stress is zero giving rise to the plane stress condition. This state is shown in Figure 2.10. Plane stress testing includes specimens with several notch radii, providing alternate stress states as seen in Table 2.2. Plane stress specimen geometries are pre-determined based on the specimens used by Seidt[21]. The thickness and notch width dimensions are set at 0.76mm and 3.05mm, respectively for the notched specimens. The three notched specimens have radii of 14.29mm (SG2), 4.76mm (SG3), and 0.40mm (SG4). Stress triaxialities and effective plastic fracture strains are calculated from LS-DYNA simulations using the methods established above. The results of these simulations are presented in Table 2.2. These simulations predict average triaxialities ranging from 0.400 to 0.583 and Lode parameters ranging from -0.014 to 0.845.

These specimens are manufactured using the same methods described for the plastic deformation tension specimens (see section 2.2.1). All specimens are measured prior to testing. Thickness and width at the minimum cross section are recorded.
Table 2.2: Experimental outline for the plane stress fracture testing

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Geometry</th>
<th>Specimen Dimensions</th>
<th>( \sigma^* )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG1</td>
<td>Thin Smooth Specimen</td>
<td>Gage Length: 5.08mm</td>
<td>0.400</td>
<td>0.845</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Width: 2.03mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Thickness: 0.762mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG2</td>
<td>Thin Large Notched Specimen</td>
<td>Notch Radius: 14.29mm</td>
<td>0.431</td>
<td>0.719</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min Notch Width: 3.05mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: 0.762mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG3</td>
<td>Thin Medium Notched Specimen</td>
<td>Notch Radius: 4.76mm</td>
<td>0.489</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min Notch Width: 3.05mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: 0.762mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG4</td>
<td>Thin Small Notched Specimen</td>
<td>Notch Radius: 0.40mm</td>
<td>0.583</td>
<td>-0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min Notch Width: 3.05mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness: 0.762mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.2 Plane Strain Fracture Testing

Thick tension specimens are tested for a state of plane strain in the center of the specimen, where $\varepsilon_x$, $\gamma_{xz}$, $\gamma_{yz}$ are assumed to equal zero. Although the transverse strains ($\varepsilon_{xx}$) near the edge are non-zero they become close to zero at the center of the specimen. A graphical representation of this strain state can be seen in Figure 2.11.
Plane strain specimen geometries are pre-determined based on previous research done by Seidt[21]. Three geometries are tested including a smooth gage section and two notched specimens. The thickness and notch width dimensions were set at 25.4mm and 2.032mm, respectively along with two notch radii of 12.7mm, 4.763mm. Simulations are run and stress triaxialities and Lode parameters are calculated. Results of these simulations are presented in Table 2.3. These specimens have average triaxialities ranging from 0.470 to 0.768 and Lode Parameters ranging from 0.025 to 0.506.
Table 2.3: Experimental outline for the plane strain fracture testing

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Geometry</th>
<th>Specimen Dimensions</th>
<th>$\sigma^*$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG11</td>
<td>Axisymmetric Smooth Specimen</td>
<td>Gage Length: 10.16mm Gage Width: 2.03mm Gage Thickness: 25.40mm</td>
<td>0.470</td>
<td>0.506</td>
</tr>
<tr>
<td>SG12</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 12.70mm Gage Width: 2.03mm Gage Thickness: 25.40mm</td>
<td>0.660</td>
<td>0.040</td>
</tr>
<tr>
<td>SG13</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 4.76mm Gage Width: 2.03mm Gage Thickness: 25.40mm</td>
<td>0.768</td>
<td>0.025</td>
</tr>
</tbody>
</table>
2.3.3 Axisymmetric Fracture Testing

Axisymmetric specimens have a circular cross sectional area in the gage section. This geometric shape creates a state of stress where $\sigma_y \gg \sigma_x = \sigma_z$. The stress state can be seen in Figure 2.12. Since $\sigma_2 = \sigma_3$ or $\sigma_x = \sigma_z$, the Lode parameter (Equation 1.8) for all axisymmetric specimens is 1.0. These specimens have the ability to cover triaxiality ranges of both the plane strain and plane stress specimens.

Figure 2.12: State of stress in the axisymmetric fracture specimen

Five axisymmetric geometries are determined such that the resulting average stress triaxialities are close to those from the plane stress and plane strain specimens. The minimum gage diameter for each axisymmetric specimen is set at 4.763mm. The notch radii are determined iteratively with the initial trial radius determined from Bridgemans analytical solution of the stress field at the neck of an axisymmetric tensile bar[26]. The following equation[26] relates the stress triaxiality to the dimensions of the necked sample given by

$$\sigma^* = \frac{1}{3} + \ln \left(1 + \frac{a}{2R}\right),$$  \hspace{1cm} (2.13)
where, \( a \) is the minimum cross-sectional radius, and \( R \) is the radius of the notch or neck. A sketch showing the critical dimensions of this analysis is shown in Figure 2.13[27].

![Sketch of Bridgman’s analysis of a necked axisymmetric sample](image)

Figure 2.13: Sketch of Bridgman’s analysis of a necked axisymmetric sample

Using the methods established in the previous section, a simulation of the trial geometry is performed and the stress triaxiality and effective plastic fracture strain are calculated. It should be noted that as the specimen deforms the stress state is evolving which makes the Bridgman’s approximation unreliable.

An iterative process is used to determine the notch radius required to approximately match the stress triaxiality of either a plane stress or plane strain specimen. If the axisymmetric average value is within 5% of the target value, it is determined that the radius is acceptable and the iterative process is complete. If the axisymmetric triaxiality is outside of the acceptable range (error \( \geq 5\% \)), a new radius is determined, the mesh is constructed and the simulation run. Since the notch radius is inversely proportional to the stress triaxiality, an approximation for next trial radius is made.
The final specimen dimensions are listed along with the resulting average triaxialities and Lode parameters in Table 2.4.

Attempting to match the plane stress SG4 sample leads to an unreasonably large notch radius. Due to this, there is no match to this plane stress specimen but a smaller notched axisymmetric specimen (SG10) is added to extend the covered triaxiality range. The results of this iterative procedure led to simulated average triaxialities ranging from 0.369 to 0.956 and Lode parameters of 1.0.

These specimens were fabricated by first taking a cylindrical slug oriented with its axis parallel to the rolled direction with an EDM machine. Second, the notches are turned down using a CNC lathe to maintain a consistent radius.
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Geometry</th>
<th>Specimen Dimensions</th>
<th>$\sigma^*$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG5</td>
<td>Axisymmetric Smooth Specimen</td>
<td>Gage Length: 24.13mm</td>
<td>0.369</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG6</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 34.93mm</td>
<td>0.492</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG7</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 17.46mm</td>
<td>0.564</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG8</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 11.91mm</td>
<td>0.618</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG9</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 6.75mm</td>
<td>0.751</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG10</td>
<td>Axisymmetric Notched Specimen</td>
<td>Notch Radius: 3.18mm</td>
<td>0.956</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gage Diameter: 4.76mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.4: Experimental outline for the axisymmetric fracture testing
2.3.4 Combined Loading Testing

An effective method of populating additional points on the fracture locus is to use combined loading experiments[21] where a tubular specimen undergoes torsion-tension, torsion-compression, or pure torsion loading as seen in Figure 2.14. A wide range of stress states can be achieved by varying the ratio between the specimen’s axial stress and shear stress. The axial load, $P$, can be positive or negative, giving tensile or compression stress, respectively. The specimen is also subjected to a torque, $T$, creating a state of stress unlike those presented previously. This state has both $\sigma_x$ and $\tau_{xy}$ as seen in figure 2.14, the magnitudes of which can be manipulated giving various stress states. The stress state is

$$\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} & 0 \\ \tau_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{2.14}$$

The stress triaxiality is

$$\sigma^* = \frac{\sigma_m}{\sigma} = \frac{\sigma_x}{\frac{\sigma^2_x + 3\tau^2_{xy}}{3}} = \frac{\sigma_x/\tau_{xy}}{3\sqrt{3 + (\sigma_x/\tau_{xy})^2}}, \tag{2.15}$$

and the Lode parameter (equation 1.8) is

$$\mu = \frac{\sigma_x}{2\sqrt{\left(\frac{\tau_{xy}}{\sigma_x}\right)^2 + \tau^2_{xy}}} = \sqrt{\frac{\sigma_x/\tau_{xy}}{4 + \sigma_x/\tau_{xy}}}. \tag{2.16}$$

Using Equation 2.15 and 2.16 the triaxiality and Lode parameter can be found from stress ratios. The curves in Figure 2.15, determine the ratio of axial stress to torsional stress needed to provide the desired state of stress. It should be noted that this state of stress is relatively simple and does not evolve during the test. Therefore, parallel finite element analysis is not required to determine specimen geometries. The geometries for the combined loading tests (summarized in Table 2.5) are taken from Seidt[21] to maintain consistency in testing techniques under the same project.
These tests are largely dependent on the axial torsional stress ratio, where \( \sigma_x/\tau_{xy} > 0 \) signifies a tensile axial load and \( \sigma_x/\tau_{xy} < 0 \) is compressive. Pure shear is obtained from \( \sigma_x/\tau_{xy} = 0 \). The combined loading stress state parameters are mathematically limited to a range of triaxialities and Lode numbers. Stress triaxialities can range from -0.333 to 0.333 while Lode parameter can range from -1.0 to 1.0. Loading ratios \( (\sigma_x/\tau_{xy}) \) of 1.971, 0.847, 0.00, and -0.847 were chosen for these experiments, which correspond with experiments done previously[21]. Torsion-compression tests are practically limited due to the potential for buckling in the specimen, which would result in an unwanted complex stress state.

The plane stress, plane strain, and axisymmetric specimens were fabricated from plate 4 all with the loading direction parallel to the rolled direction as seen in Figure 2.14. State of stress within a combined loading specimen
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Geometry</th>
<th>Specimen Dimensions</th>
<th>$\sigma^*$</th>
<th>$\mu$</th>
<th>$\frac{\sigma_y}{\tau_{xy}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR1</td>
<td>Combined Tension-Torsion</td>
<td>Gage Length: 3.18mm Inside Diameter: 7.93mm Outside Diameter: 9.14mm</td>
<td>0.251</td>
<td>0.702</td>
<td>1.971</td>
</tr>
<tr>
<td>LR2</td>
<td>Combined Tension-Torsion</td>
<td>Gage Length: 3.18mm Inside Diameter: 7.93mm Outside Diameter: 9.14mm</td>
<td>0.147</td>
<td>0.390</td>
<td>0.847</td>
</tr>
<tr>
<td>LR3</td>
<td>Pure Shear</td>
<td>Gage Length: 3.18mm Inside Diameter: 7.93mm Outside Diameter: 9.14mm</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>LR4</td>
<td>Combined Compression-Torsion</td>
<td>Gage Length: 3.18mm Inside Diameter: 6.35mm Outside Diameter: 9.14mm</td>
<td>-0.147</td>
<td>-0.390</td>
<td>-0.847</td>
</tr>
</tbody>
</table>
Figure 2.15: Stress state parameters for the combined loading specimens at differing stress component ratios

2.8. The line of symmetry for the torsion spool specimens, used in the plastic deformation tests, lies along the through direction of the plate. Due to the differences in fabrication orientation, varying results may be seen between the two sets of data.

2.3.5 Fracture Parameter Determination

Parallel simulations are completed for each tension fracture specimen to find the state of stress and equivalent plastic fracture strain, as seen in Figure 2.16. Theory predicts that the failure will occur due to the coalescence of voids at the center of the specimen[28]. Therefore stress state and plastic strain must also come from this point (see point of interest in Figure 2.9). Digital Image Correlation can only measure the surface strains of a specimen, however, the point of interest is in the interior of the specimen. LS-DYNA simulations are completed with the same mesh parameters as
those used for the initial specimen design process. Meshes for each of the specimen types can be seen in Appendix C. A Simplified Johnson-Cook (MAT098) material model calibrated with the data from the plasticity test series is used to model the specimen material. The mesh is constructed for three dimensional constant stress elements. The simulations are intentionally run without a failure model. Simulated results are manually truncated to match the force displacement curve of each experiment. The truncation of simulated data occurs where the experimental specimen is unloaded due to failure. Results are presented in Chapter 4.

The principle stresses, effective stress, effective plastic strain, and directional strains are extracted and tabulated for each of the experiments. Simulated strains from the surface of the specimen are compared to those measured experimentally. The simulated reaction force of the constrained specimen is also compared to experimental load data. Stress triaxiality and Lode parameter are determined from the data recorded at the point of interest using equations 1.4 and 1.8 respectively.

Experimental (DIC) and simulated displacement data are synchronized, as seen in Figure 2.17. This plot shows the simulated and experimental stresses in blue, the strains in green, and the stress state parameters in red. The simulated interior strains differ from the simulated surface strains. This is due to the difference in stress state between the interior element and surface element. The surface strains measured with DIC also disagree with the surface strains in the simulation. This is due to the fact that the element size in the simulation is significantly smaller than the virtual strain gage lengths of the DIC measurements. The simulated data is truncated at the point that the physical specimen breaks. This break is signified by a rapid drop in load which is shown as a gray vertical line. This is completed for each of the physical
tests and the corresponding stress state values are averaged, using Equation 2.11 and Equation 2.12.

Figure 2.16: Strain comparison from an experimental axisymmetric notched specimen and parallel simulation

The combined loading specimen stress state is only dependent on the loading ratio, which is directly proportional to the load and torque. Therefore no simulations are needed. The fracture strain in this case is taken from DIC data. The virtual strain gage length for these tests are similar to those used in the tension fracture tests.

Fracture strain and stress state data are used to create the fracture locus. These data are presented and discussed in Chapter 4. A complete presentation of the data for each of the specimens is found in Appendix D.
2.4 Quasi-static Strain Rate Testing Techniques

An Instron 1321 Servo-hydraulic biaxial load frame, see figure 2.18, is used to conduct the fracture, anisotropic, temperature, and any strain rate test series (strain rates at and below 1.0s\(^{-1}\)). This machine has the capability to move axially ±61.2mm and rotate ±45°. This one test apparatus can conduct uniaxial tension tests, compression tests, torsion tests, or a combination of these loading conditions. Measurements are taken with two load cells: a Lebow 6467-107 with a capacity of 89kN (1100Nm) and an Interface 1216CEW-2k with a capacity of 8.9kN (110Nm) depending on the amount of force expected. This machine is controlled by an external computer and an MTS FlexTest SE controller. The controller acquires data through MTS 493.25 Digital Universal Conditioners, with a maximum rate of data capture of 100kHz. The
load frame's actuator is controlled from a Linear Variable Differential Transformer (LVDT) and a Rotational Variable Differential Transformer (RVDT). Records from these devices are also acquired however strain computations from these measurements are susceptible to machine and grip compliance and can result in error.

Figure 2.18: Instron 1321 servo-hydraulic biaxial load frame equipped with hydraulic wedge grips
The DMML has multiple specimen gripping options. Room temperature tension tests with an axial load below 31kN are performed with MTS647.02B-22 hydraulic wedge grips. These grips accommodate several different wedge designs. The flat plane stress specimens are gripped with a flat knurled grip, while the axisymmetric and combined loading specimens are gripped with a vee notch wedge. The plane strain and combined loading specimens with an axial force greater than 31kN required the MTS647.10A-11 hydraulic wedge grips which has a maximum axial load of 120kN. For the high and low temperature testing, specially designed bars, long enough to attach the specimens within the furnace, are used. The bars are fabricated from Inconel 718 because of the material’s high strength, high operational temperatures, and good thermal properties. The bars are equipped with cooling collars and various heads depending on the loading type. The bars must be properly aligned since small deviations of concentricity of the bars are detrimental to loading conditions and the experimental results. Alignment is completed using two dial indicators set 90° apart attached to the top or bottom collet fixture. As the actuator base is rotated ±90°, the indicators deviate either positive or negative thus showing the required direction of bar adjustment. Bars are adjusted at the collet and aligned to within ±0.05mm at the specimen attachment point. This process is completed for both the top and bottom bars. Tension grips, also fabricated from an Inconel 718, thread into the 718 bars. These grips clamp the specimen into place using four #4-40 screws. Alignment grooves in the tension grips are used to center the specimen during attachment.

Compression tests are conducted using steel push rods or Inconel bars as discussed above. In all cases, Tungsten Carbide (WC) inserts are used as compression platens to avoid fixture deformation. High and low temperature tests employ the previously
discussed Inconel bars outfitted with Inconel 718 compression fixtures and tungsten carbide compression platens. At room temperature, shorter steel push rods equipped with tungsten carbide platens are used. The steel room temperature fixtures are aligned with a pin that connects both rods together until collets are tightened. After tightening, the platens are installed and checked for parallelism. The specimen-plate interference is lubricated with Molybdenum disulfide (MoS$_2$) to minimize friction and specimen barreling (a non-uniaxial stress state). The specimens are centered on the platens and a small preload ($< 0.1\sigma_y$) is applied prior to testing.

Figure 2.19: Test setup used for the quasi-static compression tests

Low strain rate shear tests are conducted by applying torque to thin walled tube specimens. The specimens have hexagonal grip flanges, which are attached to the grips with a hexagonal screw pattern. The specimen is loosely placed into the grip and the screws are tightened one at a time in a fashion that does not put a significant
amount of torque or axial load on the specimen. To ensure that the specimen is loaded along the axis of the load frame, the outer diameter of the hexagonal specimen flange is machined to match the inner diameter of the gripping bars. The grips are aligned using the indicator method described previously. The bars are made from MAR-246, a high temperature alloy. This method is used for the low, room and high temperature testing.

2.5 High Strain Rate Testing Techniques

Dynamic behavior of Ti-6Al-4V is experimentally determined using the Kolsky Bar or Split-Hopkinson Bar tests. This method, first proposed by Kolsky [29], uses elastic stress wave propagation in two long bars to determine the dynamic plastic deformation behavior of a specimen placed in the middle. This technique has become a widely used method for dynamic testing and has been modified for both tension and torsion. Typical strain rates of $500 \text{s}^{-1}$ to $8000 \text{s}^{-1}$ are obtained, depending on the sample dimensions, strength, and the machine loading conditions. The following section describes the Kolsky bars used by the DMML and appropriate data processing techniques.

2.5.1 High Strain Rate Compression Testing

The compression Kolsky Bar at the DMML, see Figure 2.20 and 2.21, consists of three 12.7mm diameter Ti-6Al-4V rods. The 610mm long striker bar is fired into the incident bar at velocities up to 40m/s. The impact creates an incident wave that has a duration of approximately 250 $\mu$s. The incident and transmitter bars are 1880mm long. A momentum trap at the end of the transmitter bar uses an energy damping material to bring the bars to rest. Strains in the incident and transmitter bars are measured
with strain gages arranged in a full Wheatstone bridge configuration. 15.0V excitation is provided through two Hewlett-Packard E3611A power supplies. The bridges are constructed from four Micro-Measurements ED-DY-125AC10C 1000Ω strain gages placed in the center of both the incident and transmitter bars. The signals are conditioned with Stanford Research Systems model SR560 preamplifier with a low pass filter. The signals are measured with a four channel 350MHz, 8 bit Tektronix TDS5034B digital phosphor oscilloscope at a rate of $2.5 \times 10^6$Hz. To reduce friction and maintain uniaxial compression in the sample, Molybdenum disulfide grease is used to lubricate the interface between the bars and the specimen. The compressive properties of Ti-6Al-4V at and above strain rates of 500s$^{-1}$ are determined with this apparatus.

Figure 2.20: Compression Kolsky bar located in the DMML

Gray[30] provides an overview of the test method and the analysis necessary for the compression Kolsky bar technique. A gas gun fires a striker bar which impacts the incident bar creating an elastic strain wave, $\epsilon_i$, that travels through the incident bar and into the specimen. The incident wave amplitude is dependent on the striker
bar velocity, \( v \), and is given by

\[
\epsilon_i = \frac{v}{2c_b},
\]

(2.17)

where, \( c_b \) is the longitudinal elastic wave velocity which is

\[
c_b = \sqrt{\frac{E_b}{\rho_b}},
\]

(2.18)

where, \( E_b \) is the elastic modulus, and \( \rho_b \) is the density. When the incident wave reaches the specimen, it deforms plastically. Part of the wave travels through the specimen into the transmitter bar. This is the transmitted wave, \( \epsilon_t \). The remainder of the incident wave reflects back into the incident bar creating a tensile wave, \( \epsilon_r \), which unloads the bar. The engineering stress in the specimen is proportional to the measured transmitted pulse and is given by

\[
\sigma(t) = \frac{E_b A_b \epsilon_t}{A_s},
\]

(2.19)

where, \( A_b \) is the cross sectional area of the bar, and \( A_s \) is the cross sectional area of the sample. The strain rate in the specimen is proportional to the difference in velocity between the ends of transmitter (\( u_t \)) and incident (\( u_i \)) bars or,

\[
\dot{\epsilon} = \frac{\dot{u}_i - \dot{u}_t}{l_s} = \frac{2c_b \epsilon_r}{l_s},
\]

(2.20)
where, \( l_s \) is the gage length of the specimen. This time dependent strain rate is integrated to find the strain history of the specimen. Forces in the two bars are found from

\[
F_i = A_b E_b (\epsilon_i + \epsilon_r),
\]

\[
F_t = A_b E_b \epsilon_t.
\]

Wave data from a typical test, seen in Figure 2.22, shows the square input pulse starting at approximately 100\( \mu s \) and ending at 350\( \mu s \). The reflected pulse starts at 475\( \mu s \) and the transmitted pulse starts at approximately 500\( \mu s \). In this case, the test is over when transmitted wave drops sharply approximately 100\( \mu s \) after the specimen loading begins, indicating specimen fracture. The previously discussed data reduction method is used to process the data in Figure 2.23. The data shows a sharp rise in both stress level and strain rate and a slower rise in strain. The specimen yields, represented by the significant decrease in slope of the stress curve at approximately 20\( \mu s \), and plastic deformation begins.

Due to the strength of the material being tested, in relation to the apparatus bars, damage to the machine is possible. WC inserts are used to protect the bars but changes in mechanical impedance will cause elastic waves to reflect. These reflections cause unwanted noise which can be eliminated through impedance matching. The mechanical impedance is given by

\[
Z = \rho A c,
\]

where, \( \rho \) is the density, \( A \) is the cross sectional area, and \( c \) is the longitudinal elastic wave speed. The density and wave speed, which is dependent on the elastic modulus, of WC are higher than that of Ti-6Al-4V. Due to this, the cross sectional area must
Figure 2.22: Typical wave data from a compression Kolsky bar experiment on Ti-6Al-4V

Figure 2.23: Reduced wave data from a compression Kolsky bar experiment on Ti-6Al-4V
be smaller to maintain a similar impedance between the bars and the inserts. For the tests performed here, 6.35mm diameter WC inserts are used as seen in Figure 2.24.

Figure 2.24: Tungsten carbide inserts used with the compression Kolsky bar

2.5.2 High Strain Rate Tension Testing

The principles of the direct tension Kolsky bar and the previously described compression Kolsky bar are similar, however, there are some differences in the machine design and operation. The most notable difference is the method of generating the loading wave in the incident bar. The construction of the direct tension bar is somewhat different than the compression bar as seen in Figures 2.25[21] and 2.26[21]. There are multiple methods of creating and incident tensile wave, however the method utilized here, described by Staab and Gilat[31], employs a long input bar that stores an initial preload which is released by fracturing a pin.

The incident wave is generated by clamping the input bar at approximately mid span with the clamp shown in 2.26. A tension load, $P$, is applied to the end opposite the specimen using a pulley system. The initial preload is proportional to the strain rate and is measured with a full Wheatstone bridge loaded between the pulley and the clamp. The clamp has a pin at the top which is broken with a hydraulic cylinder.
allowing the tensile incident wave to propagate towards the specimen. The wave magnitude is equal to half of the stored load.

The 12.7mm diameter, 7075-T651 aluminum incident and transmitter bars are 3.68m and 1.83m long, respectively. Mechanical connections all have slop in them which leads to relative motion and gives an over estimate of strain. These connection can also cause reflections resulting in noise. Here, the specimens are glued between the two bars with either Hysol Tra-Bond 2106T or J-B Kwik steel reinforced epoxy. Four Micro-Measurements ED-DY-075AM-10C 1000Ω strain gages in a full Wheatstone bridge arrangement measure strains in both bars. Gage A is located 1825mm from the specimen on the incident bar. Gages B and C are are located 365mm from the specimen on both the incident and transmitter bars, respectively. A 15.0V excitation is provided through two Hewlett-Packard 6200B power supplies. Signals from the gages are conditioned with Tektronix ADA400A differential amplifiers with a low pass filter. The signals are measured with a four channel 350MHz, 8 bit Tektronix TDS5034B digital phosphor oscilloscope at a rate of $2.5 \times 10^6$Hz.

Figure 2.25: Schematic representation of the direct tension Kolsky bar
Figure 2.26: Direct tension (left) and torsion (right) Kolsky bars located at the DMML
The strain rate, $\dot{\epsilon}$, of the specimen in the direct tension Kolsky bar is given by,

$$\dot{\epsilon} = \frac{\dot{u}_i - \dot{u}_t}{l_g},$$  \hspace{1cm} (2.24)

where, $l_g$ is the specimen gage length. $\dot{u}_i$ and $\dot{u}_t$ are the incident and transmitter bar velocities, respectively. The velocities are

$$\dot{u}_i = \frac{1}{\rho A_b c_b} \left[ F_A \left( t - \frac{l_A}{c_b} \right) + F_A \left( t - \frac{l_A}{c_b} + 2\frac{l_B}{c_b} \right) - F_B \left( t + \frac{l_B}{c_b} \right) \right],$$  \hspace{1cm} (2.25)

and

$$\dot{u}_t = \frac{1}{\rho A_b c_b} \left[ F_C \left( t + \frac{l_C}{c_b} \right) \right],$$  \hspace{1cm} (2.26)

where, $\rho$ is the density of the bars, $A_b$ is the cross sectional area of the bar, and $c_b$ is the elastic wave speed in the bar. $l_A$, $l_B$, and $l_C$ are the distances from the specimen to the strain gage bridges A, B, and C. $F_A$, $F_B$, and $F_C$ are the forces measured by the respective gages. The specimen stress history is

$$\sigma(t) = \frac{F_C}{A_s} \left( t + \frac{l_C}{c_b} \right).$$  \hspace{1cm} (2.27)
The experimental record, as seen in Figure 2.28, shows the incident wave starting at approximately 30 – 40µs and increasing to a magnitude of roughly 10kN. The incident wave reaches gage B at 325µs and appears to have a much shorter duration than that of the wave in gage A. This is because the wave is reflected when it reaches the specimen and returns to gage B, unloading the bar. The wave that propagates through the specimen is measured by gage C and is proportional to the engineering stress in the specimen. The easiest ways to control the strain rate in the specimen are varying the stored force and the specimen gage length. Processed wave data can be seen in Figure 2.29.

Figure 2.28: Typical wave data from a tension Kolsky bar experiment on Ti-6Al-4V

Impedance mis-match between the bars and the specimen adapters must be avoided to prevent elastic wave reflections. Custom designed adapters are fabricated in order to maintain a constant impedance which follows equation 2.23. The adapter-specimen
Figure 2.29: Reduced wave data from a tension Kolsky bar experiment on Ti-6Al-4V interface has two materials in parallel with one another, see Figure 2.30. The dynamic tension specimen grip section is the same width as that of the quasi-static specimen but 16.3mm in length. This section is used to adhere the specimen to the adapter. Since the specimen grip and adapter impedances are in parallel, the following relationship must be maintained to match the bar impedance,

\[ Z_b = Z_a + Z_s = \rho_a A_a c_a + \rho_s A_s c_s = \rho_b A_b c_b, \]  

(2.28)

where the subscripts \( b, a, \) and \( s \) represent the bars, adapters, and specimen, respectively. The adapter can be designed if the material properties of the bars, specimen, and the adapter are known. In this case, the adapter has outside diameter of 6.35mm, and is fabricated from 6061-T6 aluminum.
2.5.3 High Strain Rate Shear Testing

The stored-torque Kolsky Bar in Figure 2.26, is used to characterize Ti-6Al-4V in shear at strain rates above 500s$^{-1}$. The stored-torsion and direct-tension high strain rate test techniques are similar with the exception of the wave generation method. The torsion loading wave is generated by clamping and applying a pre-torque to a section of the bar, see Figure 2.26. The loading wave is released by fracturing a pin, as in the tension dynamic tests. This technique is described by Gilat[32]. The wave amplitude is equal to half the stored torque, $T$, since the wave propagates both towards and away from the specimen. The strains in the bar are measured with full Wheatstone bridges each using four Micro-Measurements 1000Ω strain gages in positions as shown in Figure 2.32[21]. Gage A is located 1715mm from the specimen on the incident bar. Gages B and C are are located 385mm from the specimen on both the incident and transmitter bars, respectively. The shear strain incident wave
amplitude, $\gamma_i$, is

$$\gamma_i = \frac{Tr_b}{2G_bJ_b}, \quad (2.29)$$

where, $r_b$ is the bar radius, $G_b$ is the shear modulus of the bar material, and $J_b$ is the polar moment of inertia of the bar. As this wave loads the specimen, a portion of the torque is transmitted through the specimen. This is proportional to the shear stress in the specimen. The remaining portion of the torque reflects back and is proportional to the shear strain rate. The angular velocity, $\dot{\theta}_i$, of the end of the incident bar is found from

$$\dot{\theta}_i(t) = \frac{1}{\rho_bJ_bC_t} [T_A(t - t_A) + T_A(t - t_A + 2t_B) - T_B(t + t_B)], \quad (2.30)$$

where, $\rho_b$ is the density of the bar material, $T_A(t)$ and $T_B(t)$ are the torque history in gage A and B, respectively, and $c_t$ is the transverse elastic wave speed which is given by

$$c_t = \sqrt{\frac{G_b}{\rho_b}}, \quad (2.31)$$

The angular velocity of the transmitter bar, $\dot{\theta}_t(t)$, is given by

$$\dot{\theta}_t(t) = \frac{1}{\rho_bJ_bC_t} [T_C(t - t_C)], \quad (2.32)$$

where, $T_C$ is the torque history in the transmitter bar measured by gage C. The shear strain rate with respect to time is now

$$\dot{\gamma}(t) = \frac{r_m}{l_s} \left[ \dot{\theta}_i(t) - \dot{\theta}_t(t) \right], \quad (2.33)$$

where, $r_m$ and $l_s$ are the mean gage radius and gage length of the specimen, respectively. The shear strain is found by integrating the strain rate with respect to time.

The shear stress is found from

$$\tau(t) = \frac{G_bJ_br_m\gamma(t)}{r_bJ_s} = \frac{r_mT_C(t + t_C)}{J_s}, \quad (2.34)$$
where, $J_s$ is the polar moment of inertia of the specimen.

The 22.23mm Kolsky bars are made from 7075-T6 aluminum. The clamped and free sections of the incident bar are 1227mm and 2283mm, respectively. The transmitter bar is 2026mm long. 20.0V excitation to each bridge is provided from HP3611A power supplies. This apparatus uses the same signal conditioning used for the direct-tension Kolsky bar.

Dynamic torsion specimens are similar to the spool specimens used for low strain rate torsion testing. The major difference between these two specimens are the gripping section. Dynamic specimens have a large round flange as seen in Figure 2.31. Dynamic specimen flanges are designed to have the same mechanical impedance as the bars. The flanges are glued into adapters, which cumulatively maintain impedance using the principles previously stated. In this case

$$Z_b = Z_a + Z_s = \rho_a J_{t,a} c_{t,a} + \rho_s J_{t,s} c_{t,s} = \rho_b J_{t,b} c_{t,b},$$

(2.35)

where, $J$ is the polar moment of inertia and the subscripts $b$, $a$, and $s$ represent the bars, adapters, and the specimen, respectively.

![Figure 2.31: Comparison of the grip sections between the low and high strain rate shear specimens](image)

Figure 2.31: Comparison of the grip sections between the low and high strain rate shear specimens
JB-Weld Kwik epoxy is used to glue the specimen to the adapters and the adapter-specimen assemble to the bars. Again, an effective method of increasing strain rate is to decrease the specimen gage length. This does have limitations, however, due to stress concentrations where the gage meets the flanges and it becomes difficult to measure strains on the surface of the specimen. Specimen gage lengths of 2.54mm and 1.78mm are used for tests at strain rates of $5.0 \times 10^2 \text{s}^{-1}$ and $1.5 \times 10^3 \text{s}^{-1}$, respectively. A transition radii of 0.38mm are machined between the flange and the gage sections of the specimens to reduce the stress concentrations.

Data from a typical high strain rate torsion test can be seen in Figure 2.33. The blue, red, and green traces show the torque histories from gage A, B, and C, respectively. Gage A shows an initial rise in torque at approximately 25$\mu$s and unloads when the return wave comes at 850$\mu$s. Gage B initially measures the same torque as Gage A. The amplitude of the wave, measured by gage B decays when the reflected pulse unloads this portion of the bar. Gage C shows the transmitted torque prior to
specimen failure at around 800µs. Dynamic torque equilibrium can be evaluated by comparing of torques measured by gages B and C at approximately 750µs.

![Graph showing torque vs. time for gages A, B, and C.]

Figure 2.33: Typical wave data from a torsion Kolsky bar experiment on Ti-6Al-4V

Processed data for the test in Figure 2.33 can be seen in Figure 2.34. These data show the shear stress in blue which, initially, accumulates slowly due to the rise time of the incident wave. The yield point of the material can coincides with the rapid change in slope of the stress. Shear strain is represented in green and shows slow accumulation in strain initially but then becomes constant at approximately 30µs. Shear strain rate, shown in red, also shows an initially slow rise followed by a leveling off when equilibrium is reached.
Titanium used in aerospace applications can experience various operating temperatures. At altitude, aircraft engine parts outside of the hot section can see subzero temperatures. Ti-6Al-4V normal operating temperatures can reach as high as 400°C. A blade-out event leads to large material deformation at high strain rates. Adiabatic heating takes place under these conditions and temperature increases of 200°C are common. A part at an operating temperature of 400°C can reach temperatures of 600°C with adiabatic heating. Because of this, the test plan includes experiments at −50°C, 200°C, 400°C, and, 600°C.

Elevated temperature tests are performed using a furnace attached to the hydraulic load frame described in section 2.4. The furnace described in depth in Chapter 6, is used for all tension, compression, and shear testing at 200°C, 400°C, and, 600°C. Digital image correlation is used to measure and record displacements and strains on the surface of the specimen. Omega, K-type thermocouples, which have an operating
range of $-200^\circ$C to $1350^\circ$C. Temperature data are recorded at 1Hz and compiled for later analysis.

Tension, compression, and shear cryogenic tests are also performed on the hydraulic load frame. Liquid nitrogen is sprayed inside the Styrofoam chamber seen in Figure 2.35(a), to reach $-50^\circ$C. K-type thermocouples are used to record the temperature of the specimen at a sampling rate of 1Hz. Fog within the chamber makes it impossible to use DIC for low temperature tests. The load frame’s LVDT and RVDT are susceptible to compliance errors. An Epsilon miniature axial extensometer model number 3442-004M050-HT1 is used to measure strain during low temperature tensile tests. The extensometer, seen in Figure 2.35(b), attaches directly to the specimen and has a 4mm initial gage length. Compression displacements are measured with an LVDT located on the compression platens, see in Figure 2.35(b). Rotations in torsion tests are measured with an RVDT located on grips attached to the spool specimen as seen in Figure 2.36. The effect of compliance is minimized since these measurements are taken close to the specimen.

Elevated and low temperature tests provide a more complete description of the plastic deformation material response under actual operating conditions. Data from these tests are presented and discussed in Chapter 3.
Figure 2.35: Cryogenic chamber and test setup for tension and compression testing of Ti-6Al-4V (a) Cryogenic testing chamber, (b) Tension and compression setup

Figure 2.36: Gripping fixture used for cryogenic torsional testing of Ti-6Al-4V (a) Fixture drawing, (b) Test setup
2.7 Digital Image Correlation

Digital Image Correlation (DIC) has revolutionized strain measurement in experimental mechanics by allowing researchers to capture full field strains on the surface of a specimen. An in depth review of this measurement technique is presented by Sutton, Orteu, and Schreier[25]. The three dimensional DIC system uses two cameras to track displacements on the surface of a deforming specimen. Strains are calculated from the tabulated displacements. Although there are several commercial systems in use, Correlated Solutions VIC-3D 2010 is used here[33].

The three dimensional DIC system is pre-calibrated by photographing a panel with known grid spacing with both cameras. This creates a three dimensional world coordinate system. The system takes two synchronized images of a speckle patterned specimen as seen in Figure 2.37(a). The software algorithm first discretizes the images into $n \times n$ pixel subsets. The gray scale values within the subsets are used to track the displacements of specimen. Once the displacements are known they are then used to calculate strains using one of several available strain tensor definitions.

Multiple post processing methods are available including: data extraction at a point, averaged within a box, or by a virtual extensometer. Data extracted at a point are useful in tracking the strain state at a the specimen’s fracture location. A virtual extensometer averages strain over its initial gage. The extensometer is useful for comparing DIC data to data acquired using more traditional instruments such as the mechanical extensometer. Average data within a box can also be extracted . Data extracted at a point or within a box includes $\epsilon_{xx}$, $\epsilon_{yy}$, $\epsilon_{xy}$, $\epsilon_{1}$, $\epsilon_{2}$, x-displacement ($u$), y-displacement ($v$) and z-displacement ($w$).
Figure 2.37: DIC data from a combined loading test with Vic-3D (a) 2D image with speckle pattern, (b) 3D visualization of specimen

Strain data for all tests, excluding the cryogenic tests and high strain rate tests, are presented with DIC. Tension data is collected with a 4mm DIC virtual extensometer which spans the fracture point. A 4mm extensometer sufficiently spans the uniaxial plane stress specimen gage length. A consistent 4mm length is used for all tension tests. Compressive strains are initially measured with an 3.8mm extensometer and transition to strains calculated from relative platen motion after the specimen yields. The strain is given as

\[
\varepsilon = \frac{u_1 - u_2}{l_o},
\]

where, \( u_1 \), is the lower platen, \( u_2 \), is the upper platen, and \( l_o \) is the initial gage length. The extensometer measures elastic deformation prior to yielding. Barreling occurs when the specimen accumulates significant plastic strain due to friction and the interface between the sample and the plates. In this case, the surface strains are no longer representative of the internal specimen strain. Platen motion is representative of the average cross-section strain.
Shear strain is calculated from three dimensional displacements of points at the upper and lower regions of the specimen gage section. These data are used with the law of cosines to calculate the relative angle of rotation between the top and bottom points as (equation 2.5). The relative angle of twist is proportional to shear strain. Although DIC data was acquired for the high strain rate tests it was only used for comparison purposes. High strain rate data reported in Chapter 3 is measured using the techniques outlined in Section 2.5 since the strain gages have significantly better temporal resolution.

Several camera setups spanning a wide range of frame rates are available at the DMML. For strain rates lower than \(1.0 \times 10^{-2} \text{s}^{-1}\), Point Gray Research GRAS-20S4M-C cameras are used. The cameras acquire images at frame rates up to 19fps at \(1624 \times 1224\) resolution. Either Schneider 35mm or Sigma 50mm lenses are used with the cameras. Photron MC2 cameras are used at strain rates of \(1.0 \text{s}^{-1}\). These are capable of 2000fps at \(512 \times 512\) resolution. Photron SA1.1 cameras are used for strain rates at and above \(500 \text{s}^{-1}\). These cameras acquire \(1024 \times 1024\) resolution images at a frame rate of 5400fps. Higher frame rates can be achieved at reduced resolution. A common frame rate for tests under this project is between 125,000fps and 250,000fps. Either 90mm or 180mm Tamron lenses are used with the Photron SA1.1 cameras.

DIC provides substantial advantages over classic strain measurement instruments such as mechanical extensometers or strain gages. Strain gages are cumbersome to install and are limited to strains of less than 8%. Mechanical extensometers are easy to use, however they are unable to capture strain localizations. Differences in stress strain curves measured by the load frame’s LVDT and RVDT are compared
to DIC measurements in Figure 2.38. The strain values from these two sources are considerably different because the DIC measurement is not subjected to compliance errors. This is especially apparent in the compression data due to the large required forces which result in more compliance.

Figure 2.38: Strain measurement comparison between digital image correlation and the load frame measurement
Chapter 3: Plastic Deformation of Ti-6Al-4V Experimental
Results and Discussion

Experimental results generated during the plastic deformation test series, described in Table 2.1, are presented here. Quasi-static and high strain rate tension, compression, and torsion (shear) test data are presented. Data from tension specimens oriented in several directions within the plate and tests conducted at various temperatures are also presented. All plates tested show notably different plastic deformation characteristics when the data is compared. In order to keep each plate easily identifiable within the presented plots, a color scheme of blue, red, green, and black is used for plate 1, 2, 3, and 4, respectively. Different orientations and temperatures are differentiated with line types or shades. To allow for an easier discussion, tension and compression data from plate 4 in the rolled direction at a strain rate of $1.0s^{-1}$ at room temperature is set as the baseline. Data spread for each test configurations can be seen in Appendix A. Representative curves from each of the tests are selected and presented here.

3.1 Experimental Results from the 2.29mm Plate Stock

Plastic deformation data from tests on a 2.29mm thick Ti-6Al-4V plate, labeled plate 1, are presented here. The plate, purchased from Tri-Tech, was rolled at RMI
Titanium and conforms to AMS-4911 Standards. The test methods described in Chapter 2 were used to generate the following data. Data from this specific plate is presented here and compared to the other plate stocks in Section 3.5.

### 3.1.1 Strain Rate Test Series Results

Plate 1 tension stress strain curves at two different strain rates are presented in Figure 3.1. The plate is clearly rate sensitive for both yield and flow stresses. Fracture strain in Figure 3.1 look similar at both rates. Strain hardening and fracture strain at $1.0\text{s}^{-1}$ and $662\text{s}^{-1}$ are also similar. Results of the compression tests on plate 1 at two different strain rates can be seen in Figure 3.2. The material displays strain rate sensitivity for yield and flow stresses and fracture strains. Compression hardening characteristics are similar at strain rates of $1.0\text{s}^{-1}$ and $1393\text{s}^{-1}$.

![Figure 3.1: Tension strain rate dependence for plate 1](image_url)
Figure 3.2: Compression strain rate dependence plate 1

3.1.2 Specimen Orientation Test Series Results

Anisotropy test series data for plate 1 in tension can be seen in Figure 3.3. The data shows similar yield and plastic deformation characteristics in the rolled and transverse (90°) directions. The 45° data have a similar yield point but different hardening characteristics and lower flow stresses.

Figure 3.3: Tension anisotropy data for plate 1
3.2 Experimental Results from the 3.56mm Plate Stock

Plastic deformation data from a 3.56mm thick Ti-6Al-4V plate, labeled plate 2, are presented here. The plate, also purchased from Tri-Tech and was rolled at TIMET, conforms to AMS-4911 standards. The test methods described in Chapter 2 are used to generate the following data. Data from this specific plate are presented here and compared to the other plate stocks in Section 3.5.

3.2.1 Strain Rate Test Series Results

Tension and compression stress strain curves for plate 2 are presented in Figure 3.4 and Figure 3.5, respectively. In both cases, the material displays rate dependent yield and flow stresses and fracture strains. Yield and flow stresses increase with increasing strain rate while the fracture strains decrease.

![Graph showing tension strain rate dependence for plate 2](image)

Figure 3.4: Tension strain rate dependence for plate 2
3.2.2 Specimen Orientation Test Series Results

Tension data from specimens fabricated in three orientations within plate 2 can be seen in Figure 3.6. This plate shows similar yield, plastic deformation, hardening, and fracture characteristics for all orientations evaluated. According to the data in Figure 3.6 the material appears to be isotropic.
3.3 Experimental Results from the 6.35mm Plate Stock

The 6.35mm thick Ti-6Al-4V plate, labeled plate 3, was extensively tested previously[12]. Additional tests are presented here. The plate was purchased from Tri-Tech and rolled at Allegheny Ludlum to conform to AMS-4911 standards. The test methods described in Chapter 2 were used to generate the data. A comparison of plate 3 to the other stocks is presented in Section 3.5.

3.3.1 Temperature Test Series Results

Tension test data at $-50^\circ$C, 200°C, 400°C, and 600°C are presented in Figure 3.7. The stress monotonically decreases with increasing temperature. Strain hardening is also clearly effected by the change in temperature. The data shows an increasing fracture strains at elevated temperatures indicating an increase in ductility. The $-50^\circ$C tests show an increase in flow stresses and a reduction in fracture strain implying a brittling effect of the material at lower temperatures.

![Figure 3.7: Tension temperature test series data for plate 3](image-url)
Elevated and room temperature compression test data were previously presented [12]. Compression tests data at $-50^\circ C$ are compared to these data in Figure 3.8. The material shows an increase in flow stresses and a significant decrease in failure strains at $-50^\circ C$. The material shows significant ductility and will continue to deform above strains of 60% at and above room temperature. At $-50^\circ C$ the material fractures at approximately 35%.

![Compression temperature test series data for plate 3](image)

Figure 3.8: Compression temperature test series data for plate 3

### 3.4 Experimental Results from the 12.7mm Plate Stock

Plastic deformation data from a 12.7mm thick Ti-6Al-4V plate, labeled plate 4, are presented here. The plate was purchased from Titanium Industries, Inc., was rolled at Allegheny Ludlum and conforms to AMS-4911 standards. The test methods described in Chapter 2 were used to generate the data. Data from this specific plate are presented here and compared to the other stocks in Section 3.5.
3.4.1 Strain Rate Test Series Results

Plate 4 shows significant strain rate dependence in tension, compression, and shear. Tension strain rate test series data can be seen in Figure 3.9. Yield and flow stresses increase with increasing strain rate, however, the failure strains are significantly decrease at and above $1.0s^{-1}$. The dynamic curves show a different elastic modulus than the low rate curves. This is due to the fact that elastic modulus cannot be accurately measured using of a Kolsky bar because dynamic force equilibrium does not exist early in the test.

![Figure 3.9: Tension strain rate test series data for plate 4](image)

Compression data, shown in Figure 3.10, also exhibits an increase in yield and flow stresses with increasing strain rate. The initial peak oscillating nature of the high strain rate data is not material response but error caused by force in equilibrium and three dimensional wave propagation in the bars. The material also displays decreasing failure strains in compression, especially at and above $1500s^{-1}$. In both tension and compression, there is a clear change in strain hardening between $1.0 \times 10^{-2}s^{-1}$ at $1.0s^{-1}$.

78
Shear test data, shown in Figure 3.11, also demonstrate strain rate dependence for yield and flow stresses as well as failure strains. Shear failure strains are similar for strain rates at and below 1.0s$^{-1}$, however at strain rates higher than 1.0s$^{-1}$, failure strain reduces dramatically.
3.4.2 Specimen Orientation Test Series Results

Plate 4 demonstrates anisotropic properties in both tension and compression which can be seen in Figures 3.12 and 3.13, respectively. Stress strain curves for the $45^\circ$ and $-45^\circ$ specimens are similar in tension and compression. They are notably different than curves from the rolled and transverse directions. Failure strains vary from 0.15 to 0.19 for the directions tested. In compression, the specimens have different failure behavior. The through direction in compression shows notably lower yield and flow stresses and no failure at strains up to 0.5. All other specimens fail at strains ranging from 0.27 to 0.40.

![Figure 3.12: Tension anisotropy data for plate 4](image)

Figure 3.12: Tension anisotropy data for plate 4
3.4.3 Temperature Test Series Results

Plate 4’s tension temperature dependence can be seen in Figure 3.14. The material displays monotonically decreasing yield and flow stresses with increasing temperature. There are significant increases in ductility from 25°C to 200°C and from 400°C to 600°C. Compression results also display decreasing stresses with increasing temperature, see Figure 3.15. Unlike in tension, Ti-6Al-4V has a significant increase in compressive fracture strain between 200°C and 400°C. Shear test results, see in Figure 3.16, also display falling stresses with increasing temperature. Ductility in shear increases with every increased temperature. The cryogenic shear curve displays a lower shear modulus than the room temperature data. This is due to measurement error and not a physical property of the material. The displacement between these tests were not measured using the same method as described in Subsection 2.2.3 and Section 2.6.
Figure 3.14: Tension temperature dependence for plate 4

Figure 3.15: Compression temperature dependence for plate 4
3.5 Comparison of the Various Plate Stocks Tested

Although all plates are within AMS specifications, they show notably different plastic deformation characteristics. Differences discussed here are outside of test data spread and are attributed to differences in plate characteristics.

3.5.1 Tension Comparison

In tension, plate 4 has higher yield and flow stresses compared to plates 1, 2, and 3 see Figure 3.17. These curves are for room temperature tests at a strain rate of $1.0\text{s}^{-1}$ for specimens fabricated in the rolled direction. Fracture strains are similar for all plates and range from 0.14 to 0.16. Strain hardening characteristics are similar for all curves in Figure 3.17.

A complete plate stock comparison for all tensile strain rate dependence tests can be seen in Figure 3.18. Plate 1’s flow stresses are 6% lower and 6% higher than baseline (Plate 4 at Room Temperature, $1.0\text{s}^{-1}$) at $1.0\text{s}^{-1}$ and $662\text{s}^{-1}$, respectively.
Plate 2’s results are similar for flow stresses but display much higher failure strain at 1.0s\(^{-1}\). Plate 3 at strain rates of 1.0 \times 10^{-4}s^{-1}, 1.0 \times 10^{-2}s^{-1}, 1.0s^{-1}, 538s^{-1}, and 1332s^{-1} the flow stresses are $-18\%$, $-9\%$, $-5\%$, $6\%$, and $9\%$ different than the baseline, respectively. Plate 4’s flow stresses are $-13\%$, $-10\%$, $9\%$, and $13\%$ different than the baseline at strain rates of 1.0 \times 10^{-4}s^{-1}, 1.0 \times 10^{-2}s^{-1}, 640s^{-1}, and 1645s^{-1}, respectively. Plate 4 exhibits a smaller difference in flow stress between 1.0 \times 10^{-4}s^{-1} and 1.0 \times 10^{-2}s^{-1} than plate 3. Plates 1 and 3 have similar failure strains between each of the strain rates. There is a clear change in Plates 2 and 4 at and above 1.0s\(^{-1}\). Strain hardening is similar for all plates at all strain rates.

Tension data from tests on specimens oriented in various directions withing all four plates are presented in 3.19. Plate 1’s rolled and transverse flow stresses are about 6% lower than baseline. Its 45° flow stresses are 16% lower than baseline. All orientations
Figure 3.18: Comparison of tension tests at various strain rates at room temperature in the rolled direction, (a) plate 1, (b) plate 2, (c) plate 3, (d) plate 4
have similar fracture strains which approximately match the baseline. Flow stresses, in all three directions, for plate 2 are approximately 8% lower than baseline. All orientations in this plate have similar fracture strains and are about 19% higher than baseline. For plate 3, the rolled and transverse directions display similar behaviors and have 6% and 4% lower flow stresses than the baseline, respectively. $\pm 45^\circ$ directions display similar behavior and have about 16% lower flow stress than baseline. Failure strains all approximately match the baseline and range from 0.12 to 0.17. Plate 4 data in the rolled and transverse directions display similar behaviors with an approximate flow stress of 1226 MPa (Tension Baseline). $\pm 45^\circ$ directions display similar behaviors and have approximately 10% lower flow stress than the baseline. Excluding the $45^\circ$ direction in plate 1, strain hardening behavior from all tests in Figure 3.19 are similar.

A comparison of tension tests at various temperatures on specimens fabricated from plates 3 and 4 are displayed in Figure 3.20. These tests are conducted on rolled direction specimens at $1.0s^{-1}$. The data shows a convergence of material characteristics at and above 200$^\circ$C. Plate 3’s yield and flow stresses at −50$^\circ$C increase more than those for plate 4. There is also a significantly larger reduction in ductility for plate 3 at this temperature. Both materials become more ductile at higher temperatures.
Figure 3.19: Comparison of tension tests at various fabrication orientations at room temperature and a strain rate of $1.0\text{s}^{-1}$, (a)Plate 1, (b)Plate 2, (c)Plate 3, (d)Plate 4
Figure 3.20: Comparison of tension tests at various temperatures at a strain rate of 1.0s\(^{-1}\) from the rolled direction for plate 3 and 4

3.5.2 Compression Comparison

Compression data at various strain rates from plate 3 and plate 4 are compared in Figure 3.21. Plates 1 and 2 are not shown since they were only tested in the through direction. Baseline is described as the room temperature test at 1.0s\(^{-1}\) in the rolled direction from plate 4.

Plate 3 displays flow stresses that are approximately \(-21\%\), \(-15\%\), \(-11\%\), \(-1\%\), and \(1\%\) different from the baseline for strain rates of \(1.0 \times 10^{-4}s^{-1}\), \(1.0 \times 10^{-2}s^{-1}\), \(1.0s^{-1}\), \(1728s^{-1}\), and \(3022s^{-1}\), respectively. Plate 4 data differs from the baseline by \(-10\%\), \(-1\%\), \(13\%\), and \(20\%\) at respective strain rates of \(1.0 \times 10^{-4}s^{-1}\), \(1.0 \times 10^{-2}s^{-1}\), \(1474s^{-1}\), and \(3879s^{-1}\). At low strain rates \((\leq 1.0 \times 10^{-2}s^{-1})\), after an approximate strain of 0.28, plate 4 fails in shear at a 45° degree angle. Plate 3, however, continues to deform and does not fail below a strain of 0.35. Both plates fail in shear at or below
an approximate strain of 0.30 at high strain rates ($\geq 1000\text{s}^{-1}$). In compression, the strain hardening behavior is similar in all corresponding tests between the two plates. Both plates have a significant strain hardening change at a strain rate of $1.0\text{s}^{-1}$.

Figure 3.21: Comparison of compression testing at various strain rates from the rolled direction for plates 3(a) and 4(b)

Stress strain curves from specimens fabricated in the thickness direction of the different plate stocks are compared in Figure 3.22. These tests are conducted at room temperature at a strain rate of $1.0\text{s}^{-1}$. These data imply that all the plate stocks have similar characteristics at this strain rate. Data from specimens orientated in several directions within plates 3 and 4 are shown in Figure 3.23. A comparison of these data shows that they have strongly anisotropic characteristics. Ductility in the through direction for plate 3 is similar to the transverse direction but much lower than the rolled, $\pm 45^\circ$. Flow stresses for this plate in the rolled and $\pm 45^\circ$ directions are lower than those in the transverse. Plate 4 exhibits very ductile behavior only in the through
thickness orientation. Flow stresses in the through directions are approximately 5% lower than the others. Differences in these plates fall well outside of the data spread. Data spread plots for all plastic deformation testing can be found in Appendix A.

Plate 3 is strongly anisotropic in compression and it’s trends do not follow those seen in tension. Plate 4 compression data are more isotropic than plate 3, however, there are some notable differences in properties between the tested orientations. Rolled and transverse, and $\pm 45^\circ$ have similar properties with only a slight strain hardening differences between the two groups. The through direction has a much higher ductility and lower flow stress. The through direction for plates 3 and 4, however, does not agree with the in-plane compressive behavior for these plates and therefore only gives an incomplete comparison.

![Figure 3.22: Comparison of plates 1, 2, 3, and 4 in compression at a strain rate of 1.0s$^{-1}$ in the through thickness direction](image)
A comparison of data from tests at various temperatures on plates 3 and 4 are presented in Figure 3.24. These tests were conducted on samples oriented in the rolled direction at 1.0s$^{-1}$. Tension stress strain curves converge at 200$^\circ$C, however, compression curves do not converge until 600$^\circ$C. Plate 3’s compressive flow stress increase in cryogenic tests is smaller in compression than in tension. Plate 4 becomes much more ductile above 200$^\circ$C. Plate 3 is very ductile, at and above room temperature, but it displays a brittle failure at $-50^\circ$C.
3.6 Johnson-Cook Plasticity Model Parameter Determination

In this section Johnson-Cook Plasticity material parameters are determined from previously presented Plate 4 data. Since the plastic deformation characteristics in tension, compression, and shear are considerably different, each loading condition should have its own unique set of parameters. Parameters presented here are found from rolled direction tension data from plate 4. These parameters are compared to those found previously. This includes parameters for the plate 3 stock[12]. Previously found tabulated parameters can be seen in Table 1.2.

Coefficients within the first set of brackets in Equation 1.1 are found when the second and third set of brackets are both equal to one. The second bracket is one when the strain rate is equal to the reference strain rate ($\dot{\varepsilon}_o = 1.0s^{-1}$). The third
bracket is equal to one when the material temperature is equivalent to the reference temperature \( (T = 25^\circ C) \). Equation 1.1 reduces to,

\[
\sigma = [A + Be^n].
\]

Equation 3.1

\( A \) is determined from the yield point of the material. \( B \) and \( n \) are found with a curve fit of the data. These parameters are determined to be 1062 MPa, 431 MPa, and 0.50, respectively. Effective stress versus equivalent plastic strain curves for each set of the JC model parameters is compared with the test data in Figure 3.25. The Johnson parameters clearly underestimate yield and flow stresses but it has similar strain hardening. The Yatnalkar model is comparable in yield and flow stresses as well as strain hardening. The Lesuer model fits the data reasonably well, however, the fit diverges at low and high strains. Finally, the Milani model captures the yield stress but overestimates flow stress and strain hardening for the Plate 4 data.

Figure 3.25: Comparison of several Johnson-Cook constitutive model parameters to plate 4 test data
The parameter, $C$, is determined by curve fitting normalized stresses at the different strain rates. Stress magnitudes, $\sigma$, are taken from each strain rate at a strain of 5%. These values are then normalized to the reference strain rate ($1.0 \text{s}^{-1}$) stress magnitude. Equation 1.1 becomes,

$$\frac{\bar{\sigma}}{\sigma_r} = \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} \right) \right]$$

(3.2)

$C$ is determined through a linear curve fit to the stresses versus logarithmic strain rate. The normalization value is

$$\sigma_r = [A + Be^n] \left[ \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]$$

(3.3)

The test data with various model parameter fits are plotted in Figure 3.26. The Lesuer and Johnson models predict similar strain rate dependence as Plate 4. The Yatnalkar parameters overestimate the strain rate sensitivity while the Milani parameters greatly underestimate it.

The JC temperature parameter, $m$, is determined from normalized stresses at various temperatures at a strain rate of $1.0 \text{s}^{-1}$. The stress magnitudes are taken at 5% strain temperatures of $25^\circ \text{C}$ to $600^\circ \text{C}$. The stresses are normalized in by

$$\frac{\bar{\sigma}}{\sigma_r} = \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right],$$

(3.4)

where the normalized stress is taken as

$$\sigma_r = [A + Be^n] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} \right) \right]$$

(3.5)

A curve fit of the normalized stresses yields 0.69 for the temperature parameter. Normalized stress data are plotted with several JC model parameters in Figure 3.27. The Lesuer, Johnson, and Milani parameters underestimate the effect of the temperature on the stress.
Figure 3.26: Comparison of several Johnson-Cook constitutive model parameters to plate 4 tension strain rate data extracted at a strain of 5% at room temperature in the rolled direction.

Figure 3.27: Comparison of several Johnson-Cook constitutive model parameters to plate 4 temperature data in tension at a strain rate of 1.0s\(^{-1}\)
The Johnson-Cook parameters found in the literature poorly fit the plastic characteristics of plate 4, however, this does not imply that the parameters were improperly found. There are large differences between various thickness plate stocks of the same Ti-6Al-4V material. Processing of the material plays a significant role in the plate’s plastic deformation response. Thus it is recommended that the actual plate stock to be used in the application of interest is fully understood prior to using a generic Johnson-Cook Material Model. The Johnson-Cook model has its limitations, for example it does not accurately model changes in material hardening from one strain rate or temperature to another. The model also cannot model the anisotropic behavior or tension-compression asymmetries. These shortcomings are the prime motivating factor for researchers to develop more complex models such as MAT224.

3.7 Yield Criterion

Many of the current plasticity models use $J_2$ flow theory[1]. This theory uses a universal effective stress strain curve to model deformations at all combinations of stress states. Errors will occur, however, if effective stress versus equivalent strain curves in tension, compression, and shear do not coincide. Figure 3.28(a) shows a comparison of these values for similar strain rates. All curves in the figure are from plate 4 at 1.0s$^{-1}$ and room temperature, the tension and compression are fabricated in the rolled direction while shear tests are fabricated from the through direction. A comparison of the effective stress versus equivalent strain curves in tension, compression, and shear show significant asymmetry. $J_2$ flow theory is only capable of modeling isotropic materials. All the plate stocks tested, except plate 2, are anisotropic. Results from anisotropic testing in tension and compression for plate 4 are shown in Figure 3.28(b).
These results indicate that $J_2$ plasticity theory is unable to adequately characterize the material.

Figure 3.28: Plate 4 (a) asymmetry and (b) anisotropy test data

3.8 Conclusions

Test data for several Ti-6Al-4V plates are presented here. Tests were carried out in tension, compression, and shear at quasi-static and dynamic loading rates. The material has been tested in several orientations with in the plate. Multiple temperatures were also tested.

The response of Ti-6Al-4V is highly dependent on loading rate as seen by the flow stresses in Figure 3.29. Additionally, strain hardening and failure strains can also be rate dependent. As strain rate increases, the yield and flow stress also increase while failure strains decrease. There is a notable change in strain hardening at and above $1.0 \text{s}^{-1}$, in compression.

Excluding Plate 2, the material shows significant anisotropic characteristics. In compression, Plates 3 and 4 show considerably different anisotropic characteristics. In
tension, the rolled and transverse stress strain curves from plates 3 and 4 are similar. This is also the case for the ±45° stress strain curves. There is a notable difference between tensile, compressive, and shear yield and flow stresses, failure strains, and strain hardening.

Plates 3 and 4 have significant temperature dependence between −50°C to 600°C, as seen in Figure 3.30. As the temperature increases the yield and flow stresses decrease while failure strains increase. Plate 3 has a significantly higher increase in flow stress between room temperature and −50°C than Plate 4 does. In tension, the stress strain curves of plates 3 and 4 converge at 200°C while in compression, they do not converge until above 600°C. In compression, plate 3 experiences shear failure at −50°C while plate 4 experiences shear fracture at temperatures below 400°C.

Although the four different plate stocks researched here are compliant with the same Aerospace Materials Standards, they have significant differences in plastic deformation characteristics. These plates have large differences in strength, failure
Figure 3.30: Temperature dependence of various plate stocks of Ti-6Al-4V in multiple loading conditions

strains, anisotropy, strain hardening, and failure type. While modeling this material, care should be taken to ensure that appropriate material properties are used for the specific plate stock being utilized. The material also has different characteristics in tension, compression, and shear. Ti-6Al-4V is, for the most part, anisotropic. These properties, however, differ under tension, compression and with the material stock. Strain hardening, failure strain, failure type, yield stress, and flow stress are all dependent on strain rate. Any material model that is used to model the dynamic behavior of Ti-6Al-4V must be able to accurately model the strain rate reported characteristics.
Experimental results from the ductile fracture testing described in Section 2.3 are presented here. Tension test results for plane stress, axisymmetric, and plane strain specimens, and combined loading axial-torsional test results are shown. Specimens are fabricated from plate 4 due to size restrictions of plates 1, 2 and 3. Engineering stress (or force normalized by initial area) and engineering strain are reported for all tension geometries. A 4mm virtual extensometer is used to measure strain for each tension experiment presented here. Data spread for each geometry tested can be seen in Appendix B. Representative curves from each of the tests have been selected and presented here.

4.1 Plane Stress Experiments

The plane stress specimens, discussed in Chapter 2, are have a thin, flat, smooth or notched geometry (see Table 2.2). These specimens have stress triaxialities ranging from 0.400 to 0.583. Lode parameters range from 0.014 to 0.845.

Results from the plane stress tension tests are presented in Figure 4.1. The smooth dog-bone at room temperature at a strain rate of $1.0 \times 10^{-2}$ has a flow stress of 1018 MPa and an engineering failure strain of 0.21. These curves show that as the
stresses increase and failure strains decrease as the notch width is decreased. The 14.29mm notch radius specimen has a 14% lower failure strain and a 6% higher stress than the smooth specimen. The 4.76mm notch radius has a 38% lower failure strain and a 9% higher flow stress than the smooth specimen. The 0.40mm specimen is dramatically different. It has 76% lower failure strains and 28% higher flow stresses than the smooth sample. These data are used to create the fracture locus for Ti-6Al-4V.

![Graph](image)

Figure 4.1: Plane stress tension results for various notch sizes of Ti-6Al-4V

### 4.2 Axisymmetric Experiments

The axisymmetric test specimens, discussed in Chapter 2, consist of a smooth specimen and five notched specimens with various notch radii. These specimens provide data at multiple stress triaxalities overlapping both the plane stress and plane
strain points. Triaxialities range from 0.369 to 0.956. All specimens have a Lode number equal to one due to their cross sectional geometry.

Axisymmetric test results are presented in Figure 4.2. As previously discussed, with decreasing notch radii the stresses increase and failure strains decrease. The axisymmetric smooth specimen has a failure strain of 0.33 and a peak flow stress of 1045 MPa. Failure strains decrease by 40%, 42%, 48%, 55%, and 67% while flow stresses increase at 7%, 11%, 13%, 19%, and 26% from the smooth specimen for the respective notches. These data are used to formulate the fracture locus.

![Figure 4.2: Axisymmetric tension results for various notch sizes of Ti-6Al-4V](image)

4.3 Plane Strain Experiments

Plane strain specimens, as discussed in Chapter 2, are dog bone specimen with much larger thickness than width. The large thickness ensures that the transverse
compressive strains are approximately zero at the center of the specimen. DIC measurements are used to confirm this assumption.

The test results are presented in Figure 4.3. The three specimens represent stress triaxialities ranging from 0.470 to 0.768. Again, as notch radius decreases, the stresses increase and failure strains decrease. The plane strain smooth specimen has an approximate peak stress of 1092 MPa and a failure strain of 0.17. The 12.7mm notch radius specimen has a 30% lower failure strain and a 7% higher stress than the smooth sample. The 4.76mm notch radius specimen has a 53% lower failure strain and a 16% higher stress than the smooth sample.

![Figure 4.3: Plane strain tension results for various notch sizes of Ti-6Al-4V](image)

Strain field, measured with DIC, are seen in Figure 4.4. These strain fields are just prior to specimen failure. Ideally, the transverse strain ($\epsilon_2$) at the center of the specimen would be zero, which gives a perfect plane strain condition. The data in
Figure 4.4 shows that the transverse strain in the center of the specimen is not zero. The notched specimens have substantially less transverse strains than the smooth sample. The stress and strain state of the smooth sample is not ideal. This results in the high Lode parameter value (0.506) for the plane strain smooth specimen.

![Figure 4.4: DIC strain field data from plane strain specimens with various geometries](image)

**4.4 Combined Loading Experiments**

Thin walled tube specimens are loaded in tension-torsion ($\sigma/\tau = 1.971$ and $\sigma/\tau = 0.847$), torsion ($\sigma/\tau = 0$), and compression-torsion ($\sigma/\tau = -0.847$) to gain additional fracture locus data points. Data from these tests are presented in Figure 4.5. The combined loading specimens have stress triaxialities ranging from -0.148 to 0.252 and lode parameters ranging from -0.394 to 0.706. The displacement and angle of rotation data presented in Figure 4.5 is acquired from digital image correlation. Displacement
of two points, roughly 3mm apart on the surface of the specimen are used to calculate the displacements and rotations. Displacement is simply the difference in the vertical motion of the two points. The angle of rotation is calculated using data from these points in equation 2.5. This is the same method used to determine angle of twist and shear strain in the torsional experiments described in Chapter 3. Time history of a tension-torsion experiment is seen in Figure 4.6.

As the axial to shear stress ratio increases, the failure angles decrease. The compression-torsion sample \((\sigma/\tau = -0.847)\) has a larger cross sectional area to prevent buckling in the specimen during loading. Although these specimens have a larger wall thickness, they require a similar angle of rotation at failure than its tension-torsion counterpart \((\sigma/\tau = 0.847)\). Initially, the stress state parameters are fluctuating they settle at the desired values following yielding of the specimen, see Figure 4.6. Unlike with the tension tests, the stress states do not evolve significantly after yielding for the combined loading tests. Stress, strain, and stress state time histories can be found in Appendix B for each of the loading conditions.

![Figure 4.5: Combined axial-torsional test results for various notch sizes of Ti-6Al-4V](image-url)
4.5 Fracture Point Determination and Locus Creation

For tension tests, fracture locus points and stress states are found by analyzing test data and parallel simulations, see Figure 4.7. This procedure is introduced in Subsection 2.3.5. The simulated data is cropped at the drop in load and the physical tests, which indicates a specimen failure. The DIC frames are shown one frame prior to failure while the simulation is shown at the equivalent displacement to the DIC. The curves from both are also shown. The blue curves represent the stress, the green represent the strain, and the red represent the stress state parameters. A vertical gray line represents the fracture point. Three variations of strain are shown, center simulation, surface simulation, and surface DIC. The center simulation and surface simulation differ slightly due to high stresses and therefore higher strains in
the center of the specimen. The two surface strains differ due to differences in gage lengths between the simulation mesh and the DIC.

These parallel experiments and simulations are completed for each of the physical tests to assess fracture strain data spread. The stress state is calculated using Equations 1.4 and 1.8 from simulated stress state records extracted at the internal element up to the identified point of failure. Combined loading stress states and fracture strains are found from experimental data. Fracture strains are measured using DIC. Care was taken to ensure that virtual strain gage lengths are similar to those of the tension specimens. Stress state parameters are calculated from the axial force and torque data using Equations 2.15 and 2.16. A history plot of the combined load tension-torsion test can be seen in Figure 4.6. Results for each of these tests can be seen in Table 4.1. Comparison of simulated and experimental data for each tension geometry can be seen in Appendix D.

Failure strain data is plotted versus stress triaxiality and Lode parameter in Figure 4.8. In these plots, plane stress specimens are represented with blue squares, the axisymmetric specimens with red circles, the plane strain specimens with green triangles, and the combined loading specimens with black diamonds. Error bars represent the range of failure strain for each load condition. The plane stress smooth specimens and the axisymmetric smooth specimens have the largest ranges of failure strains. Some specimens have similar stress states yet large differences in failure strains. For example, the SG11, SG6, and SG3 specimens have similar triaxialities ($\sigma^* \approx 0.484$) but failure strains ranging from 0.20 to 0.46. The LR3, SG12, SG13, and SG4 tests all have similar Lode parameters ($\mu \approx 0.016$) but failure strain range from 0.12 to 0.49. Neither of these stress state parameters can accurately describe the
Figure 4.7: Data from an experiment and parallel simulation of a plane stress specimen

108
Table 4.1: Results of the ductile fracture of Ti-6Al-4V testing

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Geometry Type</th>
<th>Geometry</th>
<th>Failure Strain</th>
<th>Stress Triaxiality</th>
<th>Lode Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG1</td>
<td>Plane Stress</td>
<td></td>
<td>0.59</td>
<td>0.400</td>
<td>0.845</td>
</tr>
<tr>
<td>SG2</td>
<td></td>
<td></td>
<td>0.44</td>
<td>0.431</td>
<td>0.719</td>
</tr>
<tr>
<td>SG3</td>
<td></td>
<td></td>
<td>0.43</td>
<td>0.489</td>
<td>0.528</td>
</tr>
<tr>
<td>SG4</td>
<td></td>
<td></td>
<td>0.14</td>
<td>0.583</td>
<td>0.014</td>
</tr>
<tr>
<td>SG5</td>
<td>Axisymmetric</td>
<td></td>
<td>0.31</td>
<td>0.369</td>
<td>1.0</td>
</tr>
<tr>
<td>SG6</td>
<td></td>
<td></td>
<td>0.31</td>
<td>0.492</td>
<td>1.0</td>
</tr>
<tr>
<td>SG7</td>
<td></td>
<td></td>
<td>0.32</td>
<td>0.564</td>
<td>1.0</td>
</tr>
<tr>
<td>SG8</td>
<td>Axisymmetric</td>
<td></td>
<td>0.27</td>
<td>0.618</td>
<td>1.0</td>
</tr>
<tr>
<td>SG9</td>
<td></td>
<td></td>
<td>0.27</td>
<td>0.751</td>
<td>1.0</td>
</tr>
<tr>
<td>SG10</td>
<td></td>
<td></td>
<td>0.22</td>
<td>0.956</td>
<td>1.0</td>
</tr>
<tr>
<td>SG11</td>
<td>Plane Stress</td>
<td></td>
<td>0.21</td>
<td>0.470</td>
<td>0.506</td>
</tr>
<tr>
<td>SG12</td>
<td></td>
<td></td>
<td>0.22</td>
<td>0.660</td>
<td>0.040</td>
</tr>
<tr>
<td>SG13</td>
<td></td>
<td></td>
<td>0.21</td>
<td>0.768</td>
<td>0.025</td>
</tr>
<tr>
<td>LR1</td>
<td>Combined Loading</td>
<td></td>
<td>0.29</td>
<td>0.252</td>
<td>0.706</td>
</tr>
<tr>
<td>LR2</td>
<td></td>
<td></td>
<td>0.51</td>
<td>0.150</td>
<td>0.400</td>
</tr>
<tr>
<td>LR3</td>
<td></td>
<td></td>
<td>0.43</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>LR4</td>
<td></td>
<td></td>
<td>0.42</td>
<td>-0.148</td>
<td>-0.394</td>
</tr>
</tbody>
</table>
failure behavior of Ti-6Al-4V individually. Together, however, a three dimensional fracture locus can be defined using both triaxiality and Lode parameter.

Figure 4.8: Failure strain versus triaxiality(a) and Lode parameters(b) for each of the specimen geometries and loading conditions

The Ti-6Al-4V fracture surface is presented in Figure 4.9. Equivalent plastic failure strain is plotted on the z-axis versus stress triaxiality and Lode parameter on the x-axis and y-axis, respectively. Plane stress, plane strain, and combined loading results are represented by circles, triangles, and diamonds, respectively. Axisymmetric specimens are displayed as square markers (Lode parameters equal to one). Biharmonic Spline Interpolation[34] is used to create the surface. Areas of low strain are represented in blue while high strains are represented in red. A low valley transitions into a high peak because the plane strain (SG11) and plane stress (SG3) data. These two specimens have considerably different geometries and fracture strains yet similar stress state parameters. It is possible that triaxiality and Lode parameter are not
enough to characterize the fracture surface of Ti-6Al-4V. It is also possible that failure does not occur exactly at the centers of the samples, as have been assumed here. Further study on the subject may be warranted.

![Three dimensional view of the Ti-6Al-4V fracture locus](image)

Figure 4.9: Three dimensional view of the Ti-6Al-4V fracture locus

4.6 Johnson-Cook Fracture Parameter Determination

Johnson-Cook fracture parameters are determined from the test data presented in this Chapter as well as Chapter 3. Fracture strain data at several stress triaxialities, temperatures, and strain rates is required to formulate these parameters. Failure strains used to determine the stress state dependence parameters ($D_1$, $D_2$, and $D_3$) are those found in the previous section. Failure strains used to determine the strain rate dependent parameter ($D_4$) are measured with 4mm DIC extensometers described in the plastic deformation testing. Failure strains used to determine the temperature dependent parameter ($D_5$) are measured with a 2mm DIC extensometer. A smaller
extensometer is to capture the increased localization strains as temperature increases. Data at various temperatures and strain rates, previously shown in Chapter 3, are assumed to have a stress triaxiality of 0.400. Strain data from extensometers are used to determine the parameters instead of parallel simulations.

Parameters from each bracketed expression in Equation 1.2 are found individually. The various stress state tests are performed at a strain rate of $1.0 \times 10^{-2} s^{-1}$. Since the reference strain rate ($\dot{\varepsilon}_o$) is $1.0 s^{-1}$, the strains used to find these parameters will be higher than if the tests were performed at the reference strain rate. A scale factor is used to adjust $D_1$ and $D_2$ which is found from $D_4$ and is given by

$$SF = \left[ 1 + D_4 \ln \left( \frac{1.0 \times 10^{-2} s^{-1}}{1.0 s^{-1}} \right) \right]^{-1}. \quad (4.1)$$

Parameters $D_1$, $D_2$, and $D_3$, are fitted to data at various stress states (Figure 4.10) at the test strain rate ($\dot{\varepsilon}_o = 1.0 \times 10^{-2} s^{-1}$) and temperature ($T = 25^\circ C$). At the reference strain rate and temperature the JC fracture equation is

$$\varepsilon_f^p = [D_1 + D_2 e^{D_3 \sigma^*}]. \quad (4.2)$$

Figure 4.10 shows the model predicted fracture strain. $D_1$, $D_2$, are determined and scaled to be $-0.81$ and $1.18$, respectively. $D_3$ is determined to be $-0.15$. Compared to the experimental data the newly determined parameters predict significantly higher strains than the parameters previously determined by Johnson[22]. Clearly, Johnson’s parameters underestimate all of the fracture strain data in Figure 4.10. As discussed in Section 4.5, some of these specimens have similar stress triaxialities yet considerably different fracture strains. This indicates a short coming in The Johnson-Cook fracture model, which defines the failure strain as a function of only the stress triaxiality. Therefore it is unable to capture the fracture strain spread plotted in Figure 4.10.
The term, $D_4$, is found by curve fitting normalized fracture strain data at different strain rates. The normalized fracture strain is

$$
\frac{\epsilon_f}{\epsilon_r} = \left[1 + D_4 \ln \left(\frac{\dot{\epsilon}}{\epsilon_o}\right)\right],
$$

(4.3)

where,

$$
\epsilon_r = [D_1 + D_2 e^{D_3 \sigma^*}] \left[1 + D_5 \left(\frac{T - T_r}{T_m - T_r}\right)\right],
$$

(4.4)

where, $\sigma^*$ is equal to 0.400 and $T = 25^\circ C$. Normalized fracture strain data are plotted with the best fit in Figure 4.11. From this fit the $D_4$ term is found to be $-0.012$. The data shows that fracture strain decreases slightly with increasing strain rate. Johnson’s parameters underestimate the fracture strains and predict that fracture strain increases with strain rate.
The final JC parameter, $D_5$, is determined by curve fitting normalized fracture strain data at various temperatures. The normalized fracture strain is

$$\frac{\varepsilon_f^{\psi}}{\varepsilon_r} = \left[ 1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right], \quad (4.5)$$

where,

$$\varepsilon_r = \left[ D_1 + D_2 e^{D_3 \sigma^*} \right] \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_o} \right) \right], \quad (4.6)$$

where, $\sigma^*$ is equal to 0.400 and $\dot{\varepsilon}/\dot{\varepsilon}_o$ is equal to one. A $D_5$ parameter value of 2.10 is determined to best fit the data. Normalized fracture strain data are plotted with the best fit prediction in Figure 4.12. The Johnson parameters overestimate the fracture strain of this material.
Chapter 3 shows large differences in not only flow stress but also failure strains between various plate stocks. This explains why the Johnson parameters do a relatively poor job of predicting the fracture behavior of the 12.7mm thick plate described here. It is important to fully characterize the response of the working material prior to using Johnson-Cook Material parameters found in the literature. Figure 4.10 shows that it is advantageous to use more complex models, such as MAT224, since stress triaxiality alone is unable to describe this material’s failure properties.

4.7 Conclusions for the Ti-6Al-4V Fracture Testing

The ductile fracture of Ti-6Al-4V at several stress triaxialities and Lode parameters is experimentally tested. The testing is completed on plane strain (thin, flat), axisymmetric (round cross sectional), plane strain (thick, flat), and combined loading
(thin walled tube) specimens. For each of the tension specimens, several geometries are tested with increasingly sharp notches. With decreasing notch radius, fracture strains decrease and stresses increase. Increasing temperatures gives higher failure strains due to an increase in ductility. Failure strain decreases slightly with increasing strain rates. As seen in Chapter 3 the material can also have different failure strains in different orientations.

As seen in Figure 4.8, the stress triaxiality is clearly not enough to fully characterize the failure of the material. The Lode Parameter is included for a more complete description of the stress state at failure. From these data a fracture locus has been created, additional views of which are available in Appendix E.

New Johnson-Cook fracture model parameters are determined and presented in Table 4.2. There are substantial differences than those determined by Johnson[22]. The differences between the two sets of fracture model parameters are most likely caused by differences in plate stocks. Care should be taken to ensure that the model parameters adequately capture the failure behavior of the specific plate stock.

Table 4.2: Comparison of Ti-6Al-4V Johnson-Cook constitutive parameters found in the literature to those determined for plate 4

<table>
<thead>
<tr>
<th>Name</th>
<th>$A(MPa)$</th>
<th>$B(MPa)$</th>
<th>$n$</th>
<th>$C$</th>
<th>$m$</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$D_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johnson</td>
<td>862</td>
<td>331</td>
<td>0.34</td>
<td>0.012</td>
<td>0.8</td>
<td>−0.09</td>
<td>0.25</td>
<td>−0.5</td>
<td>0.014</td>
<td>3.87</td>
</tr>
<tr>
<td>Lesuer</td>
<td>1098</td>
<td>1092</td>
<td>0.93</td>
<td>0.014</td>
<td>1.1</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Yatnalkar</td>
<td>1055</td>
<td>426</td>
<td>0.50</td>
<td>0.023</td>
<td>0.8</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Milani</td>
<td>1051</td>
<td>924</td>
<td>0.52</td>
<td>0.0025</td>
<td>0.98</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Hammer</td>
<td>1062</td>
<td>431</td>
<td>0.50</td>
<td>0.016</td>
<td>0.69</td>
<td>−0.81</td>
<td>1.18</td>
<td>−0.15</td>
<td>−0.012</td>
<td>2.10</td>
</tr>
</tbody>
</table>
Chapter 5: Summary and Conclusions of the Ti-6Al-4V Testing

Plastic deformation and ductile fracture of Ti64 is investigated experimentally. Plastic deformation behavior is presented in Chapter 3 while the ductile fracture behavior is presented in Chapter 4. Plastic deformation characterization is performed for four different plates with thicknesses of 2.29\textit{mm}, 3.56\textit{mm}, 6.35\textit{mm}, and 12.7\textit{mm}. These plates are labeled Plate 1, 2, 3, and 4, respectively. The ductile fracture testing is performed only on Plate 4. The testing was funded by the FAA’s Uncontained Engine Debris Mitigation Program, the ultimate goal of which is to make jet engines more reliable and safer to operate. Differences discussed in the materials are outside of data spread, which can be seen in Appendix A and B. These data are used by GWU and the FAA to calibrate the LS-DYNA material model, MAT224.

5.1 Plastic Deformation Experimental Conclusions

Detailed results from the plastic deformation test series are found in Chapter 3. Experimental methods used to determine the plastic deformation characteristics are described, at length, in Chapter 2. Limited tension and compression tests are conducted on plates 1 and 2 while plates 3 and 4 are subject to a comprehensive test plan. Plate 4 also includes shear testing. The majority of the plate 3 testing was done
by Yatnalkar[12]. A complete test outline is presented in Table 2.1. Tension testing is conducted with similarly sized plane stress smooth dog-bone specimens. Compression testing is completed with cylinder specimens. Torsion tests are conducted on thin walled tube specimens. Load measurements are taken using either a load cell or Kolsky bar depending on the test setup and strain rate. Displacements and strains are measured with three dimensional digital image correlation.

Strain rate dependent testing is conducted in tension and torsion at strain rates between $1.0 \times 10^{-4}s^{-1}$ and $1.5 \times 10^{3}s^{-1}$ and in compression up to $8.0 \times 10^{3}s^{-1}$. The material displays significant rate dependence throughout the entire range of strain rates. The material has increasing yield and flow stresses with increasing strain rate. Plates 3 and 4 show a significant change in strain hardening rate between $1.0 \times 10^{-2}s^{-1}$ and $1.0s^{-1}$ in both tension and compression. Failure strain is also influenced by the strain rate where lower failure strains are measured at high strain rates. Shear test results for plate 4 show similar trends in shear stresses and failure strains for increasing strain rates.

Anisotropic properties within the plate are investigated by testing specimens machined in the rolled, $45^\circ$ from rolled, transverse, and $-45^\circ$ from rolled directions. Compression anisotropic testing is also conducted in the through direction. In tension, plates 1, 3, and 4 display an anisotropic behavior while plate 2 is isotropic for the directions tested. In compression, plate 3 has significant anisotropic behavior while plate 4 appears only slightly anisotropic. Depending on the plate stock, differences are seen in yield stress, flow stress, strain hardening rates, and failure strain in both tension and compression. There is also asymmetry between the tension and compression characteristics.
For plates 3 and 4 tests are performed at various temperatures ranging from \(-50^\circ C\) to \(600^\circ C\). Results from these tests indicate that yield and flow stress, strain hardening, failure strains, and failure mode are strongly dependent on temperature. Flow stresses decrease and failure strain increase as temperatures increase. At low temperatures, compression specimens exhibit shear failure while at higher temperatures they do not. The two plates have converging material responses at \(200^\circ C\) in tension and at \(600^\circ C\) in compression.

Although each of the four plate stocks fall under the same AMS specification, a comparison between them shows significant differences in the material properties. These differences are seen in the yield and flow stresses, strain hardening, failure strains, and failure modes. The strength of Plate 4 is higher than the others. Plate 3 has the highest degree of anisotropy while plate 2 is essentially isotropic. Anisotropic effects are also not similar between the plates. All plates showed tension/compression asymmetry.

### 5.2 Ductile Fracture Experimental Conclusions

Detailed results from the ductile fracture test series are found in Chapter 4. Methods used to test the fracture specimens are described, in detail, in Chapter 2. All specimens in this test series are fabricated from Plate 4 in the rolled direction. Complete testing outlines are presented in Tables 2.2, 2.4, 2.3, and 2.5. Experimental data are compared to simulation results in Appendix D. Ductile fracture tests are conducted on plane stress, axisymmetric, and plane strain tension specimens and combined loading (thin-walled tube) specimens. Four different plane stress specimens are tested, including: a smooth dog-bone and three notched specimens. Axisymmetric
specimens include: one smooth and five with various sized notches. Plane strain specimens include: one smooth and two notched specimens. Combined loading tests include four different axial-torsional loading ratios. Force and torque are measured with a load cell and displacements are measured with three dimensional digital image correlation.

As the notch radius decreases for plane stress, axisymmetric, and plane strain specimens the stresses increases and the failure strain decreases. Plane stress specimens have stress triaxialities ranging from 0.400 to 0.583, Lode parameters ranging from 0.014 to 0.845, and failure strains from 0.14 to 0.59. Axisymmetric specimens have stress triaxialities ranging from 0.369 to 0.956, Lode parameters all equal to 1.0, and failure strains from 0.22 to 0.31. Plane strain specimens have stress triaxialities ranging from 0.470 to 0.768, Lode parameters from 0.025 to 0.506, and failure strains from 0.21 to 0.22. Combined loading specimens have stress triaxialities ranging from −0.147 to 0.251, Lode parameters ranging from −0.390 to 0.702, and failure strains from 0.29 to 0.51. Models that use the stress triaxiality alone to describe failure strain are unable to predict the failure of the specimen under the various loading conditions tested. The Lode parameter is used to create a three dimensional fracture locus in the stress triaxiality and Lode parameter stress space.

Failure strains found by comparing experimental data to simulation results are used to construct the locus. These strains are determined from the center element of the simulated specimen since theory indicates failure will initiate there[28]. Multiple views of the fracture locus are found in Appendix E. The fracture locus can be used to predict fracture of Ti-6Al-4V under various states of stress. These data are used to calibrate the MAT224 fracture model for Ti-6Al-4V.
5.3 Overall Project Conclusions

It is unlikely that the Johnson-Cook model can accurately predict the response of this material. A more complex model, such as MAT224 in LS-DYNA is required. The Johnson-Cook model is also unable to incorporate anisotropy and tension/compression asymmetry. The Model also cannot model the changes in strain hardening at various strain rates and temperatures observed in Chapter 3. Due to the significant difference in the plates tested here, it is recommended that users characterize the actual stock being used and not solely relying on data found in literature. It may also be helpful if the material processing is more closely controlled to ensure uniform properties between plate thicknesses and lots.

Ti-6Al-4V’s mechanical characteristics display both strain rate and temperature dependence. The material is anisotropic and asymmetric response in tension, compression, and shear. Fracture characteristics of Ti-6Al-4V are influenced by the state of stress, characterized here by stress triaxiality and Lode parameter. Fracture strain is dependent on the strain rate and temperature. Different plate stocks of the material, which fall under the same specifications, have significant differences.

Data is delivered to the Federal Aviation Administration and George Washington University who are developing and validating the LS-DYNA material model, MAT224. Technical support, ballistic impact testing, and material analysis is provided by the National Aeronautics and Space Administration. The Ohio State University’s contribution of this project is to characterize 2024-T351[21] and Ti-6Al-4V[12] for plastic deformation and ductile fracture. Future work will include punch testing of Ti-6Al-4v as well as a full characterization of Inconel 718. This work falls under the FAA’s ongoing Uncontained Engine Debris Mitigation Program.
Chapter 6: Strain Measurements at Temperatures up to 800°C utilizing Digital Image Correlation

6.1 Introduction

Measuring strain at elevated temperatures is challenging. This chapter presents a straightforward and repeatable method to measure full field strains at temperatures up to 800°C using a three-dimensional Digital Image Correlation system. High temperature strain measurement techniques include: 1) using the signal from the controller LVDT, 2) high temperature extensometer, and 3) high temperature strain gages. The LVDT is subject to machine compliance errors that vary from test to test with parameters such as grip location, grip force, or push/pull rod material and length. High temperature extensometers measure the strain between two ceramic knife edges attached to the specimen. The actual body of the extensometer typically sits outside the heated zone and can be water cooled. These extensometer work well but they assume that the strain is uniform between the knife edges, often have a limited strain measuring range, and need to be removed prior to specimen failure. High temperature strain gages can be cumbersome to use. These gages need to be temperature compensated since their gage factors change with temperature. They often have a limited strain measurement range and they only give data at one point on the specimen.
The goal of this chapter is to develop a method to optically measure strain at elevated temperatures up to 800°C. Results from this method do not exceed a reasonable DIC projection errors as compared to room temperature measurements. Thermal expansion tests are performed with the technique and are used to validate the test method by comparing to measured CTE’s handbook values. DIC greatly enhances data because transverse, shear strains, and out of plane displacements can be measured on the entire visible surface of the specimen. These measurements are very useful to study both the plastic deformation and failure behavior of materials at elevated temperatures.

Using DIC above room temperatures has significant challenges. First, the sample must be visible to external cameras, effectively ruling out close-box furnaces and induction. Thermal lensing of gases (air) can cause optical problems for the measurement system. If a furnace with a window is used, the window must be free to expand. If it is confined, it may deform and create a lensing effect. Survivability of the speckle pattern is also an issue. Standard paints cannot survive elevated temperatures making them impractical for this application. The paint must endure the high temperatures and the larger deformations caused by typical increases in ductility at these temperatures.

6.1.1 Literature Review

Digital Image Correlation has become an invaluable tool in experimental mechanics and researchers are adapting this measurement technology for use at, more complex, test conditions. Previous researchers have used DIC at elevated temperatures including: Lyons et al.[35], Grant et al.[36] and Pan et al.[37]. These researchers use
various methods and equipment and their work provides valuable insight for those using DIC at elevated temperatures.

Lyons[35] evaluates a method using a furnace to heat a specimen while collecting image data through a window at temperatures up to 650°C. The furnace window and variations in the refractive index of the heated air were found to be sources of error in the measurement. A sapphire window was used and the accuracy of the measured displacement field was strongly influenced by its optical quality. The addition of an external fan and optical grade sapphire window reduced these errors to acceptable levels. Coefficient of Thermal Expansion (CTE) and elastic deformation measurements were taken.

Grant[36] investigates the use of DIC in measuring CTE at temperatures up to 800°C using CCD camera sensors. The researchers found that infrared radiation (IR) had a negative effect on the measurements. They developed a technique using blue illuminators and optical bandpass filters to reduce these effects. These illuminators and filters allowed only light at the upper range of the visible spectrum (420nm to 480nm) through to the CCD, thus reducing detrimental IR.

Pan, et al.[37], demonstrate a method using DIC to measure full field deformations at temperatures up to 1200°C using CMOS camera sensors. The researchers had similar problems with IR effects and were able to minimize them with the use of a bandpass filter (428nm to 470nm) and blue light illumination. A black speckle pattern was applied to the bare metal. The pattern was made from black cobalt oxide mixed with a commercial high temperature inorganic adhesive. Specimens were heated using an infrared radiator and CTE were measured.
6.2 Experimental Setup

The method introduced here uses a custom enclosed furnace which uniformly heats the specimen. This furnace was designed in conjunction with Applied Test Systems Inc. The digital image correlation system needs to be calibrated prior to testing. The calibration could be rendered invalid by positionary changes between the cameras and the specimen. Vic-3D defines a three dimensional world coordinate system from two dimensional images of a grid with known spacing in both camera sensors. Changes in the optical path for the stereo rig to the specimen will increase the measurement error. To maintain a consistent optical path, the front of the furnace, which contains the window, is rigidly mounted to the load frame. The back of the furnace opens on a hinge granting access to the specimen, see Figure 6.1(c). The 38.1mm × 101.6mm window is made from optical quartz, see in Figure 6.1(a). Since the back section of the furnace opens, the calibration can be preformed without significant window displacements. Optical quartz combines good thermal properties with low light deflection reducing lensing, which can cause errors in DIC measurements. The window is mounted in a ceramic fixture that allows it to freely expand minimizing internal stresses that may cause lensing.

The furnace includes an internal Inconel 718 fan to circulate the air which is powered by an external motor mounted on top. The air circulation allows for faster and more uniform specimen heating. The circulation also reduces thermal lensing from optical distortions that are caused by temperature gradients in the air that change the local refractive index. The fan is connected to the motor through an external chain drive and rotates at 40rpm.
Figure 6.1: Furnace used with digital image correlation, (a) optical quartz window, (b) 3D DIC system setup, (c) interior of furnace
Photron MC2.1 cameras are mounted vertically due to the orientation of the window as seen in Figure 6.1(b). The cameras are operated at 512 × 512 resolution at 1000fps. Sigma 50mm F2.8 DG Macro lenses provided a suitable field of view for the specimens. CMOS camera sensors are known to be susceptible to IR light[35] and thus filters are used to increase image quality. Two types of IR filters are generally available. These are absorptive filters and a reflective filters. The former reduces IR by absorbing the energy, possibly causing the filters to heat up and thermally expand. Filter deformation is a concern since this could have a lensing effect and give higher correlation errors. The latter filter type reflects the light, reducing temperature increases due to IR heating. Tiffen Hot Mirror reflective IR filters are used to prevent heating and deformation of the filter. The hot mirror filter reduces IR pollution by reflecting wavelengths above 700nm as seen in Figure 6.2[38]. Fiber optic lamps provide the necessary lighting through the window as seen in Figure 6.1(b). Image glare is removed using B+W 55mm linear polarization filters. The polarization filters are placed between the lenses and the hot mirror filter to reduce the effects of heating. The recorded images provide sufficient contrast for the digital image correlation software.

Force and torque are measured using an axial-torsional load cell mounted in series with the upper grip. A heat shield between the furnace and the load cell prevents temperature increases in the cell from convection and radiation. To prevent conduction heat transfer, the grips are water cooled outside of the furnace which keeps the grip temperature near the load cell at or below room temperature. The furnace has two thermocouples that provide feedback for a PID controller. The surface of the specimen is instrumented with at least one attached thermocouple using Omega CC
high temperature cement. The grips were also measured with thermocouples. When more than one thermocouple was attached to the specimen, the average between the two at the time of test was recorded as the test temperature. During heating, temperature data is logged at a rate of $1\,Hz$ and saved for further analysis.

Normal paint is not a viable option at these temperatures. Materials typically become more ductile the closer they get to their melt temperatures, so larger strains are expected in localization regions. This requires flexible paint to deform with the specimen without delaminating. The previous work discussed in Section 6.1.1 considered elastic deformation or small displacements due to thermal expansions [35][36][37]. For Ti-6Al-4V, local plastic strains on the order of 50% to 60% are expected at 600°C. Commercially available Rust-oleum High Heat paint, which has a reported operating temperature of 1093°C is used for the base coat and speckel pattern.
6.3 Validation of Measurement System

6.3.1 Optical Validation

Figure 6.3 shows the optical quality of digital pictures taken with the cameras, lenses, filters, and paint described above. These pictures show the evolution of the image quality as the temperature increases up to 900°C. The images get darker as temperature is increased to 700°C. The increase in light above this temperature is due to significant IR emanating from the Inconel Bars. The image quality is generally good and has enough contrast to calculate DIC data up to 800°C.

![Image Quality from Room Temperature to 900°C](image)

Figure 6.3: Image quality from room temperature to 900°C

6.3.2 Coefficient of Thermal Expansion Validation Testing

The introduction of a new measurement method requires initial validation testing. To validate the experimental setup, images of a test specimen are recorded as temperature is increased. Temperature is increased in steps to allow the system to stabilize.
Three dimensional digital image correlation is used to measure the increase in length as the material expands due to the increase in temperature. From the measured displacements, the coefficient of thermal expansion, $\alpha$, is calculated through:

$$\alpha = \frac{L_i (T_f - T_i)}{\Delta L}, \quad (6.1)$$

where $\Delta L$, is the change in specimen length, $L_i$ is the initial measured length, and $T_f$ and $T_i$ are the final and initial temperature, respectively. Ti-6Al-4V is tested because it has been extensively studied and tabulated [39]. Measured CTE's at various temperature differences, $\Delta T$, are plotted with published data in Figure 6.4[39]. The data shows good correlation at $\Delta T$'s above 450°C. Displacement measurements at lower temperatures were susceptible to noise due to the small deformations.

![Graph showing the comparison of measured Ti-6Al-4V thermal expansion coefficients to previously published data](image-url)

Figure 6.4: Comparison of measured Ti-6Al-4V thermal expansion coefficients to previously published data
The validation tests showed good agreement at temperature differences above 450°C corresponding to approximately 4500µε. The noise to data ratio seen in the CTE tests are much higher than those in the plastic deformation testing, due to the much higher strain magnitudes expected. Results from a typical CTE test can be seen in Figure 6.5[39]. The high levels of noise at the beginning of the test are due to the small deformations measured with the DIC system. These data coupled with the low ∆T cause the noise.

![Figure 6.5: Measured data from a coefficient of thermal expansion test on Ti-6Al-4V](image)

For each set of images processed Vic-3D quantifies the amount of error and tabulates it. Based on the calibration, a given point in the camera one image has a predicted line (epipolar line) along which the point must lie in the camera two image[38]. The projection error is the distance, in pixels, from the expected distance and values below 0.05 are ideal. Projection errors from a CTE test are shown in Figure 6.6. The
projection error increases from 0.06 at room temperature to approximately 0.12 at 100°C to 860°C. Room temperature projection errors are slightly higher than normal due to the presence of the window. As temperature increases, the projection errors increase.

![Graph showing projection error versus temperature](attachment:projection_error_temperature_graph.png)

**Figure 6.6:** Projection error versus temperature for a coefficient of thermal expansion test on Ti-6Al-4V

The goal of any experimental measurement system is to minimize error between the physical event and the recorded data. There is significant room for errors due to the complex nature of these tests. Window lensing, gaseous lensing, thermal expansion, and relative motion of lenses or windows are all potential sources of errors. Although DIC measurement projection errors are higher at high temperatures, they are still within reasonable levels compared to room temperature tests.
6.4 Experimental Methods and Results of the Various Loading Conditions at High-temperatures

High temperature data is required for tension, compression, and torsion (shear). Techniques for each of the loading types are discussed here. Complete experimental data can be seen in Chapter 3. Data spread for this data can be seen in Appendix A. Although, this system is capable of measurements up to 860°C tests are only performed at 200°C, 400°C, and 600°C.

6.4.1 Tension Measurement Techniques and Results

The water cooled Inco718 push/pull rods are aligned using dual depth gages prior to testing. The grips are specially designed for high temperature tension tests are seen in Figure 6.7. Both the top and bottom grips have recessed notches with a similar width to that of the specimen grip section. This recess ensures that each specimen is properly aligned. The specimen is affixed to the grip with an Inco718 clamp using high temperature #4 – 40 × 1/2 screws. For temperatures at or below 400°C a high nickel ferrous alloy (A286) is used, for tests above 400°C Inco718 screws are used. HCP Boron Nitride Powder, a high temperature solid lubricant, is applied to the threads prior to testing to prevent oxidation and binding of the screws. Two thermocouples were placed on the bars and two were placed on the specimen just outside of the gage section using Omega CC high temperature cement.

Digital image quality, at room temperature, 200°C, 400°C, and 600°C, are shown in Figure 6.8. A 4mm virtual extensometer(see Figure 6.9 at 25°C), which sufficiently spans the gage section, is used to measure strain.
Figure 6.7: Grip method and experimental setup for high temperature tension testing

Figure 6.8: Digital image quality of tension specimens at various temperatures
DIC results from the tension tests on Ti-6Al-4V at various temperatures are presented in Figure 6.9. These strain fields correspond to the point just prior to specimen failure. At elevated temperatures, the paint delaminated resulting in data loss in the necking region. The 4mm extensometer, however, gave good results at all temperatures. The figure shows that the extensometer is outside of the affected region and the data is usable until fracture.

![Figure 6.9: Axial strain measured with 3D digital image correlation just prior to failure at various temperatures and speckle pattern adhesion for tension](image)

An engineering stress strain curve constructed using strain data from the 4mm extenometer is compared to the one constructed using strain from the LVDT is shown in Figure 6.10. This plot presents data for a tension specimen at 600°C at a strain rate
of 1.0s\(^{-1}\). The DIC data shows increased stiffness in the initial portion of the curve and much larger strains after necking begins. The initial deviation between the two curves is caused by load frame and grip compliance. Since the DIC strain is measured directly on the surface of the sample, the compliance is eliminated. The post necking portion of the curve, where DIC strains exceed LDVT strains, can be explained by the extreme necking localization in the gage section shown in Figure 6.9 at 600°C. The 4mm extensometer is close to this localization region. At the onset of necking, the deformation rate (measured by the extenometer) increases dramatically. The LVDT strain measurement assumes that all the deformation takes place uniformly within the 5.08mm smooth section of the sample. This artificially decreases the strain and creates the variance shown in Figure 6.10.

![Graph showing comparisons of strain measurements for tension at 600°C](image)

Figure 6.10: Comparisons of strain measurements for tension at 600°C
The reliability of paint adhesion decreased with increasing temperature, see Figure 6.9. The paint becomes brittle at high temperatures. In addition, Ti-6Al-4V undergoes larger deformations in the necking region as the material gets closer to the melting temperature. Strains for the elevated temperature tests are calculated from a 4mm extensometer which lies outside of the paint delamination region. Alternative painting options were not explored since the extensometer obtained valuable data. A new painting method or material is needed to measure failure stains in the localized region.

6.4.2 Compression Measurement Techniques and Results

Larger compliance errors exits in compression due to the high forces involved. Compression strains are typically corrected by subtracting the system compliance from the LVDT record. The system compliance must be determined at each of the different temperatures. Three dimensional DIC eliminates the need to determine compliance since measurements are made directly on the compression specimen.

Aligned Inconel 718 push rods are with 12.7mm diameter WC inserts as seen in Figure 6.11. The specimen is centered on the platens prior to testing. HCP Boron Nitride Powder is placed between the specimen and the WC inserts to reduce contact force friction. A compressive, uniaxial loading condition is desired and friction causes radial stresses. Thermocouples were located on the top and bottom tungsten carbide platens. Attaching the thermocouple directly to the specimen may artificially increase the measured load since the Omega CC cement is capable of carrying load.

Ideally, the cameras would be positioned horizontal to the loading direction, but the orientation of the window makes this impossible. The cameras are carefully placed
vertically so that data is measured both on the specimen and the WC platens. Images of the platens and compression specimen at 200°C, 400°C, and 600°C are shown in Figure 6.12. A virtual extensometer, roughly the length of the specimen, is used to measure elastic strains. The motion of the platens is used to measure plastic strains.
Paint adhesion is also an issue in the compression testing, see Figure 6.13. The paint delaminated after yield at temperatures at and above 400°C. For these tests, the relative platen motion is used to measure strain. Note that DIC measurements capture the shear failure mode at 25°C and 200°C. Ti-6Al-4V is much more ductile at 400°C and 600°C as seen in Figure 6.13.

Figure 6.13: Axial strain measured with 3D digital image correlation just prior to failure at various temperatures and speckle pattern adhesion for compression

Stress strain curves constructed for strains measured with DIC and strains measured with the LVDT are seen in Figure 6.14. The figure shows data from a compression test at 600°C at a strain rate of 1.0s⁻¹. DIC measures the elastic modulus of the material much more accurately than the LVDT. The deviation in the elastic
region is caused by system. The DIC measurements eliminate compliance since they are directly measured on the surface of the specimen.

Paint delamination did not have a significant effect on compression test results since strains are calculated with an extensometer in the elastic region and relative platen motion after yield.

### 6.4.3 Torsion Measurement Techniques and Results

DIC is also used to measure shear strain in torsion tests. This eliminates the need to correct the data for system compliance. Ti-6Al-4V is a relatively strong material making grip screw compliance an important issue. In addition, the surface of the specimen is not visible due to the specimen orientation with respect to the window.
Tracking brackets are attached to the upper and lower specimen flanges using a high
temperature cement as seen in Figure 6.15(a). The brackets are fabricated from 4340
steel and are bent $90^\circ$ to provide visible surface to track with DIC. The distance from
the end of the bracket to the center of the specimen is recorded and eventually used
to calculate shear strain.

![Figure 6.15: High temperature torsion tracking bracket setup and DIC results, (a) high temperature torsion test setup with tracking brackets, (b) tracking bracket DIC results for initial and deformed results](image)

Three dimensional DIC is used to measure the displacements of the tracking brackets in both the horizontal (y-direction) and depth (z-direction), as shown in Figure 6.15(b). Tracking bracket displacement values, measured specimen dimensions, and
bracket distances are used to calculate shear strain or:

\[ \gamma_s = \frac{r_m \Delta \theta}{L_g}, \]  

(6.2)

where, \( r_m \) is the mean radius of the specimen, \( L_g \) is the gage length, and \( \Delta \theta \) is given by:

\[ \Delta \theta = \arccos \left[ \frac{r_b^2 + (r_b - \Delta z)^2 - \Delta x^2}{2r_b (r_b - \Delta z)} \right], \]  

(6.3)

where, \( r_b \) is the distance from the center of the specimen to the bracket surface, \( \Delta x \), is the vertical displacement, and \( \Delta z \), is the out of plane displacement.

Although strain is not measured directly on the sample, the brackets are able to eliminate machine compliance since they are directly attached to the specimen. This gives more accurate shear strain results than those calculated by the machine RVDT. Shear stress versus shear strain curves from DIC and the RVDT are compared in Figure 6.16. The RVDT strains, which are generally overestimated, include system compliance errors. This measurement technique provides more accurate results for high temperature shear testing.
Figure 6.16: Differences in strain measurements for torsion at 400°C

6.5 Summary and Conclusions

The implementation of Digital Image Correlation for high temperature testing gives more accurate strain measurements for tension, compression, and torsional shear testing. The DIC system is able to measure full field strains of tension and compression at temperatures up to 600°C. At high strains, specifically in localization regions, problems with paint adhesion caused local data loss at 400°C and 600°C. Further research on speckling techniques could eliminate this issue. Tests described here are limited to 600°C, but this technique works well at temperatures up to 860°C. The development of this technique of strain measurement expanded the capabilities of the Dynamic Mechanics of Materials Laboratory to provide high quality mechanical test data at elevated temperatures.
Appendix A: Experimental Results from the Ti-6Al-4V Plastic Deformation Test Series

The experimental results from each of the test sets are presented here to show the amount of data spread in each test series. Data for the Tension and compression test series are presented in true stress versus true strain. Torsion data is presented in shear stress versus shear strain. Results and discussion is presented in Chapter 3.
A.1 Tension Test Series

A.1.1 Tension Strain Rate Dependent Test Series for the 2.29mm Plate Stock

Figure A.1: Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0 s^{-1}$, room temperature, rolled direction

Figure A.2: Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 650 s^{-1}$, room temperature, rolled direction
A.1.2 Tension Orientation Dependent Test Series for the 2.29mm Plate Stock

Figure A.3: Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, $45^\circ$ from rolled

Figure A.4: Tension test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, transverse direction
A.1.3 Tension Strain Rate Dependent Test Series for the 3.56mm Plate Stock

Figure A.5: Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, rolled direction

Figure A.6: Tension test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 600s^{-1}$, room temperature, rolled direction
### A.1.4 Tension Orientation Dependent Test Series for the 3.56mm Plate Stock

Figure A.7: Tension test data spread: 3.56mm plate stock, \( \dot{\varepsilon} = 1.0s^{-1} \), room temperature, 45° from rolled

Figure A.8: Tension test data spread: 3.56mm plate stock, \( \dot{\varepsilon} = 1.0s^{-1} \), room temperature, transverse direction
A.1.5 Tension Temperature Dependent Test Series for the 6.35mm Plate Stock

Figure A.9: Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $-50^\circ C$, rolled direction

Figure A.10: Tension test data spread: 6.35mm plate stock, $\dot{\epsilon} = 1.0s^{-1}$, $200^\circ C$, rolled direction
Figure A.11: Tension test data spread: 6.35mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $400^\circ C$, rolled direction

Figure A.12: Tension test data spread: 6.35mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $600^\circ C$, rolled direction
A.1.6 Tension Strain Rate Dependent Test Series for the 12.7mm Plate Stock

Figure A.13: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \times 10^{-4} \text{s}^{-1}$, room temperature, rolled direction

Figure A.14: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 E - 2 \text{s}^{-1}$, room temperature, rolled direction
Figure A.15: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, rolled direction

Figure A.16: Tension test data spread: 0.5” plate stock, $\dot{\varepsilon} = 500s^{-1}$, room temperature, rolled direction
A.1.7 Tension Orientation Dependent Test Series for the 12.7mm Plate Stock

Figure A.17: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1500s^{-1}$, room temperature, rolled direction

Figure A.18: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, 45° from rolled
Figure A.19: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, room temperature, transverse direction

Figure A.20: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, room temperature, $-45^\circ$ from rolled
A.1.8 Tension Temperature Dependent Test Series for the 12.7mm Plate Stock

Figure A.21: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 s^{-1}$, $-50^\circ C$, rolled direction

Figure A.22: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 s^{-1}$, $200^\circ C$, rolled direction
Figure A.23: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 400°C, rolled direction

Figure A.24: Tension test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 600°C, rolled direction
A.2 Compression Test Series

A.2.1 Compression Strain Rate Dependent Test Series for the 2.29mm Plate Stock

Figure A.25: Compression test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1.0\,\text{s}^{-1}$, room temperature, rolled direction

Figure A.26: Compression test data spread: 2.29mm plate stock, $\dot{\varepsilon} = 1500\,\text{s}^{-1}$, room temperature, rolled direction
A.2.2 Compression Strain Rate Dependent Test Series for the 3.56mm Plate Stock

Figure A.27: Compression test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, room temperature, rolled direction

Figure A.28: Compression test data spread: 3.56mm plate stock, $\dot{\varepsilon} = 1500\text{s}^{-1}$, room temperature, rolled direction
A.2.3 Compression Temperature Dependent Test Series for the 6.35mm Plate Stock

Figure A.29: Compression test data spread: 6.35mm plate stock, $\dot{\varepsilon} = 1.0\, s^{-1}$, $-50^\circ C$, rolled direction

A.2.4 Compression Strain Rate Dependent Test Series for the 12.7mm Plate Stock

Figure A.30: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 E - 4\, s^{-1}$, room temperature, rolled direction
Figure A.31: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0E - 2 s^{-1}$, room temperature, rolled direction

Figure A.32: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 s^{-1}$, room temperature, rolled direction
Figure A.33: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1500\text{s}^{-1}$, room temperature, rolled direction

Figure A.34: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 4000\text{s}^{-1}$, room temperature, rolled direction
Figure A.35: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 7000\text{s}^{-1}$, room temperature, rolled direction

A.2.5 Compression Orientation Dependent Test Series for the 12.7mm Plate Stock

Figure A.36: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, room temperature, 45° from rolled
Figure A.37: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \text{s}^{-1}$, room temperature, transverse direction

Figure A.38: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0 \text{s}^{-1}$, room temperature, $-45^\circ$ from rolled
Figure A.39: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, through direction

A.2.6 Compression Temperature Dependent Test Series for the 12.7mm Plate Stock

Figure A.40: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $-50^\circ$C, rolled direction
Figure A.41: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 200°C, rolled direction

Figure A.42: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 400°C, rolled direction
Figure A.43: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 600°C, rolled direction

A.2.7 Compression Additional for the 12.7mm Plate Stock

Figure A.44: Compression test data spread: 6.35mm plate stock, $\dot{\varepsilon} = 1.0E - 4s^{-1}$, room temperature, rolled direction, Researcher Comparison and surface finish Tests
Figure A.45: Compression test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, rolled direction, Alternate Geometry

A.3 Shear Test Series

A.3.1 Shear Strain Rate Dependent Test Series for the 12.7mm Plate Stock

Figure A.46: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0E - 4s^{-1}$, room temperature, through direction
Figure A.47: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0E - 2s^{-1}$, room temperature, through direction.

Figure A.48: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, room temperature, through direction.
Figure A.49: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 500s^{-1}$, room temperature, through direction

Figure A.50: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1500s^{-1}$, room temperature, through direction
A.3.2 Shear Temperature Dependent Test Series for the 12.7mm Plate Stock

![Graph](image_url)

Figure A.51: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, $-50^\circ C$, through direction

![Graph](image_url)

Figure A.52: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0s^{-1}$, 200$^\circ C$, through direction
Figure A.53: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, 400°C, through direction

Figure A.54: Shear test data spread: 12.7mm plate stock, $\dot{\varepsilon} = 1.0\text{s}^{-1}$, 600°C, through direction
Appendix B: Experimental Results from the Ti-6Al-4V Ductile Fracture Test Series

The spread in measured data from the fracture test series are presented here. All data for the plane stress, plane strain, and axisymmetric tests is presented in a engineering stress versus engineering strain to normalize the data for slight deviations in specimen size. Combined loading tests data spread is presented showing 4 different data sets: (a) are the axial force displacement curves, (b) are the torque angle curves, (c) are the stress triaxiality versus time, and (d) are the Lode Parameter versus time. Data spread for the punch tests are presented with force displacement curves. Discussion of this data was presented in Chapter 4.
B.1 Plane Stress Test Series

Figure B.1: Fracture test data spread: plane stress notched, notch=14.29mm, 12.7mm plate stock, SR=1.0−2s−1, room temperature, rolled direction

Figure B.2: Fracture test data spread: plane stress notched, notch=4.76mm, 12.7mm plate stock, SR=1.0−2s−1, room temperature, rolled direction
Figure B.3: Fracture test data spread: plane ppress notched, notch=0.40mm, 12.7mm plate stock, SR=1.0^{-2}s^{-1}, room temperature, rolled direction

B.2 Axisymmetric Test Series

Figure B.4: Fracture test data spread: axisymmetric smooth, 12.7mm plate stock, SR=1.0^{-2}s^{-1}, room temperature, rolled direction
Figure B.5: Fracture test data spread: axisymmetric notched, notch=34.93mm, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction

Figure B.6: Fracture test data spread: axisymmetric notched, notch=17.46mm, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction
Figure B.7: Fracture test data spread: axisymmetric notched, notch=11.9mm, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction

Figure B.8: Fracture test data spread: axisymmetric notched, notch=6.75mm, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction
Figure B.9: Fracture test data spread: axisymmetric notched, notch=3.18mm, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction

B.3 Plane Strain Test Series

Figure B.10: Fracture test data spread: plane strain smooth, 12.7mm plate stock, SR=1.0$^{-2}$s$^{-1}$, room temperature, rolled direction
Figure B.11: Fracture test data spread: plane strain notched, notch=12.7mm, 12.7mm plate stock, SR=1.0^{−2}s^{−1}, room temperature, rolled direction

Figure B.12: Fracture test data spread: plane strain notched, notch=4.76mm, 12.7mm plate stock, SR=1.0^{−2}s^{−1}, room temperature, rolled direction
B.4 Combined Loading Test Series

Figure B.13: Combined loading force displacement data spread:, 12.7mm plate stock, $\sigma/\tau=1.971$, room temperature, rolled direction
Figure B.14: Combined loading stress state parameter data spread; 12.7mm plate stock, $\sigma/\tau=0.847$, room temperature, rolled direction
Figure B.15: Combined loading stress state parameter data spread; 12.7mm plate stock, $\sigma/\tau=0.0$, room temperature, rolled direction
Figure B.16: Combined loading stress state parameter data spread; 12.7mm plate stock, $\sigma/\tau=-0.847$, room temperature, rolled direction.
Appendix C: Finite Element Meshes used in the Tension Specimen Design for the Fracture Characterization Test Series

The mesh sizes for the simulated fracture experiments are presented here. These meshes were used in LS-DYNA simulations results of which are presented in Appendix D. Results from these simulations are used in development of the fracture locus and presented in Chapter 4. For each of the specimens a constant mesh density of approximately 65.6 elements/cm is used. The Axisymmetric specimens are shown in a section view to show the center elements.
C.1 Plane Stress Test Series

Figure C.1: Mesh for plane stress smooth specimen

Figure C.2: Mesh for plane stress specimen with a notch of 14.29mm
Figure C.3: Mesh for plane stress specimen with a notch of 4.76mm

Figure C.4: Mesh for plane stress specimen with a notch of 0.40mm
C.2 Axisymmetric Test Series

Figure C.5: Mesh for axisymmetric smooth Specimen (section view)

Figure C.6: Mesh for axisymmetric specimen with a notch of 34.93mm (section view)
Figure C.7: Mesh for axisymmetric specimen with a notch of 17.46mm (section view)

Figure C.8: Mesh for axisymmetric specimen with a notch of 11.91mm (section view)
Figure C.9: Mesh for axisymmetric specimen with a notch of 6.75mm (section view)

Figure C.10: Mesh for axisymmetric specimen with a notch of 3.18mm (section view)
C.3 Plane Strain Test Series

Figure C.11: Mesh for plane strain smooth specimen

Figure C.12: Mesh for plane strain specimen with a notch of 4.76mm
Figure C.13: Mesh for plane strain specimen with a notch of 12.70mm
Appendix D: Comparison of Experimental Data and Simulations of Fracture Test Series

The fracture points found from comparing simulations to physical results. The comparisons of the plane stress, axisymmetric, and plane strain tests are presented here. The first and second principle strain comparison of the DIC surface strains to the simulation surface strains. Levels of the respective strains are identical between the DIC and simulated specimens. The included plots provide a comparison of stress levels and surface strains. The strains from the center of the simulated values are also shown, which is where the failure points are taken. The stress triaxialities and Lode Parameter are displayed as taken from the center element.

Combined loading DIC data and time history is also presented. Strain data is taken from a DIC point strain on the surface of the specimen near the fracture point. Simulations are not performed on these specimens because their stress states are only dependent on axial-torsional loading ratio.
D.1 Plane Stress Test Series

Figure D.1: History comparison of simulated and experimental fracture data for the plane stress smooth specimen
Figure D.2: History comparison of simulated and experimental fracture data for the plane stress large notch specimen R=14.29mm
Figure D.3: History comparison of simulated and experimental fracture data for the plane stress medium notch specimen R=4.76mm
Figure D.4: History comparison of simulated and experimental fracture data for the plane stress small notch specimen R=0.40mm
D.2 Axisymmetric Test Series

Figure D.5: History comparison of simulated and experimental fracture data for the axisymmetric smooth specimen.
Figure D.6: History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=34.93mm
Figure D.7: History comparison of simulated and experimental fracture data for the axisymmetric notched specimen $R=17.46\,\text{mm}$
Figure D.8: History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=11.91mm
Figure D.9: History comparison of simulated and experimental fracture data for the axisymmetric notched specimen R=6.75mm
Figure D.10: History comparison of simulated and experimental fracture data for the axisymmetric notched specimen $R=3.18\text{mm}$
D.3 Plane Strain Test Series

Figure D.11: History comparison of simulated and experimental fracture data for the plane strain smooth
Figure D.12: History comparison of simulated and experimental fracture data for the plane strain large notch R=12.7mm
Figure D.13: History comparison of simulated and experimental fracture data for the plane strain small notch $R=4.76\text{mm}$
D.4 Combined Loading Test Series

Figure D.14: history of experimental fracture data for the combined loading $\sigma/\tau = 1.971$
Figure D.15: history of experimental fracture data for the combined loading $\sigma/\tau = 0.847$
Figure D.16: history of experimental fracture data for the combined loading $\sigma/\tau = 0.00$
Figure D.17: history of experimental fracture data for the combined loading $\sigma/\tau = -0.847$
Appendix E: Additional Views of the Fracture Locus for Ti-6Al-4V

Additional view of the fracture locus for Ti64 will be presented here. This locus has been developed with the methods presented in Chapter 2. Detailed results from each of the tests are presented in Chapter 4. Plane stress, axisymmetric, plane strain, and combined loading results are displayed with a circle, square, triangle, and diamond respectively. The $x$, $y$, and $z$ axes represent the stress triaxiality, Lode parameter, and plastic fracture strains respectively.
Figure E.1: Fracture locus for Ti-6Al-4V in the stress triaxiality - Lode parameter plane

Figure E.2: Fracture locus for Ti-6Al-4V in the stress triaxiality - failure strain plane
Figure E.3: Fracture locus for Ti-6Al-4V in the Lode parameter - failure strain plane

Figure E.4: Three dimensional view of the Ti-6Al-4V fracture locus
Bibliography


