ABSTRACT

PENDER, KYLE MATTHEW. Development of a Hybrid Drawing and Hydroforming Operation. (Under the direction of Gracious Ngaile.)

The drawing process is a common metal forming operation that is utilized to produce a variety of near net shape components that feature a uniform cross-section. The current process features a number of design challenges, and research is currently conducted in order to reduce drawing load, improve process time, and eliminate environmentally unfriendly lubricants. A novel, hybrid drawing die design is proposed in the current study to eliminate the necessity of current lubrication practices by incorporating a hydroforming element to supply high pressure fluid to the reduction region of the die.

The objectives of this research include the achievement of a hydrodynamic fluid regime in the reduction region of the hybrid drawing die in an effort to eliminate the necessity of conversion coating lubrication strategies in the cold drawing industry. Additionally, surface finish improvements and increased material formability can be realized by altering the state of stress in the reduction region of the drawing die by coupling the high pressure fluid (hydroforming element) to the drawing operation.

Upon identifying the major design considerations for the hybrid drawing design, the specific design geometry is developed by optimizing geometry parameters via finite element analysis (FEA) using DEFORM 2D. Variations in the number of die sections, die section half-angle, and die section offset radius are manipulated to promote the most uniform strain distributions in the resulting drawn sample.

Numerical simulations are conducted using ANSYS Workbench 14.5 to observe die stresses in the extrusion and drawing die designs to predict the robustness needed to sustain the stresses generated by forming various billet materials. Determination of the proper billet geometry for the preliminary extrusion operation is utilized to prepare higher strength samples for the final drawing operation while maintaining a conservative factor of safety against die failure.

Additional numerical analysis is conducted to predict the steady-state drawing load for the hybrid drawing operation by approximating the effect of fluid pressure in DEFORM 2D. Utilizing two simulation approaches to approximate the high pressure fluid, as well as considering two friction conditions, four simulation cases are developed to predict bounds for the experimental load requirements for steady-state drawing. FEA is also utilized to predict the steady-state drawing load for the conventional drawing operation to determine the effective fluid pressure that predicts a steady-state load reduction in the drawing operation for 6061-O
aluminum billets as compared to the conventional operation.

Drawing experiments are conducted with two billet materials, 6061-O aluminum and 6061-T6 aluminum, and comparisons between samples drawn using the hybrid drawing die and a conventional die are discussed. Specifically, steady-state drawing load, hardness distribution in the radial direction of the steady-state drawn region, and surface topography are investigated for comparison. Additionally, observation of the reduction region of the sample is observed to assess the achievement of a hydrodynamic fluid film as well as other alterations to the lubrication mechanism.

Comparison of drawn 6061-O and 6061-T6 aluminum samples show tribological improvements for the hybrid drawing operation as compared to the conventional operation based on surface topography of the steady-state drawn billet. Additionally, observations of the reduction region on the drawn sample prove the achievement of a hydrodynamic fluid film at a specified fluid pressure. Steady-state drawing load data is compared to predicted drawing load from the numerical analysis, and the resulting load prediction error is analyzed and discussed.
Development of a Hybrid Drawing and Hydroforming Operation

by
Kyle Matthew Pender

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

Mechanical Engineering

Raleigh, North Carolina

2014

APPROVED BY:

Jeffrey Eischen    Eric Klang

Gracious Ngaile
Chair of Advisory Committee
Kyle Pender was born October 6, 1989 to Danny and Teresa Pender in Goldsboro, North Carolina. He graduated from Wayne Country Day School in Goldsboro, NC, and he received his BS in Mechanical Engineering from North Carolina State University in May 2012. During his undergraduate and graduate school career, he became intrigued by metal working and fabrication, including welding, metal forming, and machining processes. He continued his education at North Carolina State University and received his MS degree in Mechanical Engineering in May 2014.
ACKNOWLEDGEMENTS

First, I would like to thank my parents, Danny and Teresa, who have always supported me unconditionally. They have always been there for me when I have needed advice or motivation to continue my pursuit for higher education. They are very proud of my achievements, and their confidence in me has given me the perseverance to continue to work diligently.

There are so many people that were instrumental in my research, and I am grateful that I have had so many great people around me to provide advice and resources that have helped me complete my experiments. First, special thanks to Skip Richardson and Jason Vassey for machining the precise components of the hybrid drawing die design that I could not fabricate myself. Next, thanks to Mike Breedlove for providing machining advice and always helping me with my experimental design work. Also, thanks to Steve Cameron for providing machining advice, completing components of my experimental set-up, and giving me the opportunity to work alongside him as I made components for my experiments. Lastly, thanks to Gary Lofton for taking pressure off of me in the senior design lab to complete my thesis and for helping me fabricate elements of my experiments.

Thanks to all of the members of the AMTL that have helped me with experiments and finite element analysis as I have conducted my research. Specifically, thanks to James Lowrie for helping me with ANSYS issues, heat treatment of experimental parts, and experiment set-up. Also, thanks to Bandar Alzahrani for his help on simulations and experiments. Thanks to Lin Li for making food for everyone and helping me with experiments. Lastly, thanks to Ryan Kordsmeier for his help with experiments and his frustum expertise. I could not have made nearly the amount of progress that I have without everyone’s help.

Finally, I would like to thank my advisor, Dr. Gracious Ngaile, for giving me the opportunity to research in a lab where I could apply both my academic and practical skills effectively.
# TABLE OF CONTENTS

**LIST OF TABLES** ................................................................. vii

**LIST OF FIGURES** ............................................................. viii

**CHAPTER 1 INTRODUCTION** .................................................. 1
  1.1 Objectives and Approach ................................................ 1
  1.2 Thesis Organization ..................................................... 3

**CHAPTER 2 LITERATURE REVIEW** .......................................... 5
  2.1 Introduction ................................................................ 5
  2.2 Drawing Process .......................................................... 5
    2.2.1 Industrial Applications ........................................... 6
      2.2.1.1 Bar Drawing .................................................. 7
      2.2.1.2 Wire Drawing ............................................... 7
      2.2.1.3 Tube Drawing ............................................... 8
    2.2.2 Analytical Approaches ............................................ 9
    2.2.3 Optimal Die Half-Angle ................................ .......... 12
    2.2.4 Summary of Drawing and Areas of Future Research ....... 14
  2.3 Tribological Considerations in Metal Forming .................... 15
    2.3.1 Typical Steel Lubrication Techniques ....................... 15
    2.3.2 Typical Aluminum Lubrication Techniques ................ 16
    2.3.3 Impact of Conversion Coatings ................................ 17
    2.3.4 Summary of Tribological Considerations and Areas of Future Research ..................................................... 20
  2.4 Tube Hydroforming ....................................................... 20
    2.4.1 Basic Principles .................................................. 21
    2.4.2 Industrial Applications .......................................... 21
    2.4.3 Loading Path Determination .................................... 22
    2.4.4 Tube Hydroforming Equipment ................................ 23
    2.4.5 Summary of Hydroforming and Areas of Future Research .... 24
  2.5 Hybrid Metal Forming Processes ...................................... 24
    2.5.1 Hybrid Forming/Forming Operations .......................... 25
    2.5.2 Hybrid Machining/Forming Operations ....................... 28
    2.5.3 Summary of Hybrid Processes and Areas of Future Research ... 29
  2.6 Hydrodynamic/Hydrostatic Fluid-Assisted Forming Processes .... 30
    2.6.1 Experimental Applications ....................................... 30
      2.6.1.1 Hydrostatic/Hydrodynamic Extrusion ................... 30
      2.6.1.2 Hydrodynamic Drawing ................................... 33
    2.6.2 Relevance to Hybrid Drawing Design .......................... 35
  2.7 Conclusion ..................................................................... 35

**CHAPTER 3 NUMERICAL SIMULATIONS** .................................... 36
  3.1 Introduction ............................................................... 36
  3.2 Billet Material Characterization and Selection .................... 37
CHAPTER 4 HYBRID DRAWING DIE AND EXPERIMENTAL SET-UP DESIGN ..... 75
4.1 Introduction ....................................................... 75
4.2 Design Conception of Hybrid Die ................................ 75
4.3 Unique Characteristics of the Hybrid Drawing Design ....... 76
4.4 Hybrid Drawing Die Design ........................................ 78
4.5 Experimental Set-up ................................................ 83
4.5.1 Sample Preparation ............................................. 84
4.5.2 Hybrid Drawing Set-up ........................................... 90
4.5.3 Stroke Limitations and Billet Sizing ......................... 91
4.5.4 Sample Chuck .................................................... 93
4.5.4.1 Gripping Mechanism, Version One ....................... 93
4.5.4.2 Gripping Mechanism, Version Two ....................... 94
4.6 Conclusion .......................................................... 99

CHAPTER 5 EXPERIMENTAL RESULTS .................................. 101
5.1 Introduction ........................................................ 101
5.2 Experimental Procedure Overview .............................. 101
5.3 Hybrid Drawing Samples .......................................... 102
5.3.1 Surface Topography ............................................. 103
5.3.1.1 Macro Surface Observations ............................... 103
5.3.1.2 SEM and OM Surface Observations .................... 105
5.3.2 Drawing Load Data .............................................. 107
5.3.2.1 6061-O Aluminum Samples ............................... 107
5.3.2.2 6061-T6 Aluminum Sample ............................... 110

3.3 Hybrid Die Design Determination ................................ 41
3.3.1 Assumptions and Methodology .................................. 43
3.3.2 Design Variables .................................................. 44
3.3.2.1 Offset Radius .................................................. 44
3.3.2.2 Number of Die Sections and Die Section Half-Angle ...... 45
3.3.3 Conclusion .......................................................... 47
3.4 Extrusion Operation Simulations .................................... 47
3.4.1 Extrusion Die Stresses ............................................. 48
3.4.2 Determination of Initial Billet Geometry .................... 50
3.5 Hybrid Drawing Die Simulations .................................. 57
3.5.1 Die Stress Simulations for Drawing Die Design ............ 58
3.5.2 Simulation without Fluid Supply .............................. 62
3.5.3 Simulation with Fluid Supply ................................... 64
3.5.3.1 Half Pressure Window ....................................... 65
3.5.3.2 Full Pressure Window ........................................ 67
3.5.4 Comparison of Hybrid Die Simulation Results ............. 69
3.6 Conventional Drawing Die Simulations ......................... 70
3.6.1 Drawing Load Prediction ....................................... 71
3.6.2 Comparison of Hybrid and Conventional Die Drawing Load 73
3.7 Analysis Conclusions ............................................... 74
5.4 Conventional Drawing Samples ................................................................. 111
  5.4.1 Drawing Load Data ........................................................................... 111
    5.4.1.1 6061-O Aluminum Samples ....................................................... 111
    5.4.1.2 6061-T6 Aluminum Sample ...................................................... 112
5.5 Discussion of Hybrid vs. Conventional Samples .................................... 113
  5.5.1 Surface Comparison .......................................................................... 113
    5.5.1.1 6061-O Aluminum Samples ....................................................... 113
    5.5.1.2 6061-T6 Aluminum Samples ...................................................... 114
  5.5.2 Knoop Hardness Comparison .............................................................. 115
    5.5.2.1 6061-O Aluminum Samples ....................................................... 116
    5.5.2.2 6061-T6 Aluminum Samples ...................................................... 117
  5.5.3 Drawing Load Comparison ................................................................. 118
    5.5.3.1 6061-O Aluminum Samples ....................................................... 119
    5.5.3.2 6061-T6 Aluminum Samples ...................................................... 123
5.6 Conclusion ............................................................................................... 125

CHAPTER 6 DISCUSSION OF EXPERIMENTAL AND NUMERICAL RESULTS .... 126
  6.1 Introduction ............................................................................................. 126
  6.2 Numerical Analysis vs. Hybrid Drawing Experiments ......................... 126
    6.2.1 DEFORM 2D vs. Hybrid Drawing Load Prediction ......................... 126
    6.2.2 ANSYS vs. Hybrid Drawing Drawing Load Prediction ....................... 132
  6.3 ANSYS vs. Conventional Drawing Experiments .................................... 132
  6.4 Conclusion ............................................................................................... 134

CHAPTER 7 CONCLUDING REMARKS AND FUTURE WORK .................... 136

REFERENCES ............................................................................................... 138

APPENDICES ............................................................................................... 141
  APPENDIX A MULTILINEAR ISOTROPIC HARDENING CURVES ................ 142
  APPENDIX B EXPERIMENTAL DRAWING LOAD: 6061-O AL SAMPLES ....... 144
LIST OF TABLES

Table 3.1  $K$ and $n$ values determined from power law curve fitted to experimental flow stress data. .............................................................. 40
Table 3.2  Material characteristics for extrusion simulations. ........................................ 48
Table 3.3  Number of elements for various machined billet diameters. ......................... 53
Table 3.4  Maximum equivalent die stress and factor of safety for 6061-T6 aluminum and AISI 1018 extrusion simulations. ........................................ 53
Table 3.5  Equivalent plastic strain ranges for various machined samples. .................. 54
Table 3.6  Forming limit strains for $\eta = 0.5$ and $\eta = 0.65$. .................................. 56
Table 3.7  Comparison of equivalent billet stress from extrusion simulations and hybrid drawing simulations. ................................................. 57
Table 3.8  Material characteristics for extrusion simulations. ...................................... 59
Table 3.9  Simulation parameters for hybrid die stress simulations. ............................. 59
Table 3.10 Maximum equivalent stress for various materials. ........................................ 61
Table 3.11 Steady-state drawing load data for hybrid drawing simulations for various materials and frictional conditions. ................................. 64
Table 3.12 Comparison of steady-state drawing load for half pressure (Half) and full pressure (Full) window approaches ($\mu = 0.05$). ......................... 69
Table 3.13 Comparison of steady-state drawing load for half pressure (Half) and full pressure (Full) window approaches ($\mu = 0.15$). ......................... 69
Table 3.14 Steady-state drawing load data for conventional drawing simulations for various materials and frictional conditions........................................ 72
Table 3.15 Comparison of drawing load for hybrid die (no pressure) and conventional die for various friction cases.............................................. 73
Table 4.1 Stress convergence results. .............................................................................. 96
Table 5.1 Average steady-state drawing load for various experiment configurations...... 108
Table 5.2 Average steady-state drawing load (raw and effective) for various experiment configurations (sorted by increasing raw and effective drawing load, respectively). .................................................. 121
Table 6.1 Comparison of experimental and numerical steady-state drawing load for $\mu = 0.05$ ......................................................................................... 130
Table 6.2 Comparison of experimental and numerical steady-state drawing load for $\mu = 0.15$ ......................................................................................... 131
Table 6.3 Comparison of experimental and numerical steady-state drawing load for conventional drawing samples. ............................................. 134
## LIST OF FIGURES

| Figure 1.1 | Conceptual die design section view.                      | 2 |
| Figure 2.1 | Conventional drawing die.                               | 6 |
| Figure 2.2 | Schematic of a typical draw bench.                      | 7 |
| Figure 2.3 | Multi-pass wire drawing mechanism.                      | 8 |
| Figure 2.4 | Examples of tube drawing operations.                    | 9 |
| Figure 2.5 | The spherical field (left) and triangular field (right). | 11 |
| Figure 2.6 | Comparison of upper and lower bound solutions for a given die half-angle. | 12 |
| Figure 2.7 | Dependence of work terms on the die half-angle.         | 12 |
| Figure 2.8 | Comparison of ideal and actual deformation.             | 13 |
| Figure 2.9 | Optimum die half-angle for varying friction factor.     | 13 |
| Figure 2.10| Effective strain distribution along the cross-section of drawn bars where a is the die half-angle. | 14 |
| Figure 2.11| Typical lubricant strategy for various aluminum alloys versus surface expansion. | 17 |
| Figure 2.12| Friction factors of the four lubricants tested with double cup extrusion experiments. | 19 |
| Figure 2.13| Shear friction factors predicted for 6061-T6 samples using different lubricants and experimental conditions. | 20 |
| Figure 2.14| Tube hydroforming process.                             | 21 |
| Figure 2.15| Possible loading path and process window for the tube hydroforming process. | 22 |
| Figure 2.16| Typical tube hydroforming control system for high pressure fluid supply. | 24 |
| Figure 2.17| Schematic of a combined deep drawing and cold forging operation. | 25 |
| Figure 2.18| Hybrid component created by combined deep drawing and cold forging operation. | 25 |
| Figure 2.19| Schematic of a curved profile extrusion operation.      | 26 |
| Figure 2.20| Schematic of extrusion with in-line electromagnetic compression. | 26 |
| Figure 2.21| Forming results of extruded aluminum tubes with electromagnetic forming. | 27 |
| Figure 2.22| Hybrid stretch forming and incremental sheet forming process. | 27 |
| Figure 2.23| Sample component formed with a deformation machining operation. | 28 |
| Figure 2.24| Schematic of tooling used to create superficial cold forming in a turning operation. | 29 |
| Figure 2.25| Apparatus for hydrostatic extrusion operation.          | 30 |
| Figure 2.26| Analysis zones: 1) Inlet zone, 2) Work zone, and 3) Outlet zone. | 31 |
| Figure 2.27| Comparison of numerical and experimental extrusion results. | 31 |
| Figure 2.28| Schematic of hydrostatic extrusion press with back pressure zone. | 32 |
| Figure 2.29| Extrusion results for grey cast iron a) with back pressure and b) without back pressure. | 32 |
| Figure 2.30| Extrusion results for bismuth a) with back pressure and b) without back pressure. | 33 |
| Figure 2.31| Hydrodynamic wire drawing apparatus schematic.          | 33 |
| Figure 2.32| Die wear with dry soap lubrication (left) and oil lubrication (right). | 34 |
Figure 2.33 Schematic of the die-less reduction unit used to generate a hydrodynamic polymer film. .................................................. 34

Figure 3.1 AISI 1018 steel compression test samples prior to testing. ....................... 38
Figure 3.2 AISI 1018 steel compression test samples after testing. .......................... 38
Figure 3.3 Polished and etched cross section of a AISI 4340 cylindrical sample showing distorted flow lines due to barreling ........................................... 39
Figure 3.4 Experimental data from compression test samples for various materials utilized for numerical analysis ................................................. 40
Figure 3.5 Geometry approximation to determine die reduction as a function of die section parameters ................................................. 42
Figure 3.6 Variation in die section offset radius ..................................................... 44
Figure 3.7 Effect of offset radius on effective stress contour for constant die half-angle and number of die sections ................................................. 45
Figure 3.8 Variation in number of die sections ..................................................... 46
Figure 3.9 Effective strain measured from the center of the drawn sample for various configurations .................................................. 47
Figure 3.10 Simulation set-up for full extrusion samples ........................................... 49
Figure 3.11 Equivalent stress contours (psi) for die stress (l to r): AISI 1018, 6061-T6, 6061-O. ........................................................... 49
Figure 3.12 Predicted load from extrusion simulations ......................................... 50
Figure 3.13 Mesh and starting geometry for machined extrusion simulations: a) 1.2", b) 1.25", c) 1.3", d) 1.35", e) 1.4", f) 1.45". ................................. 52
Figure 3.14 Equivalent billet stress from hybrid drawing simulations for 6061-T6 aluminum versus ideal work approach ............................................. 55
Figure 3.15 Equivalent billet stress from hybrid drawing simulations for AISI 1018 steel versus ideal work approach ............................................. 55
Figure 3.16 Simulation set-up for hybrid die stress analysis ..................................... 58
Figure 3.17 Equivalent stress contour for die sections (left) and die container (right) for 6061-O aluminum (stress in psi) ............................................. 60
Figure 3.18 Equivalent stress contour for die sections (left) and die container (right) for 6061-T6 aluminum (stress in psi) ............................................. 60
Figure 3.19 Equivalent stress contour for die sections (left) and die container (right) for AISI 1018 steel (stress in psi) ............................................. 61
Figure 3.20 Simulation model for hybrid die drawing load analysis ............................ 62
Figure 3.21 6061-O hybrid die drawing load prediction for two friction cases ............ 63
Figure 3.22 6061-T6 hybrid die drawing load prediction for two friction cases .......... 63
Figure 3.23 Half pressure window utilized to simulate fluid pressure in hybrid die design. 65
Figure 3.24 Steady-state drawing load results for various supplied pressures ($\mu = 0.05$). 66
Figure 3.25 Steady-state drawing load results for various supplied pressures ($\mu = 0.15$). 66
Figure 3.26 Full pressure window utilized to simulate fluid pressure in hybrid die design. 67
Figure 3.27 Steady-state drawing load results for various supplied pressures ($\mu = 0.05$). 68
Figure 3.28 Steady-state drawing load results for various supplied pressures ($\mu = 0.15$). 68
Figure 3.29 Conventional drawing simulation model with meshed components .......... 71
Figure 3.30 6061-O conventional die drawing load prediction for two friction cases .... 71
Figure 5.12 6061-T6 aluminum sample drawing load curve at 10,000 psi fluid pressure.  . 110
Figure 5.13 6061-O aluminum sample drawn with conventional drawing die. ............... 111
Figure 5.14 Drawing load curves for samples drawn with the conventional drawing die. 112
Figure 5.15 6061-T6 aluminum sample drawn with conventional drawing die. ............... 112
Figure 5.16 Drawing load curve for 6061-T6 aluminum sample drawn with the conven-
tional drawing die. ......................................................................................... 113
Figure 5.17 6061-O aluminum steady-state surface comparison between conventional
(left) and hybrid (right) drawn samples. .......................................................... 114
Figure 5.18 6061-T6 aluminum steady-state surface comparison between conventional
(left) and hybrid (right) drawn samples. .......................................................... 114
Figure 5.19 Knoop hardness indentation profile. ...................................................... 115
Figure 5.20 Knoop hardness values for 6061-O aluminum samples drawn using a con-
ventional die and the hybrid drawing die at a supplied pressure of 10,000 psi. An annealed, undrawn sample is the control. ..................................................... 116
Figure 5.21 Knoop hardness values for 6061-T6 aluminum samples drawn using a con-
ventional die and the hybrid drawing die at a supplied pressure of 10,000 psi. An undrawn sample is the control................................................................. 117
Figure 5.22 Schematic to determine effective drawing load under hydrodynamic lubri-
cation. .............................................................................................................. 119
Figure 5.23 Experimental drawing load curves for various experiment configurations. . 120
Figure 5.24 Effective drawing load curves for various experiment configurations. ........ 120
Figure 5.25 Curved extrusion sample (top) versus straight extrusion sample (bottom). . 123
Figure 5.26 Sample sheared by container top (left) and resulting sample surface (right). 123
Figure 5.27 6061-T6 aluminum experimental drawing load curves for hybrid and con-
ventional drawing samples. .......................................................... 124
Figure 5.28 Comparison of effective drawing load curve to conventional drawing load
for 6061-T6 aluminum samples. .......................................................... 124

Figure 6.1 DEFORM 2D and experimental drawing load comparison for 5,000 psi fluid
pressure. .............................................................................................................. 127
Figure 6.2 DEFORM 2D and experimental drawing load comparison for 6,000 psi fluid
pressure. .............................................................................................................. 127
Figure 6.3 DEFORM 2D and experimental drawing load comparison for 7,000 psi fluid
pressure. .............................................................................................................. 128
Figure 6.4 DEFORM 2D and experimental drawing load comparison for 8,000 psi fluid
pressure. .............................................................................................................. 128
Figure 6.5 DEFORM 2D and experimental drawing load comparison for 9,000 psi fluid
pressure. .............................................................................................................. 129
Figure 6.6 DEFORM 2D and experimental drawing load comparison for 10,000 psi fluid
pressure. .............................................................................................................. 129
Figure 6.7 ANSYS and experimental drawing load comparison for 6061-T6 aluminum
hybrid drawing sample. ...................................................................................... 132
Figure 6.8 ANSYS and experimental drawing load comparison for conventionally
drawn 6061-O aluminum samples. .................................................................... 133
Figure 6.9  ANSYS and experimental drawing load comparison for conventionally
drawn 6061-T6 aluminum sample. .............................................. 133

Figure A.1  Multilinear isotropic hardening curve for 6061-O aluminum. ................. 142
Figure A.2  Multilinear isotropic hardening curve for 6061-T6 aluminum. ................. 143
Figure A.3  Multilinear isotropic hardening curve for AISI 1018 steel.................... 143

Figure B.1  Drawing load for 6061-O samples using conventional die. ...................... 144
Figure B.2  Drawing load for 6061-O samples using hybrid die at 5,000 psi fluid pressure.145
Figure B.3  Drawing load for 6061-O samples using hybrid die at 6,000 psi fluid pressure.145
Figure B.4  Drawing load for 6061-O samples using hybrid die at 7,000 psi fluid pressure.146
Figure B.5  Drawing load for 6061-O samples using hybrid die at 8,000 psi fluid pressure.146
Figure B.6  Drawing load for 6061-O samples using hybrid die at 9,000 psi fluid pressure.147
Figure B.7  Drawing load for 6061-O samples using hybrid die at 10,000 psi fluid pressure.147
1.1 Objectives and Approach

Due to the current limitations of the bar drawing process, this research is motivated by several major considerations. Namely, the formability of high strength materials can be realized due to the unique lubrication mechanism proposed with the hybrid die design. Also, the negative environmental impact of current lubrication strategies in the conventional drawing operation necessitates the development of an improved tribological condition that can be facilitated by the proposed hybrid operation. Furthermore, by eliminating the current lubrication approach, improved process time and reduced drawing load can be realized via the hybrid drawing operation.

Based on these motivations, the following objectives have been proposed to address the limitations of the current drawing operation:

1. Design and develop a hybrid drawing process that incorporates hydroforming aspects to achieve a hydrodynamic fluid film in the reduction region of the hybrid die.

2. Eliminate the necessity of harmful lubrication strategies and maintain superior surface quality of cold drawn samples by introducing a high pressure fluid in the reduction region of the drawing die.

3. Optimize die geometry via finite element analysis to minimize drawing load and predict uniform strain distribution in the final drawn sample.

4. Use finite element analysis to simulate the high pressure fluid interaction in the hybrid drawing operation.

5. Perform experiments to assert the achievement of a hydrodynamic fluid regime in the reduction region of the hybrid drawing die and determine the novelty of the design.
To expound on these major objectives, a conceptual schematic of the potential hybrid drawing die design is presented in Figure 1.1. To incorporate the hydroforming element, high pressure fluid is routed through a die container, which supplies fluid to the reduction region of the die such that the fluid reaches the drawn billet. Combined with this pressure, drawing force \( (F_d) \) is applied to the workpiece on the outlet of the die to reduce the sample from the original diameter, \( D_o \), to the final diameter, \( D_f \). The reduction is facilitated by a number of individual die sections that both create the reduced, conical shape for the drawing die as well as assist the hydroforming element by providing routes for the high pressure fluid to reach the workpiece in the reduction region of the die.

To rationalize this concept, initial design aspects were determined for the experimental die design. Once the foundation for the design was obtained, finite element simulations were utilized to determine die design parameters. The simulations were then expanded to approximate the fluid interaction in the reduction region of the die. Development of the experimental set-up was conducted in parallel, and, upon completion of the necessary
experimental tooling, various samples were drawn at different fluid pressures to determine the achievement of a hydrodynamic fluid regime in the reduction region of the die.

### 1.2 Thesis Organization

Chapter 1 provides general background information on the drawing process and highlights some of the applications and limitations of the process that motivate the research. Additionally, the objectives of this study are highlighted, and the procedures and tools utilized to conduct the research effort are presented.

Chapter 2 contains an expansive literature review on the drawing process, notable hydroforming aspects, lubrication considerations, novelty of hybrid metal forming processes, and hydrodynamic/hydrostatic fluid-assisted forming processes that is relevant to this research effort. The review covers commons aspects of these processes as well as typical limitations that are exploited with the current study.

Chapter 3 provides detailed information regarding the numerical simulations conducted in ANSYS Workbench 14.5 and DEFORM 2D. The Finite Element Analysis (FEA) simulations describe the strategy used to determine the ideal die profile used for experimental work. Additionally, further simulations predict expected die stresses, observe the conventional drawing operation, and approximate the effect of fluid pressure within the reduction area of the hybrid drawing die.

Chapter 4 discusses the development of the hybrid die design as well as the determination and design of necessary experimental tooling for the drawing operation. The major aspects of the die design that are developed in this section include the novelty of the design itself, the evolution of the sealing mechanism utilized for the die to maintain fluid pressure within the reduction region of the die, and the measures taken to adapt the experimental set-up to available laboratory equipment.

Chapter 5 highlights experimental results gathered from samples drawn using both the hybrid drawing die and conventional die. Drawing load data is obtained to assert effective load reduction using the hybrid drawing operation compared to a conventional drawing process. Also, surface topography of the drawn samples in both the steady-state region of the samples as well as the reduction region are discussed as a means to describe the tribological conditions produced by the high pressure fluid supply utilized in the hybrid drawing operation.

Chapter 6 provides detailed discussion of the experimental results versus the numerical results generated from FEA simulations in ANSYS and DEFORM 2D. Notable similarities and errors
are presented to determine the robustness of the FEA simulations in predicting the physical attributes of the hybrid drawing process.

Chapter 7 presents the conclusions of the research and the future work that will be conducted to further develop the process and validate the operation as a novel substitute for the conventional drawing operation.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This research effort required a broad scope of several areas in literature to achieve proper understanding of the capabilities and physical nature of the hybrid drawing operation. Specifically, the drawing process was observed in literature to determine the current process description, observe limitations of the process, and determine aspects for consideration in the development of the hybrid process. Since a hydroforming element was incorporated as the hybrid forming element, relevant aspects of the hydroforming process were researched. Additionally, hybrid metal forming processes were observed in order to determine the state-of-the-art in manufacturing process modification as well as to observe the nature in which these hybrid processes improved the current processes. Finally, observation of hydrodynamic and hydrostatic fluid-assisted forming processes were considered, as these operations most closely mimic the proposed physical attributes of the hybrid drawing operation. The culmination of this expansion of knowledge has provided sufficient understanding to design the hybrid drawing process and observe the novelty of the process as a viable manufacturing process.

2.2 Drawing Process

The drawing process is incorporated in a number of applications, and it utilizes the tensile force on a billet, wire, or other workpiece at the outlet of the die, which induces indirect compressive loading to reduce the cross-sectional area of the workpiece. Among the applications of drawn materials includes shafts for power transmission, electrical wiring, cables, welding electrodes, paper clips, and other uses [1]. Numerous materials can be cold drawn, but the area reduction with respect to the flow stress of the material chosen should be considered to avoid product defects. Drawn materials are usually in the form of rods, wires, or tubes, and the cold forming process has the ability to provide a number of advantages, including near net shape parts,
good surface finish, favorable mechanical properties, and adaptability for mass production [1]. Figure 2.1 is an example of a conventional drawing die. Some of the basic features are the steel casing, or container, of the die, which often features a modular die composed of hardened steel, carbide, or other wear resistant material [1]. With regards to the reduction half-angle of the die, there is generally a gradual entry into the die (bell) and the approach half-angle achieves the final area reduction of the workpiece that is drawn. Typical die half-angles range between 6° and 15° [2]. A bearing, or land, feature serves to remove damage on the surface of the workpiece due to die wear as well as to size the final dimension of the workpiece [1]. Finally, the back relief allows the drawn workpiece to expand slightly and is utilized to minimize abrasion of the workpiece if the process is halted or if the die is misaligned [2].

![Figure 2.1: Conventional drawing die [1].](image)

Research efforts have focused to optimize the drawing process via numerous avenues. Analytical approaches have been proposed to predict typical drawing load, optimal die half-angle, and other pertinent design parameters. Tribological conditions are also critical to the success of drawing operation; thus, a variety of lubrication strategies have been verified experimentally to extend die life and promote high surface quality of the final product. Finally, product defects can plague the operation if improper process parameters have been used, so identification of acceptable parameters has been observed.

### 2.2.1 Industrial Applications

There are a variety of products that are manufactured via the drawing process. These parts feature a constant cross-section, and, while the cross-sectional area can vary drastically, the basic classes of drawing products include drawn bars, wires, and tubes.
2.2.1.1 Bar Drawing

Rod or bars can be drawn in order to reduce the cross-sectional area of a given workpiece and provide greater strength due to work hardening of the material as a result of the cold forming process. In general, a rod must be swaged, or pointed, before the drawing process can take place [1]. This process is conducted by extruding or forging the tip of the workpiece such that it can pass through the reduction section of the die. At this point, the gripper of the draw head (or carriage) can grab the swaged end of the sample and draw the remainder of the workpiece, as described in Figure 2.2.

![Figure 2.2: Schematic of a typical draw bench [2].](image)

It is necessary to lubricate the rod in a cold drawing application, and the most common method used is through a conversion coating [1]. Typically, the rod is coated using a zinc phosphate conversion coating followed by a soap or wax outer coating layer [1].

2.2.1.2 Wire Drawing

Many of the state-of-the-art drawing improvements have been focused in the area of wire drawing due to the demand for greater productivity in manufacturing. Reduction of wire is most effectively achieved via a drawing process, whereas rod drawing can be performed through extrusion, forging, or a number of other applications due to the larger cross-section that can resist buckling more readily than a wire-sized cross-section. Wires are typically drawn as a multi-stage process. Since the initial diameter of the wire is small, there are limitations to the maximum area reduction, and, as a result, multiple passes through increasing reductions
are necessary to achieve the final diameter. Figure 2.3 is a schematic of a typical multi-pass wire drawing process. Typically, an increase in pulley diameters is utilized to generate the proper drawing speed increase for the wire as it passes through the reduction dies.

![Figure 2.3: Multi-pass wire drawing mechanism [1].](image)

Lubrication of the wire is achieved by either a wet or dry drawing process. In a wet drawing process, both the wire and the die may be completely immersed in a lubricant bath that serves to lubricate the wire as well as conduct heat away from the drawn wire and die [1]. A dry wire drawing operation involves pulling the wire through a box filled with lubricant, known as a stuffing box, prior to being drawn through the series of dies [1].

### 2.2.1.3 Tube Drawing

Seamless tubes are manufactured via a tube drawing operation, and these tubular cross-sections are typically more valuable than comparable tubes that are rolled and welded (leaving a seam along the length of the tube). Drawn tubes can either be swaged like rod or wire drawing practices, or the tube can be gripped internally with a set of varying-diameter jaws that reduce in diameter as the initial tube is drawn through the die. There are a variety of drawing methods for tubes, depending on the required precision of the outer diameter, inner diameter, and tube wall thickness. Mandrels are incorporated in many tube drawing processes, and they act to maintain the proper inner diameter of the tube, and, inherently, the wall thickness [1]. Varieties of tube drawing methods, with and without a mandrel, are described in Figure 2.4.
Referring to Figure 2.4, case (a) shows a tube drawn without the use of a mandrel, indicating that the inner diameter or final thickness of the tube is less critical than the outer diameter. Cases (b) - (d) illustrate different mandrel varieties that help establish a more precise inner diameter and tube thickness [1].

2.2.2 Analytical Approaches

Several analytical approaches have been presented in literature to predict the drawing force or stress required to motivate plastic flow through a reduction die. In general, three major independent parameters affect the drawing forces experienced for a given drawing operation: the reduction ratio of the conical, converging die, the die half-angle, and the friction experienced between the die and the workpiece. It follows that the drawing force is the dependent variable that is a function of these major parameters.

In [3], an ideal work approach was presented by Hosford, et al. that provides a simple approach to the determination of drawing force. Using a work balance, the ideal approach assumes that the external work required to promote plastic flow is equal to the energy consumed to deform the workpiece. That is, since there are typically unmeasurable uncertainties regarding frictional effects, non-homogeneous deformation, and the exact manner of strain hardening of a material in complex deformation modes, a deformation efficiency factor, $\eta$, can be defined to accommodate for these uncertainties. This efficiency term is simply a ratio of the ideal work, $w_i$, and the actual work, $w_a$ (where, in reality, $w_a > w_i$), and, in practice, this factor varies between 0.5 and 0.65 [3].

With a power-law hardening material assumed, the ideal work per unit volume, $w_i$, is given by [3]

$$w_i = \frac{K \varepsilon^{n+1}}{n+1} \quad (2.1)$$

which leads to the predicted drawing stress
where \( K \) is the strength coefficient, \( n \) is the strain hardening exponent, and \( \sigma_d \) is the drawing stress. While this approach does not accommodate directly for the effects of friction, die half-angle, and reduction, the approximation is often used to predict the maximum drawing reduction for a single pass drawing operation when utilizing the efficiency factor.

Another method proposed in [3] is based on a force balance on a slab of metal with a differential thickness. This approach, known as slab analysis, formulates a differential equation that considers plastic flow variations in a single direction. This approach extends the results of the ideal work method by incorporating possible frictional effects into the analysis; however, the approach is limited by the fact that energy due to redundant work is neglected. From [3], the drawing stress, \( \sigma_d \), is predicted by

\[
\sigma_d = \frac{\sigma_a}{\eta} \left( 1 + \frac{\mu \cot \alpha}{\mu \cot \alpha} \right) (1 - e^{-\mu \cot \alpha \varepsilon_k})
\]  

(2.3)

where \( \alpha \) is the die half-angle, \( \varepsilon_k \) is the homogeneous strain, and \( \mu \) is the friction coefficient. \( \sigma_a \) is the average flow stress of the material, given by

\[
\sigma_a = \frac{K \varepsilon_h^{n+1}}{n+1}
\]  

(2.4)

and the homogeneous strain is related to the initial and final diameter of the drawn cross-section by

\[
\varepsilon_k = 2 \ln \frac{D_o}{D_f}
\]  

(2.5)

Avitzur, et al. [4] presented a limit analysis for determining several quantities related to a typical drawing operation. Known as limit analysis, the power requirement for the operation is more accurately predicted by solving for a lower bound and an upper bound solution. The upper bound analysis is based on satisfying yield criteria and geometric self-consistency, and the outcome is an overestimate of actual stresses and forces [3]. Conversely, lower bound analysis is based on satisfaction of stress equilibrium, and the resulting stresses and forces
produced are either too low or correct for the process [3]. This limit analysis has the versatility to predict the required drawing force, optimal die design, and plastic flow patterns of the billet.

A foundational assumption of this analysis is to divide the body of the billet into several zones, divided by a velocity field (upper bound) or a stress field (lower bound) [4]. In this work, the upper bound approach was observed with both spherical and triangular velocity fields, shown in Figure 2.5. These flow fields were used to produce the flow change of the material, and the method observed the rate of energy consumption by the flow field versus the rate of external work.

![Figure 2.5: The spherical field (left) and triangular field (right) [4].](image)

The comparison of the spherical and triangular field upper bound solutions are illustrated in Figure 2.6. Additionally, the lower bound analysis (based on stress equilibrium) was plotted to determine the bounds of the actual stresses. High friction losses produce the negative slope at low die half-angles for each analysis since there is greater contact length between the workpiece and the die. Distortion becomes dominant for higher die half-angles, thus producing the positive slopes consistent with an increasing load requirement. The lower bound analysis followed the characteristics of the upper bound curves for low die half-angles, but the increase of redundant work (which is omitted from the lower bound analysis) at high die half-angles prevents the curve from producing a similar positive slope at higher die half-angles [4].
2.2.3 Optimal Die Half-Angle

The optimal die half-angle is a critical design requirement that serves to minimize the energy requirement in the drawing operation. This parameter is difficult to ascertain, though, due to the balance of work terms that are inversely related with die half-angle. Specifically, the frictional work associated with the operation decreases with an increase in die half-angle since the contact length between the die and the workpiece is reduced. The redundant work experienced in the operation, however, increases with an increase in die half-angle. The relationship is illustrated by Figure 2.7.

Figure 2.6: Comparison of upper and lower bound solutions for a given die half-angle [4].

Figure 2.7: Dependence of work terms on the die half-angle ($w_r =$ redundant work and $w_f =$ frictional work) [3].
The redundant work term is the amount of work required to shear the material which produces internal distortion. In an ideal process, where redundant work is ignored, only homogeneous deformation is considered which allows plane sections of material to remain plane during a reduction. In Figure 2.8, the difference in material flow between an ideal condition and one which considers redundant work is illustrated. The assumption that the deformation remains homogeneous under-predicts the actual drawing load experienced for the operation.

![Figure 2.8: Comparison of ideal and actual deformation [3].](image)

Luis, et al. derived an equation for the prediction of the optimal die half-angle in [5]. This relationship was built from an upper bound technique, extended from previous work by Avitzur in [6, 7], and is given by

\[
\alpha_{opt} = \sqrt{\frac{3}{2} m \ln \frac{R_o}{R_f}}
\]  

(2.6)

where \(m\), \(R_o\), and \(R_f\) are the shear friction factor, initial bar diameter, and final bar diameter, respectively. Using this relationship, optimal die half-angles were predicted versus area reduction for a variety of friction factors, shown in Figure 2.9.

![Figure 2.9: Optimum die half-angle for varying friction factor [5].](image)
In [8], friction and redundant shear were investigated in order to determine an optimal die half-angle for a bar drawing operation. From the analysis, the optimum die half-angle was assumed to exist when 1) the stress and strain distribution across the diameter of the drawn bar became uniform and 2) the drawing load reached a minimum value. The numerical results suggested that the optimal die half-angle was greatly influenced by the coefficient of friction, and this impact was greater for larger area reductions considered. Effective strain distributions across the radius of the cross-section for a variety of die half-angles are presented in Figure 2.10. From these results, the most uniform strain distribution occurred with a die half-angle of 6.17°.

These approaches for observing the optimal die half-angle have been compared to experimental results, and the finite element approach has proven to quantify the optimal die half-angle with some success. This approach follows in the determination of the optimal die half-angle for the hybrid drawing die.

2.2.4 Summary of Drawing and Areas of Future Research

While a breadth of knowledge regarding the drawing operation is already well-established, continuing research efforts have been conducted to improve the prediction of drawing forces, enhance optimal die designs, and improve the overall manufacturing process. In this research, basic principles of the drawing process, analytical approaches, and prediction of optimal die half-angle were observed in the design of a hybrid drawing process. Taking elements from...
these research efforts, an optimized, novel approach has been developed that addresses many of the common design elements with a focus to achieve proper die half-angle and reduce drawing load that could be implemented in the current drawing industry.

2.3 Tribological Considerations in Metal Forming

In cold forming operations, tribological considerations are critical due to large surface expansion, high normal pressure at the tool-workpiece interface, and elevated die temperature [9]. As a result, advanced lubrication systems are necessary to prevent premature tool life and inadequate surface finish on finished parts. As an extension of insufficient lubrication, increased drawing load can result as well. Lubrication techniques can be broken down into two main categories and three subcategories. First, it is common to treat a workpiece with a conversion coating (for better lubrication adhesion) or simply apply a lubricant without a conversion coating. Next, the basic lubricants utilized include soap lubricants, solid lubricants, or oil lubricants [9]. Several challenges and process considerations are revealed when considering these aspects of lubrication, and the following sections highlight the major aspects of lubrication in metal forming operations.

2.3.1 Typical Steel Lubrication Techniques

General carbon steel and low alloy steels are similarly lubricated, and the process outlined in [9] provides a descriptive background of the typical techniques utilized in manufacturing practices. The three major operations considered include 1) Cleaning, 2) Phosphating (Conversion Coating), and 3) Lubrication.

In terms of cleaning the raw billet, mechanical and/or chemical processes are utilized. Shot blasting of the raw surface is a typical mechanical cleaning method, and it provides better adhesion for the phosphating and soap layer [9]. Also, this process is very useful for cleaning raw materials with heavy mill scale or greasy surfaces. Next, water soluble salts are typically utilized to further degrease the raw material. Following this operation, pickling is performed on the degreased surface. This process is utilized to further remove rust and scale from the raw material, and typical pickling solutions include sulphuric or hydrochloric acid. A cold water rinse is generally followed by this step which prepares the raw material for the phosphating stage.

Phosphating is a common lubrication step that causes a chemical reaction on the surface of the raw steel material that provides improved lubricant adhesion on the surface of the raw material [9]. Using ions of zinc, phosphate, and nitrate, the iron content on the surface
dissolves via a chemical reaction, and zinc phosphate is deposited on the surface of the raw material [9]. Changing the surface characteristics of the material improve lubricant adhesion since the lower iron content of the phosphating layer is more amenable to subsequent lubricant application.

Lubrication must be used in conjunction with the zinc phosphate layer, and, as mentioned, the typical lubricant types include soap, solid, and oil lubricants. The typical soap lubricant in composed mainly of sodium stearate, which is utilized for forming operations with medium surface expansion characteristics due to a limit of interfacial temperature generation with this type of lubricant [9]. Solid lubricants (commonly molybdenum disulphide or graphite) are incorporated for forming operations with large surface expansion and temperature generation [9].

Oil lubricants are the final lubricant class utilized in steel forming operations, with high quality mineral oils with special alloying additives being the most common lubricant selection. These lubricants are typically not used in conjunction with a phosphating layer, thus this lubrication strategy is limited to low surface expansion forming operations [9].

### 2.3.2 Typical Aluminum Lubrication Techniques

Aluminum alloys have a large tendency for pick-up of workpiece material on the die surface, thus sufficient lubrication is pivotal to maintain suitable die life and prevent excess forming loads [10]. Since the processing strategies have been discussed in detail for typical steel lubrication, variations for aluminum workpiece lubrication will be highlighted. Aluminum alloys do not necessarily require the use of a conversion coating, although this is dependent on the severity of the forming operation incorporated, as shown in Figure 2.11. Specifically, 5000 and 6000 series aluminum alloys can be lubricated without a conversion coating for low to medium surface expansion operations, while a conversion coating is necessary for large reductions [10].
For aluminum operations that do not require the use of a conversion coating, the most typical lubricant is zinc stearate, but other lubricants, such as mineral oil (with graphite), mineral oil (with EP additives), grease, and lanoline, are also utilized [9]. Alternatively, lubrication of aluminum with a conversion coating is most often accomplished with three conversion coatings: zinc phosphate, calcium aluminate, and aluminum flouride [10]. Sodium stearate soap is most commonly coupled with these conversion coatings as a lubrication layer.

2.3.3 Impact of Conversion Coatings

In recent years, it has been shown that conversion coatings have both negative impacts on the environment and adverse effects on the surface of coated materials. As recently as 2007, the EU has introduced new legislation in order to protect human health regarding exposure to harmful chemicals, forcing the manufacturing industry to become more aware of environmental and health concerns linked to lubrication strategies in forming operations [11]. Similar regulations have been introduced domestically which require the development of new lubrication strategies to avoid these environmental and health concerns [11]. Two of the major harmful conversion coatings are zinc phosphate and aluminum flouride. These coatings have proven to be excellent lubrication coatings due to the superior adhesion of soap lubricants to the converted surface; however, the waste produced by these conversion coatings
is hazardous, and it is necessary to treat the waste water or dispose of the waste, which is both time consuming and expensive in a large manufacturing environment.

Specifically, the zinc phosphate conversion coating process requires samples to be soaked in various baths to clean and coating the raw materials, and these baths become polluted with heavy metals, such as lead and cadmium [12]. The heavy metals and oils that are produced are unusable; thus, the solids must be disposed as hazardous waste, which is expensive, time consuming, and harmful to the environment [12]. Additionally, the zinc phosphate coating can diffuse into the workpiece during heat treatment, which promotes corrosion and surface embrittlement on the formed product [12].

Aluminum flouride conversion coatings have become popular as a cold forging conversion coating in Japan, and it is desirable to eliminate it due to the harmful waste that is produced due to the process. This conversion coating can produce similar lubrication properties to materials coated with zinc phosphate coatings, but the aluminum flouride coating is possibly more harmful due to the flourine produced in the waste of the process [13].

In an effort to avoid the environmental impact of conversion coatings in the lubrication process, research has been conducted to introduce new lubrication strategies that promote improved die wear, surface finish, and reduced process time. In [14], zinc phosphate conversion coatings were exploited using a tribo-test versus a variety of other novel lubricants. The test performed rod drawing experiments with dies that featured different grooved patterns. The increased depth of grooves in the dies induced increased levels of local surface expansion in the sample to emulate typical surface expansion experienced for different forging operations.

Results of the experimental work showed that two lubricants that utilized calcium and sodium soaps performed similarly to samples with a zinc phosphate conversion coating and soap lubricant. The calcium and sodium soap lubricants made a notable improvement over the conversion coating lubrication process since the disposal of harmful waste and additional phosphating process time was eliminated.

Another tribo-test was presented in [12] by utilizing the large surface expansion, double cup extrusion process. The proprietary lubricants used for the experiments were MEC Homat, Daido AquaLub, and MCI Z-Coat. Experimental testing was carried out using AISI 8610 steel billets, and the three lubricants mentioned were compared to samples lubricated with a zinc phosphate conversion coating. Friction factors were then predicted for each lubrication strategy, and it was shown that the MEC Homat and Daido AquaLub samples (friction factor between 0.03 and 0.04) performed better than the zinc phosphate + soap coating (friction factor between 0.06 and 0.07), as depicted graphically by Figure 2.12 [12].
New surface processing techniques for AISI 1522 steel were observed in [15] to alleviate the necessity of the zinc phosphate conversion coating. Specifically, a boron salt-based process (TS 620) and a silicate-based process (TS 956) were compared to the zinc phosphate conversion coating. Using a new drawing-seizure experimental technique, drawing samples were coated with the mentioned coating processes and lubricated with sodium stearate soap before being drawn through a tungsten carbide drawing die. After the drawing operation, the samples were tested under a seizure test to predict the number of revolutions of the sample in contact with a tungsten carbide slider required to generate microscopic seizure. While the TS 620 process was much less effective than the zinc phosphate conversion coating process, the silicate-based TS 956 coating process proved to be as effective or more effective than the zinc phosphate conversion coating for the experiments observed [15]. These results were critical due to the fact that the new TS 956 coating process adheres to environmental constraints much better than the zinc phosphate conversion coating process [15].

A novel friction test proposed in [13] utilized a combined forward spline-backward can extrusion operation to simulate large surface expansion experienced in forming operations. This test was utilized to determine the novelty of a new double-layer-type, environmentally friendly solid lubricant (Figure 2.13) that could be a suitable substitute for aluminum flouride conversion coatings that are typically applied to aluminum alloys. This lubricant features an undercoat composed of inorganic salts (acting as binder resins) and high molecular polymer (solid lubricant) as well as a metallic soap overcoat [13].

Various spline projections were utilized for the friction testing of 6061-T6 aluminum billets, and the predicted shear friction factor of samples lubricated with the novel double-layer-type lubricant versus the aluminum flouride coating are presented in Figure 2.13. From these results, it is clear that there is comparable and/or better lubrication present with the new double-layer-type, environmentally friendly lubricant, particularly for long sliding conditions.
Figure 2.13: Shear friction factors predicted for 6061-T6 samples using different lubricants and experimental conditions (left). Double-layer-type lubricant film (right) [13].

2.3.4 Summary of Tribological Considerations and Areas of Future Research

Exhaustive research has been conducted to improve lubrication strategies in the metal forming industry. Without proper lubrication, negative impacts such as die wear, poor surface finish, increased energy consumption, and poor process time can result. Additionally, the environmental and health impact that exists with the use of harmful conversion coatings has become a major concern. While these conversion coatings are excellent in terms of lubricant adhesion, the effectiveness of the coatings is outweighed by the negative environmental impacts of the process; thus, it has become imperative to produce novel lubrication strategies that can both outperform conversion coating processes as well as have a minimal environmental impact. With this research effort, the lubrication concern is addressed via a novel process of supplying lubricant via high pressure fluid, as opposed to developing a new lubricant or coating process.

2.4 Tube Hydroforming

Tube hydroforming has become a major metal forming process that is mainly utilized in the automotive and aerospace industry. Improvements in modern machine design related to control of axial punch feeding and internal fluid pressure have warranted the process as a major contributor in mass manufacturing [16]. Products produced with this process have the benefit of weight reduction and increased strength versus previously manufacturing strategies due to the work hardened tubular structures that can be produced in a single operation [16]. Basic elements of the hydroforming process are presented in the following sections, and the relevance to the current research is highlighted.
2.4.1 Basic Principles

The tube hydroforming process modifies the shape of tubular structures to a desired shape by restricting the component in a shaped die and supplying both internal fluid pressure and axial feed on the tubular part. To restrict the typical two-piece die from opening while the tube is subjected to internal fluid pressure, a hydraulic press is utilized to clamp the two die halves together. Hydraulic cylinders provide compressive axial force on each end of the tube to maintain sealing during the operation, and the stroke of the cylinders are computer-controlled to adjust the sealing punch position as the tube translates during the forming operation. Finally, internal pressure is supplied through one of these axial feed hydraulic cylinders, and this pressure motivates the tube into the shape defined by the die cavity. These basic components comprise the typical tube hydroforming operation, and the basic evolution of the process is described by Figure 2.14.

![Figure 2.14: Tube hydroforming process [16].](image)

While the fundamental process requires well-known and available components, optimization of specific process parameters is critical for the successful forming of complex samples. The combination of axial compressive feed and internal pressure exerted on the tubular parts must be optimized (via finite element analysis, analytical approaches, or experimental testing) to avoid process failure and maintain part quality.

2.4.2 Industrial Applications

Since lightweighting has become a major design requirement in the automotive and aerospace industries, the tube hydroforming process has established a substantial footprint in these industries. Specifically, automotive components, such as exhaust products, camshafts, radiator frames, axles, crankshafts, engine cradles, frames, and other components have been manufactured via the tube hydroforming process [16].

Compared to conventional stamping and welding operations that were used prior to the development of tube hydroforming, there are a number of distinct advantages. First, weight reduction can be achieved due to efficient cross-section design and optimization of wall
thicknesses [16]. Additionally, strength and stiffness is improved due to the work hardening characteristics that are achieved with the process. Tooling cost and secondary operations (such as welding) are also eliminated since multiple features can be achieved using a single die set that were previously manufactured in stages [16].

2.4.3 Loading Path Determination

Optimization of the loading path in tube hydroforming is critical to create close tolerance, defect free, tubular components. That is, the loading path is effectively the coordination of the supplied internal fluid pressure and the compressive axial feed from the hydraulic cylinder [17]. Failure to optimize the velocity of the compressive feed punches relative to the internal pressure supplied can result in tube failure, specifically tube buckling, wrinkling, and bursting (see Figure 2.15) [18].

![Figure 2.15: Possible loading path and process window for the tube hydroforming process (left). Failed components with improper loading path (right) [17].](image)

Several approaches have been established to intuitively predict the onset of these failure modes. Finite element analysis can be utilized to predict reasonable axial feed and internal pressure levels at each interval of the forming operation with an iterative process, but this approach can still be time consuming due to the numerous simulations that are required to determine a reasonable loading path for experiments.

Yong, et al. [19] utilized a heuristic optimization approach coupled with finite element simulation data to determine the optimal loading path for a spherical bulge tubular structure. The iterative finite element approach incorporated 200 simulations that were utilized to train and test an artificial neural network (ANN). With the ANN defined, a genetic algorithm (GA) was
utilized to predict the minimum result of the objective function defined to minimize thinning in the tube, a major process parameter which could ultimately lead to tube bursting [19]. This formulation was a function of six design variables, internal pressure and respective punch feed rate at three stages in the forming operation. The GA was also subjected to a volume constraint to restrict tube bulging. Using the optimized internal pressures and axial punch displacements generated from the GA to determine the loading path, experimental testing was conducted. Average thinning rates of 9.3% were measured from the experimental samples, well within the predicted critical thinning rate of 25% [19]. This hybrid loading path determination proved useful and more robust than brute force finite element optimization strategies, and the results indicated that this approach could be extended to a variety of formed tube geometries.

In [17], the loading path of several tube hydroforming components was predicted using only certain parameters of a given tube. An analytical model was determined to predict the required internal pressure curve, and the complimenting axial feed curve was obtained through finite element analysis using an iterative process. A cubic spline interpolation was then used to fit the resulting data to the predicted results, and these curves were categorized in a database in an effort to reduce computation time for loading path prediction.

2.4.4 Tube Hydroforming Equipment

The major components necessary for a successful tube hydroforming experiment include a hydraulic press (to resist die opening), a die set (to define the final part shape), a hydraulic system (to provide compressive axial feed on the tube), and a high pressure fluid system (to supply internal pressure). While each of these components and systems are critical, the supply of high pressure fluid is most important to this research effort.

The hydraulic press serves a major, simple purpose: to resist the internal pressure supplied to the tube and prevent separation of the die halves. Also, the separate hydraulic system utilized to drive the sealing punches are dynamically controlled according to the specified loading path for the desired geometry.

The high pressure system utilized to supply internal fluid pressure to the tube is generally designed using a stand-alone hydraulic pump that is not related to the hydraulic systems used for punch actuation and die retainment. A pressure intensifier is incorporated to generate fluid pressures up to 60,000 psi to satisfy many combinations of part designs and tube materials for forming [20]. Also, it is necessary to design control valves that can both accurately deliver fluid and withstand the high pressures necessary for the operation. A typical schematic for the high pressure control system is described by Figure 2.16.
The control system utilized to achieve the proper pressure loading path must be properly designed to provide proper feedback to the controller for a tube hydroforming experiment. Closed loop control systems incorporate servo valves, sensors, and a controller that provide dynamic pressure adjustments based on sensor data.

2.4.5 Summary of Hydroforming and Areas of Future Research

The basic principles of the hydroforming operation were presented to highlight the use of control systems to provoke plastic deformation in tubular structures. Using contemporary controls and hydraulic system design, it is possible to define a dynamic pressure loading path that can be varied real-time to adapt for process requirements. In the hybrid drawing process, this approach could ultimately be utilized to minimize drawing load and improve the process.

2.5 Hybrid Metal Forming Processes

Since there is an increasing demand for low cost, low process time components in the manufacturing industry, current metal forming operations have been substituted for a variety of hybrid forming processes. Hybrid metal forming processes have been implemented in order to concurrently optimize the positive features of certain processes to improve material surface finish, enhance mechanical properties of parts, create unique part geometries, reduce manufacturing cost, and improve part precision. Typical forming processes have been coupled with subtractive machining operations as well as other forming operations to achieve these improvements.
2.5.1 Hybrid Forming/Forming Operations

An innovative hybrid process was presented by Jager, et al. [21] which combined deep drawing and cold forging (extrusion) operations. This process combined a bulk and sheet metal forming operation which generated unique, bimetallic materials. The basic principle of the design is presented in Figure 2.17, where two workpieces are loaded in a hybrid deep drawing, extrusion die. The bulk workpiece originally works as a punch to deep draw the sheet metal workpiece. Once this operation is completed, the two workpieces are coupled and forced through an extrusion die.

![Schematic of a combined deep drawing and cold forging operation](image)

**Figure 2.17:** Schematic of a combined deep drawing and cold forging operation [21].

The bimetallic components generated with this process highlight the superior strength to weight ratio of the bulk aluminum component as well as the durable, wear resistant steel surface of the cladded steel sheet metal component. An example of a component produced with this hybrid operation is presented in Figure 2.18.

![Component components](image)

**Figure 2.18:** Hybrid component created by combined deep drawing and cold forging operation [21].
A curved profile extrusion operation was proposed by Kleiner, et al. [22] in an effort to improve profile properties of extruded rods and tubes by combining the extrusion and bending operations. In general, it is difficult to maintain proper profile for curved profile rods and tubes due to cross section deformation and springback after the bending process [22]. The general operation is illustrated in Figure 2.19. By combining the extrusion and bending operation, the dual process operation of extrusion and subsequent warm bending is eliminated. Comparing the forces generated between the conventional, multi-step process and the hybrid operation, there was significant load reduction in the hybrid operation since the extruded profile is deflected real-time rather than in a separate operation.

Figure 2.19: Schematic of a curved profile extrusion operation [22].

Another hybrid operation, proposed by Jager, et al. [23], incorporates both a hot extrusion and electromagnetic forming process to produce extruded aluminum tubes with local, compressed features along the length of the extruded tube. The typical hot extrusion die was coupled with a downstream tool coil for electromagnetic compression that was utilized to perform more precise final sizing of the tube as well as produce additional features. The process schematic is provided in Figure 2.20.

Figure 2.20: Schematic of extrusion with in-line electromagnetic compression [23].
A tubular aluminum sample produced via the hybrid process is described in Figure 2.21. Clearly, the process provides novel impact in manufacturing due to the ability to locally deform the tube into a variety of additional cross sections.

![Figure 2.21: Forming results of extruded aluminum tubes with electromagnetic forming [23].](image)

In sheet forming operations, some of the major process limitations are local material thinning, geometric component accuracy, and excessive process duration. In [24], these limitations were alleviated by proposing a hybrid sheet metal forming operation that combined asymmetric incremental sheet forming (AISF) and stretch forming (SF). In AISF alone, a CNC-controlled forming tool is utilized to incrementally deform features on a sheet metal component defined by a forming die. The process time for this operation is typically too large for novelty in a manufacturing atmosphere, and there are prevailing geometric tolerance issues with the process. By combining AISF with a stretch forming operation (see schematic in Figure 2.22), the process time is markedly reduced [24]. Additionally, the incorporation of stretch forming provided a more uniform thickness distribution in the deformed sheet metal part as compared to a pure AISF operation.

![Figure 2.22: Hybrid stretch forming and incremental sheet forming process [24].](image)
2.5.2 Hybrid Machining/Forming Operations

In [25], a milling operation was coupled with a single point incremental forming (SPIF) process in an effort to manufacture previously infeasible structures. The novelty of this approach incorporates the ability to manufacture monolithic thin structures that were previously manufactured with assembled sheet metal parts. The thin part machining operation provides thin features from bulk material, and the SPIF operation is utilized by bending or stretching the thin feature to create complex geometry out of a single component, as described by Figure 2.23.

![Figure 2.23: Sample component formed with a deformation machining operation [25].]

With this hybrid process, unique components are produced which are lighter and less expensive than the parts that they replace. In addition, some of the geometries produced are not feasible by other manufacturing methods.

Another hybrid approach which utilizes machining operations is a hybrid turning tool that incorporates superficial cold forming. Turning assisted with superficial cold forming (TASCF) was presented in [26] with a focus on simultaneous machining and surface quality/mechanical property enhancement of the finished product. The basic tooling, which describes the relationship of the cutting tool to the superficial cold forming (SCF) ball is shown in Figure 2.24.
The SCF ball can be dynamically incorporated in the machining operation, as it is controlled via hydraulic pressure; therefore, traditional machining can be performed on preliminary machining passes, and the SCF operation can be reserved for the final operation. The tooling provides a means to create a more uniform, higher quality surface on machined parts with the incorporation of the SCF hybrid component.

2.5.3 Summary of Hybrid Processes and Areas of Future Research

The hybrid processes presented above highlight the creativity and novelty of manufacturing processes in an attempt to meet the increasing industrial demands for higher quality components, more complex features, reduced process time and energy consumption, and improved mechanical properties. These approaches provided motivation for the current research, as the bulk forming drawing operation has remained constant in industry for the past several decades. Successfully incorporating a hybrid process element into the current drawing operation has the ability to reduce process time and improve other aspects of the current process while simply reconditioning the standard approach to the current metal forming standard.
2.6 Hydrodynamic/Hydrostatic Fluid-Assisted Forming Processes

Several approaches have incorporated the use of a fluid medium in drawing and extrusion operations to assist the forming operation. In the hydrostatic extrusion process, high-pressure fluid is incorporated as the pressure-transmitting medium on the billet, rather than direct contact with an extrusion punch [27]. An additional benefit is that this fluid alters the stress state of the billet by exerting fluid pressure on the entire billet surface on the inlet side of the extrusion die. Also, the fluid serves as a lubricant in the reduction region of the extrusion die. In contrast, hydrodynamic lubrication is achieved in the wire drawing operation by supplying a fluid lubricant at high pressure from the inlet of the drawing die. If suitable wire/fluid speed, fluid viscosity, and fluid pressure parameters are achieved, it is possible to generate a hydrodynamic fluid film between the wire and the drawing die, eliminating metal-to-metal contact. Applications and analytical approaches of these processes have been observed.

2.6.1 Experimental Applications

2.6.1.1 Hydrostatic/Hydrodynamic Extrusion

A hydrostatic extrusion apparatus, designed to withstand a working pressure of over 140,000 psi, was developed in an effort to modify the existing extrusion operation. Using double-layer, pyramidal cylinders to house and strengthen the working region of the system, high pressure fluid was supplied to the billet and restrained by high pressure seals at both the die and at the high pressure plunger, as shown in Figure 2.25. When the plunger is driven via a hydraulic press, hydrostatic fluid pressure builds on the billet, which both acts to extrude the sample as well as provide pressure on the cylindrical portion of the billet. While comparison was not made to a comparable extrusion operation, successful extrusion of both solid aluminum rods and powder-solid composite clad rods verified the capability of the experimental process.

![Figure 2.25: Apparatus for hydrostatic extrusion operation [27].](image)
A finite element model was proposed to model a novel hydrodynamic extrusion operation in [28]. The raw billet was machined with a stepped feature to allow lubricant to flow into a boundary between the billet and the die, and, as the billet was extruded, a hydrodynamic fluid film layer was maintained. The unsteady and steady lubrication mechanisms are depicted in Figure 2.26, and the three zones considered for the analysis are described.

![Analysis zones: 1) Inlet zone, 2) Work zone, and 3) Outlet zone for unsteady lubrication (left) and steady, hydrodynamic lubrication (right) [28].](image)

Using an analytical friction model to describe the hydrodynamic lubrication mechanism, finite element simulations were conducted and compared to extrusion experiments. The comparison provided good correlation in steady-state extrusion (see Figure 2.27); however, the unsteady lubrication portion had some variation due to surface roughness of the extrusion die that was not captured in the finite element simulations [28].

![Comparison of numerical and experimental extrusion results [28].](image)
Another novel hydrostatic extrusion operation was verified experimentally by Skiba, et al. [29] which utilized a back pressure (BP) chamber to resist the formation of cracks generated in the plastic zone of the die or during stress relaxation on the outlet side of the die. The extrusion system (shown in Figure 2.28) mimics the traditional hydrostatic extrusion operation with pressurized fluid generated by a plunger, but the addition of the BP zone provides capability to cold extrude difficult forming materials, such as magnesium alloys, cast irons, or bismuth, without any final material defects.

Figure 2.28: Schematic of hydrostatic extrusion press with back pressure zone [29].

Experimental results provided percent deformation of 36% in grey cast iron and above 80% in bismuth, which were unachievable without the addition of back pressure to resist cracking in the final extruded parts. These samples, with and without back pressure, are shown in Figure 2.29 and Figure 2.30.

Figure 2.29: Extrusion results for grey cast iron a) with back pressure and b) without back pressure [29].
Figure 2.30: Extrusion results for bismuth a) with back pressure and b) without back pressure [29].

Clearly, the back pressure system enhanced the capability of the process, as these materials were unformable without the use of the BP system.

2.6.1.2 Hydrodynamic Drawing

One of the first experimental attempts to achieve a hydrodynamic wire drawing process was presented by Christopherson and Naylor [30]. In this research, a wire drawing apparatus was designed (see Figure 2.31) such that a sufficiently long tube containing high pressure fluid was mounted on the inlet side of the drawing die.

![Hydrodynamic wire drawing apparatus schematic](image)

Figure 2.31: Hydrodynamic wire drawing apparatus schematic [30].

The fluid pressure had negative impacts on the observed drawing loads for low drawing reduction since the fluid pressure created some drag in the inlet tube that was noticeable in the
resulting drawing load. However, for larger reductions, there was some slight improvement in
drawing load of samples drawn with the high pressure oil lubricant versus the soap lubricant.
There was also less die wear measured after drawing 2,500 feet of wire for the high pressure
oil lubricant case, shown in Figure 2.32.

![Figure 2.32: Die wear with dry soap lubrication (left) and oil lubrication (right) naylor55.](image)

More recently, polymer melts have been utilized as a hydrodynamic lubricant in wire drawing
[31]. In these designs, wire is pulled through a polymer melt chamber prior to the reduction
die to both coat the wire as well as motivate the polymer towards the reduction area of the die.
In [31], a copper wire was coated with a low density polyethylene melt using the schematic
shown in Figure 2.33. The system is considered a die-less operation since the tapered bore that
the wire exits has a larger diameter than the wire itself.

![Figure 2.33: Schematic of the die-less reduction unit used to generate a hydrodynamic polymer film [31].](image)

The process relies on the polymer melt to generate pressure between the wire and the tapered
bore such that plastic deformation is realized in the wire. Area reductions of 21% were
obtainable in a single pass without any die wear due to the polymer melt hydrodynamic film
generated between the wire and tapered bore [31].
2.6.2 Relevance to Hybrid Drawing Design

The demonstration of successful hydrodynamic lubrication in wire drawing and the positive effects from hydrostatic extrusion operations motivate the current research to achieve a hydrodynamic fluid film in bar drawing. Since the hybrid drawing process seeks to improve formability by locally altering the state of stress in the workpiece in addition to achieving the hydrodynamic fluid film lubrication, these processes provide insight on the capabilities and proven efforts that have observed similar approaches in the extrusion and wire drawing operations.

2.7 Conclusion

The hybrid drawing process has design and process elements that link the operation to the variety of different metal forming topics. Valuable understanding was gained regarding the capability of similar processes, common limitations in the operation, and typical lubrication practices. Specifically, lubrication approaches that have been suggested to alleviate the use of conversion coating processes have provided insight on the opportunity to remove the harmful lubrication technique from the forming industry; in this study, the lubrication method itself has been altered, rather than the lubricant type, to alleviate the need for the conversion coating processes. Furthermore, observation of the basic elements of the hydroforming operation provided insight on the approach of loading paths and the required equipment to achieve adequate fluid pressure paths that can be extended to the hybrid forming operation in this work. Also, hydrodynamic drawing and extrusion as well as hydrostatic extrusion operations were presented. While the design of these processes varies from the hybrid drawing operation, the principle of achieving a hydrodynamic fluid film in the reduction region of a conical die was verified by these operations and is extended in the current work to the hybrid drawing process. Lastly, the hybrid operations discussed exemplified the creativity of hybridization in metal forming, and the success of these novel operations was discussed to validate the current approach to combine the drawing and hydroforming operations. Overall, the literature presented has provided motivation for the research of a viable, hybrid drawing and hydroforming operation that can impact manufacturing. Using the knowledge gained from the research areas considered, careful design and evaluation of the novel operation can be conducted, and the possibility of a new, feasible drawing operation can be realized.
3.1 Introduction

Finite element analysis (FEA) provides a solution approach to complex multi-physics problems that are difficult to evaluate analytically. Discrete elements are meshed together to solve elementwise stresses and strains that produce a numerical approximation of the response of a fully-modeled geometry subject to various loading and boundary conditions. FEA packages are a useful engineering tool since multiple design iterations can be manipulated and analyzed through simulations rather than producing expensive physical prototypes to test different design elements. However, while FEA packages are powerful tools, careful assumptions and strategies must be employed to ensure that the real-world system is modeled as accurately as possible.

Extensive numerical analysis was conducted during this research to determine design parameters, predict die failure, observe billet strains, and assert the novelty of the hybrid drawing process via drawing load comparisons. First, the final hybrid die design was determined using the DEFORM 2D FEA package. Various geometry configurations were considered, and the most suitable die geometry was obtained from these simulation results. Next, ANSYS Workbench 14.5 was utilized to predict die stresses for the extrusion and drawing operations for various materials to ensure sufficient die strength for experimentation. Also, predicted drawing load was observed for both conventional drawing and hybrid drawing operations utilizing both ANSYS and DEFORM 2D.

In order to effectively and accurately utilize FEA, many considerations and approaches were considered. Material characterization was performed experimentally to accurately model material properties for the various extrusion and drawing simulations. Also, finite element techniques were employed to reduce computation time and improve solution accuracy. The following sections describe the evolution of the numerical simulation processes and present
the results that were generated from those simulations.

3.2 Billet Material Characterization and Selection

ANSYS features an extensive material catalog that accurately characterizes metallic materials, particularly in the elastic range; however, in order to obtain accurate deformation and associated stresses in a metal forming operation, it is necessary to define the plastic range of a given material, which can be characterized by the flow stress of the material. While there are some options available for nonlinear material properties within the ANSYS material library, these curves do not provide sufficient resolution over a variety of strain levels for bulk metal forming; thus, experimental testing was conducted to establish accurate characterization of the materials used for the hybrid drawing experiments.

For the following simulation results, several materials were analyzed in order to characterize the effectiveness of the hybrid drawing die design. Specifically, 6061-O aluminum, 6061-T6 aluminum, and AISI 1018 steel were modeled, as these materials were selected as candidates for experimental work. The materials were characterized by predicting the flow stress curve of the respective materials. The flow stress of a material is defined as the stress required to maintain plastic deformation for a specific strain, and the relationship [3] is given by

$$\bar{\sigma} = K\bar{\varepsilon}^n$$  \hspace{1cm} (3.1)

where $K$ is the strength coefficient and $n$ is the strain hardening exponent for a material. The strength coefficient provides the stress required to provide a strain of 1.0 for a material and the strain hardening exponent indicates the potential formability of a material, where a higher index value corresponds to a more formable material.

Compression Test to Determine Flow Stress. Experimentally, the plastic range of a metallic material can be obtained via compression testing, and the data collected can be utilized to generate a flow stress curve for the material. In the Advanced Metal Forming and Tribology Laboratory (AMTL), compression testing was conducted for 6061-O aluminum, 6061-T6 aluminum, and AISI 1018 steel to establish accurate flow stress curves for numerical analysis.

To conduct the compression testing, cylindrical samples from raw material stock were machined to a precise diameter and length, as shown in Figure 3.1. The initial length and diameter of each sample was recorded, as these values were used for further calculations.
Each sample was compressed with varying axial load via the 150 ton Press Master hydraulic press in the AMTL to obtain multiple data points that could be utilized to curve fit a flow stress relationship.

Multiple samples were plastically deformed in an effort to capture lower plastic strain values in order to accurately predict the initial curvature of the flow curve. Once this region was obtained, samples at higher strains (up to approximately 50% height reduction) were obtained to predict the higher strain region of the curve. During the process, compressive load was monitored as the sample was loaded uniformly to a predetermined value. Once this value was reached, the sample was unloaded, and the measured height was utilized to predict the plastic strain achieved during loading. Samples from a completed compression test for AISI 1018 steel are shown in Figure 3.2.

In order to predict the flow stress accurately for a given plastic strain, it was imperative to maintain proper lubrication between the sample and the compression dies fitted on the hydraulic press. This was achieved by layering solid, plastic lubricant sheets between high viscosity oil. Without this lubricating layer, the pressures between the sample and compression
dies would promote lubricant starvation, and the compression test sample would begin to "barrel". Barreling is a condition that exists when the ends of the compression sample are restricted due to excessive friction generated by lubrication failure. This lubrication break-down causes non-uniform transverse deformation, as depicted in Figure 3.3. While this condition was not eliminated completely during experimentation, barreling was minimal at higher strains.

![Figure 3.3: Polished and etched cross section of a AISI 4340 cylindrical sample showing distorted flow lines due to barreling [32].](image)

After the experimental maximum load and final sample height were recorded for the cylindrical samples, true stress and strain values were calculated. The stress was calculated by

\[
\bar{\sigma} = \frac{F}{A}
\]  

(3.2)

where \( F \) was the maximum applied load during the compression test, and \( A \) was the final area of the deformed sample. To obtain the final diameter of the sample, a constant volume assumption was utilized between the initial sample size and the final size such that the final diameter, \( D_f \), was given by

\[
D_f = \sqrt{\frac{h_o D_o^2}{h_f}}
\]  

(3.3)

Next, the true strain was determined by

\[
\bar{\varepsilon} = \ln \frac{h_o}{h_f}
\]  

(3.4)
where \( h_0 \) was the original sample height and \( h_f \) was the final compressed height. The respective true stress and strain values were presented graphically, and a power law regression line was fitted to the data to obtain the strength coefficient, \( K \), and strain hardening exponent, \( n \). Sample data for 6061-O aluminum, 6061-T6 aluminum, and AISI 1018 steel is plotted in Figure 3.4, and the corresponding \( K \) and \( n \) values are tabulated in Table 3.1.

Table 3.1: \( K \) and \( n \) values determined from power law curve fitted to experimental flow stress data.

<table>
<thead>
<tr>
<th>Material</th>
<th>( K ) (psi)</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>27,286</td>
<td>0.218</td>
</tr>
<tr>
<td>6061-T6</td>
<td>50,523</td>
<td>0.057</td>
</tr>
<tr>
<td>AISI 1018</td>
<td>102,464</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Figure 3.4: Experimental data from compression test samples for various materials utilized for numerical analysis.
This data was used for the multilinear isotropic hardening curves incorporated in the ANSYS explicit dynamics simulations, and the curves are presented in Appendix A.

### 3.3 Hybrid Die Design Determination

After the major design considerations were established for the hybrid die design, it was possible to determine various die parameters to achieve the most suitable die design. Specifically, the die section offset radius, die section half-angle, and number of die sections were obtained through the iterative simulation process. Reducing the design problem to three geometric parameters required the definition of both the original billet diameter and area reduction of the die. In practice, reductions of up to 45% are experienced for bar drawing operations [1]. In order to replicate a strenuous drawing operation that could be adapted in an industrial setting, an area reduction of 40% was selected. Additionally, the billet diameter was defined to be 1.5". The percent area reduction (Re%) was calculated by

\[
Re\% = \frac{A_o - A_f}{A_o}
\]  

(3.5)

where \(A_o\) is the original billet diameter and \(A_f\) is the final drawn billet diameter. Solving for \(A_f\), the final billet diameter used for the operation was 1.162".

In order to standardize and expedite the process to determine the most suitable die design, a SolidWorks model was driven by a design table to generate the various die configurations. Knowing the billet diameter and area reduction, it was possible to establish a geometric relationship for the stepped die configurations as a function of number of die sections, die section offset radius, die section half-angle, and die section height. The generic relationship between the area reduction and the size/shape of the die sections was facilitated by the use of right triangles, as shown in Figure 3.5.
Figure 3.5: Geometry approximation to determine die reduction as a function of die section parameters.

The triangles are defined by the height and half-angle of the respective die section, and the sum of the short leg of the triangles is utilized to calculate the reduction, \( R \), as a function of the die section parameters; however, the offset of the die sections causes the short sides of the triangles to overlap, so this component must be subtracted. For two lines tangent to a circle, the point where these lines intersect can be used to bisect the angle between the two tangent lines (see Figure 3.5). Using this principle, a right triangle having a side equal to the die section offset radius was obtained. Since the angle is related to the die section half-angle by

\[
\gamma = \frac{90 - \alpha}{2} \tag{3.6}
\]

an angle is known, allowing the small offset distance, \( \delta \), to be determined. Thus, the final relationship used to calculate the reduction can be given by

\[
R = \sum_{i=1}^{n} h_i \tan \alpha_i - \sum_{i=1}^{n-1} \delta_i \tag{3.7}
\]
where \( n \) is the number of die sections and \( \alpha \) is the die section half-angle. The offset distance is found by

\[
\delta_i = \frac{r}{\tan \gamma_i}
\]

where \( r \) is the die section offset radius. Using these relationships, a variety of die section configurations were generated, and simulations in DEFORM 2D were evaluated to determine the ideal configuration.

### 3.3.1 Assumptions and Methodology

The billet and die geometry is symmetric about a rotational axis centered on the billet. Since the loads applied to the billet are also symmetric about this axis, the model can be treated in 2D as a axisymmetric model. With this assumption, a plane section of the geometry completely defines the state of strain, and, thus, the stress, for the entire 3D geometry. This assumption reduces computation time, and a more refined mesh can be utilized to accurately model the system without the additional computational expense that would be encountered in a three-dimensional model. Additionally, the die geometry was modeled as a rigid body such that the billet was the only flexible, meshed body in the solution. Since the die stresses and strains were not considered in the determination of the design, modeling complexity was reduced with the rigid die assignment.

The boundary conditions for the simulation were minimal, as the only interactions and loads associated involved drawing the billet through the rigid die. A displacement boundary condition was assigned to the bottom edge of the billet in the drawing direction, and frictional contact between the die and billet was prescribed. A shear friction factor was utilized for this contact interaction, with a value of \( m = 0.08 \) assumed as a conservative estimate based on results presented in [12]. Lastly, the rigid die was fixed, and the axisymmetric condition assumes no displacement across the symmetry axis of the model.

The simulation results were analyzed based on the approach utilized by Majzoobi, et al. in [8]. The approach in this work determined that the optimal die half-angle existed where the effective stress and strain distribution across the diameter of the drawn sample was most uniform. Using this technique, the following simulations describe the manipulation of various design parameters in an effort to achieve the most uniform stress and strain distributions.
3.3.2 Design Variables

The general simulation parameters included an initial billet diameter \((D_o)\) of 1.500", a final billet diameter \((D_f)\) of 1.162", a percent area reduction \((Re\%)\) of 40%, and a shear friction factor \((m)\) of 0.08. The billet material section was 6061-T6 aluminum, and 2,000 elements were utilized to mesh the billet. Since DEFORM 2D utilizes an implicit solver, it was not necessary to excessively refine the billet mesh, as the direct solver provides automatic remeshing for large deformation simulations. Elements that had an unstable aspect ratio or exhibited a negative Jacobian error prompted the solver to remesh the billet geometry. The solution information from the old mesh was then interpolated onto the new mesh, and the simulation continued until the prescribed time step was reached.

3.3.2.1 Offset Radius

First, the offset radii of the die sections were observed. This radius is the rounded edge of the die section that protrudes into the reduction area of the die, and this dimension determines the size of the fluid wedge that is generated between the die and billet. The different radii configurations are depicted in Figure 3.6.

![Figure 3.6: Variation in die section offset radius.](image-url)
The offset radius was considered for a variety of die sections and die half-angles, but the results were consistent with each variation. Using a final die half-angle of 11° and a four die section configuration, the effective stress contour plots were produced in Figure 3.7.

![Figure 3.7: Effect of offset radius on effective stress contour for constant die half-angle and number of die sections.](image)

Based on the contour plots, the smallest offset radius, 0.015625", provided a very uniform stress distribution compared to the larger offset radii. As a result, this offset radius was utilized for the remainder of the design variations.

### 3.3.2.2 Number of Die Sections and Die Section Half-Angle

The number of die sections were varied as shown in Figure 3.8, where the conventional die configuration was utilized as a comparison. A two section configuration was not considered since it was desired to have multiple fluid inlet locations in the reduction area of the die; thus, since the top die section is required for sealing the internal region of the die, this configuration only produced a single fluid inlet location. Also, five die sections were the maximum number of sections considered in order to set an upper limit on the amount of components and die complexity in the design.
In practice, drawing die half-angles vary between $6^\circ$ and $15^\circ$ [1]. These angles were utilized as the lower and upper limit for the die section half-angle determination. Also, to decrease variability, the die section half-angle was increased in $1^\circ$ increments for die section combinations. With the bounds of the die section parameters determined, combinations of die section half-angle were observed for each number of die sections considered. The optimal die configurations for each number of die sections were then compared to determine the ideal number of die sections via an effective strain comparison.

The effective strain in the radial direction suggested that the optimal four and five die section configurations were most ideal. Data extrapolated from these simulations plotted the strain distribution in the radial direction (from the center of the billet to the die wall) at a location near the outlet of the drawing die, shown in Figure 3.9.
3.3.3 Conclusion

The effective strain distributions indicated a gradual increase in strain on the outer surface of the drawn billet; however, the four and five die section configurations were the most uniform. Based on these results, either of these design alternatives were determined to be ideal amongst the configurations considered. Noteworthy, drawing load comparisons were also generated from the simulation results, but the variation was very small for each of the ideal configurations. Ultimately, it was desired to reduce the amount of components in the drawing die assembly; thus, the four section configuration with a final die section half-angle of 11° was selected for experimental evaluation and further simulations.

3.4 Extrusion Operation Simulations

The extrusion operation conducted prior to the drawing operation was observed numerically to develop some insight on experimental expectations. Billet strains, die stresses, and extrusion force data were obtained to predict the proper die design as well as determine the energy requirement to perform the operation. These simulations were conducted for the three materials that were desired for experimental testing, 6061-O aluminum, 6061-T6 aluminum, and AISI 1018 steel. Explicit Dynamics simulations in ANSYS were utilized for the simulations.
A 2D axisymmetric model was utilized for the extrusion simulations, as discussed previously during the hybrid die design determination. Boundary conditions included two contact boundary conditions: 1) frictional interaction between the die and the billet and 2) frictionless interaction between the case die and the billet. Also, a displacement boundary condition on the top edge of the billet was utilized to simulate the punch to drive the billet through the die. Since die stresses were also observed, both the billet and the extrusion die were modeled as flexible bodies. The case die was not expected to be a concern, so this body was rigid and fixed. The die was prescribed with a fixed boundary condition on the bottom edge. The general simulation parameters included an initial billet diameter \( D_o \) of 1.500", a final billet diameter \( D_f \) of 1.130", a die half-angle \( (\alpha) \) of 7°, and a coefficient of friction \( (\mu) \) of 0.1. The number of elements used for the die, case die, and billet were 4,395, 225, and 2,315, respectively.

Material properties for the billet were provided by the multilinear isotropic hardening curves presented in Appendix A. The extrusion die and case die were modeled with properties of A2 tool steel (55 HRC). Additional material characteristics are presented in Table 3.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>( E ) (ksi)</th>
<th>( \nu )</th>
<th>( \sigma_Y ) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>10,000</td>
<td>0.33</td>
<td>8,000</td>
</tr>
<tr>
<td>6061-T6</td>
<td>10,000</td>
<td>0.33</td>
<td>40,000</td>
</tr>
<tr>
<td>AISI 1018</td>
<td>30,000</td>
<td>0.29</td>
<td>54,000</td>
</tr>
<tr>
<td>A2 (55 HRC)</td>
<td>30,000</td>
<td>0.29</td>
<td>290,000</td>
</tr>
</tbody>
</table>

### 3.4.1 Extrusion Die Stresses

Initially, the three billet materials were simulated by extruding the 1.5" diameter billet through the extrusion die until a pointed portion was extruded on the outlet of the die. The meshed simulation appeared as shown in Figure 3.10.
For these simulations, the die stresses and extrusion load were the major consideration. With a compressive yield strength of 290,000 psi for the A2 extrusion die, it was desired to maintain a factor of safety of 2 for each of the extruded materials considered, so the maximum equivalent stress was desired to be less than 145,000 psi. The equivalent stress contour of the die stresses for each of the three materials is shown in Figure 3.11.

Figure 3.11: Equivalent stress contours (psi) for die stress (l to r): AISI 1018, 6061-T6, 6061-O.
Additionally, for the stronger materials, it was necessary to confirm that the extrusion load did not approach the capacity of the 150 ton hydraulic press to ensure that the press was sufficient for the experiments. The load reaction data from the simulations is shown in Figure 3.12.

![Figure 3.12: Predicted load from extrusion simulations.](image)

The force reaction data predicted that the hydraulic press would be sufficient to perform the extrusion experiments. The maximum steady-state load was experienced for the AISI 1018 sample (around 90 tons), which is well within the hydraulic press capacity.

Also, as expected, the 6061-O extrusion did not generate excessive stresses on the die due to the lower strength of the material. However, the AISI 1018 and 6061-T6 samples caused peak equivalent stresses in excess of the prescribed safety factor for the extrusion die. Since this result was obtained, it was necessary to modify the original billet geometry to reduce the die stresses for the extrusion operation of these two materials. The procedure for determining this geometry modification is discussed in Section 3.4.2.

### 3.4.2 Determination of Initial Billet Geometry

Modifying the sample geometry with a machining operation required some analysis to not only predict that the sample would not damage the extrusion die, but also to ensure the
final extruded sample would be satisfactory for the drawing operation. The basic approach involved machining the end of the original billet to a reduced diameter, greater than the outlet of the extrusion die. This would reduce the die stresses during the extrusion operation but still create a work hardened, extruded end that could be utilized for the drawing operation. The following procedure was developed to determine the proper machined billet geometry:

1. Select several machined billet diameters for analysis.

2. Simulate extrusion of 6061-T6 aluminum and AISI 1018 steel for the various machined billet diameters.

3. Measure the equivalent plastic strain in the radial direction for the final extruded geometry.

4. Predict the drawing forming limit for 6061-T6 aluminum and AISI 1018 steel billet materials using an ideal work approach.

5. Use hybrid drawing simulations to determine drawing stresses and strains.

6. Compare equivalent plastic strains from the hybrid drawing simulations to the predicted forming limit.

7. Determine the approximate flow stress of the extruded region of the sample.

8. Compare the flow stress of the extruded material to the predicted drawing stress from the drawing simulations.

9. Determine feasibility of the experimental drawing operation based on analytical forming limits and comparison of drawing stresses.

Several geometries were considered for the extrusion simulations for both materials considered, and the basic simulation construction and mesh is described in Figure 3.13.
Notably, the mesh density for the case die was not refined due to the fact that this body was rigid and not observed. This component solely contained the extruded billet as the material flowed through the flexible die. Additionally, the case die was modeled such that it overlapped the extrusion die. This approach was utilized in order to prevent inaccurate material flow between the extrusion die and the case die. Also, all of the billet geometries were modeled with a filleted corner, as degenerate cells were generated in previous iterations of the simulations with a sharp corner billet geometry. The mesh density for each configuration is highlighted in Table 3.3.
Table 3.3: Number of elements for various machined billet diameters.

<table>
<thead>
<tr>
<th>Billet ø (in)</th>
<th>Billet</th>
<th>Die</th>
<th>Case Die</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2,315</td>
<td>4,395</td>
<td>225</td>
<td>6,935</td>
</tr>
<tr>
<td>1.45</td>
<td>2,504</td>
<td>4,395</td>
<td>207</td>
<td>7,106</td>
</tr>
<tr>
<td>1.4</td>
<td>2,437</td>
<td>4,395</td>
<td>207</td>
<td>7,039</td>
</tr>
<tr>
<td>1.35</td>
<td>2,421</td>
<td>4,395</td>
<td>198</td>
<td>2,421</td>
</tr>
<tr>
<td>1.3</td>
<td>2,365</td>
<td>4,395</td>
<td>180</td>
<td>6,940</td>
</tr>
<tr>
<td>1.25</td>
<td>2,268</td>
<td>4,395</td>
<td>162</td>
<td>6,825</td>
</tr>
<tr>
<td>1.2</td>
<td>2,191</td>
<td>4,395</td>
<td>162</td>
<td>6,748</td>
</tr>
</tbody>
</table>

The two critical observations of these simulations were the equivalent plastic strain ranges of the extruded billet geometries and the equivalent die stress. The die stress was the initial filter for the simulations, as any configuration that generated a factor of safety less than 2 against die failure was not considered. The largest allowable diameter for each material that maintained the factor of safety was utilized in the comparison to the hybrid drawing simulations. The results in Table 3.4 present the equivalent die stress for the 6061-T6 aluminum billet and the AISI 1018 steel billet simulations.

Table 3.4: Maximum equivalent die stress and factor of safety for 6061-T6 aluminum and AISI 1018 extrusion simulations.

<table>
<thead>
<tr>
<th>6061-T6 Aluminum</th>
<th>AISI 1018 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billet ø (in)</td>
<td>¯σ_{max} (psi)</td>
</tr>
<tr>
<td>1.5</td>
<td>150,810</td>
</tr>
<tr>
<td>1.45</td>
<td>134,880</td>
</tr>
<tr>
<td>1.4</td>
<td>116,580</td>
</tr>
<tr>
<td>1.35</td>
<td>98,050</td>
</tr>
<tr>
<td>1.3</td>
<td>83,980</td>
</tr>
<tr>
<td>1.25</td>
<td>73,070</td>
</tr>
<tr>
<td>1.2</td>
<td>73,910</td>
</tr>
</tbody>
</table>
Based on the maximum equivalent die stress in the extrusion die, the maximum machined diameter for the 6061-T6 aluminum and AISI 1018 steel samples were 1.45" and 1.25", respectively, while maintaining a factor of safety of 2 against die failure. Using the results from the extrusion simulations, the equivalent plastic strain was measured in the radial direction for each billet geometry. The resulting strain range for each billet geometry are given in Table 3.5.

Table 3.5: Equivalent plastic strain ranges for various machined samples.

<table>
<thead>
<tr>
<th>Billet $\varnothing$ (in)</th>
<th>$\varepsilon_{eff}$ (in/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.59 - 0.61</td>
</tr>
<tr>
<td>1.45</td>
<td>0.48 - 0.50</td>
</tr>
<tr>
<td>1.4</td>
<td>0.405 - 0.42</td>
</tr>
<tr>
<td>1.35</td>
<td>0.335 - 0.35</td>
</tr>
<tr>
<td>1.3</td>
<td>0.26 - 0.28</td>
</tr>
<tr>
<td>1.25</td>
<td>0.18 - 0.20</td>
</tr>
<tr>
<td>1.2</td>
<td>0.1 - 0.12</td>
</tr>
</tbody>
</table>

Using these results, the most conservative (smallest) extruded sample strain for the allowable 6061-T6 aluminum and AISI 1018 steel billet geometries were 0.48 and 0.18, respectively. These values were utilized to determine the approximate flow stress of the material for comparison to the equivalent billet stress predicted by the hybrid drawing simulations.

Next, an ideal work approach (discussed in Section 2.2.2) was utilized to predict the forming limit strain, $\varepsilon^*$, in order to draw the higher strength materials considered. This approach is often utilized to predict the maximum drawing reduction made in a single pass for a given material [3]. Using deformation efficiency ($\eta$) values of 0.5 and 0.65, the equivalent plastic strains for the drawn billet from the hybrid drawing simulations were mapped onto the respective material flow curve, along with the ideal work curves. If these numerical strain values exceed the prediction from the ideal work approach, it followed that the intended reduction would not be possible for the given material.

The forming limit strain occurs at the point where the ideal work curve intersects the flow curve for a given material. This value will produce a higher allowable strain for a calculation with a higher deformation efficiency, where die geometry and frictional conditions are more
ideal. The equivalent plastic strain values from the hybrid drawing simulations are compared graphically with the ideal work approach for 6061-T6 aluminum and AISI 1018 steel samples in Figure 3.14 and Figure 3.15, respectively.

Figure 3.14: Equivalent billet stress from hybrid drawing simulations for 6061-T6 aluminum versus ideal work approach.

Figure 3.15: Equivalent billet stress from hybrid drawing simulations for AISI 1018 steel versus ideal work approach.
The ideal work calculation resulted in the forming limit strain values provided in Table 3.6 for the two deformation efficiency ranges considered.

Table 3.6: Forming limit strains for $\eta = 0.5$ and $\eta = 0.65$.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\bar{\varepsilon}^*$ (in/in), $\eta = 0.5$</th>
<th>$\bar{\varepsilon}^*$ (in/in), $\eta = 0.65$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6</td>
<td>0.529</td>
<td>0.687</td>
</tr>
<tr>
<td>AISI 1018</td>
<td>0.555</td>
<td>0.721</td>
</tr>
</tbody>
</table>

Based on these results, the predicted equivalent plastic strain of 0.54 from the hybrid drawing simulations suggested that the 6061-T6 aluminum sample could be drawn for $\eta = 0.65$, but drawing the material exceeded the forming limit slightly for $\eta = 0.5$. In contrast, the forming limit for the AISI 1018 sample showed that the drawing operation was adequate for the material, compared to the ideal work calculation for both $\eta = 0.5$ and $\eta = 0.65$. While the ideal work approach is a good guideline for forming limit prediction, it is difficult to capture the precise physical effects of the hybrid drawing operation via a deformation efficiency factor. As a result, the 6061-T6 aluminum sample was still considered as a viable material for the drawing operation despite the slight forming limit violation predicted by the ideal work calculation.

Next, the equivalent stress results from the hybrid drawing simulations were obtained for comparison to the flow stress of the extruded samples from the extrusion simulations. With this approach, it was desired to approach a flow stress level during the extrusion operation that was greater than or equal to the drawing stress in the hybrid drawing simulations. The equivalent stress produced during the extrusion operation can be related to the work hardening in the sample, and if the work hardened, extruded end is insufficient, the extruded region will neck during the drawing operation, preventing material flow through the drawing die. The 6061-T6 aluminum and AISI 1018 steel billet geometries from the extrusion operation were compared to the most conservative hybrid drawing simulations ($\mu = 0.15$). Using the equivalent plastic billet strains from the extrusion simulations, the flow stress of the materials was approximated, and these values were compared to the equivalent stresses predicted from the hybrid drawing simulations by calculating the percent difference between the comparable values, shown in Table 3.7. Results from the annealed 6061-O aluminum sample are also presented for comparison.
Table 3.7: Comparison of equivalent billet stress from extrusion simulations and hybrid drawing simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon$, Extrusion (in/in)</th>
<th>$\sigma$, Extrusion (psi)</th>
<th>$\sigma_{\text{max}}$, Drawing (psi)</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6</td>
<td>0.48</td>
<td>48,442</td>
<td>49,599</td>
<td>2.4</td>
</tr>
<tr>
<td>AISI 1018</td>
<td>0.18</td>
<td>84,893</td>
<td>98,851</td>
<td>15.2</td>
</tr>
<tr>
<td>6061-O</td>
<td>0.6</td>
<td>24,324</td>
<td>26,219</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Each of the three billet materials predicted equivalent drawing stresses larger than the approximate flow stress calculated from the extrusion simulation equivalent plastic strains. Notably, the 6061-O results predicted a percent difference between the extruded region flow stress and the drawing stress of 7.5%. Since there should be no possible necking for this configuration since the full billet was simulated for the extrusion operation, it is possible that there is some error in the simulation parameters that predict this result. The 6061-T6 billet comparison produced an extruded region flow stress most similar to the drawing stress, with a percent difference of only 2.4%. The small strains resulting from the smaller diameter extruded geometry in the AISI 1018 steel samples caused larger disparity in the stress comparison, with a percent difference of 15.2%. This result suggested that the sample would likely yield due to insufficient work hardening on the extruded end of the sample; however, before removing the AISI 1018 steel sample from consideration for experimentation, die stress calculations on the hybrid die were first considered.

### 3.5 Hybrid Drawing Die Simulations

ANSYS was utilized to observe the hybrid die drawing operation, absent of fluid pressure, with considerations on die stresses and drawing load. Additionally, simulations were conducted to approximate the effect of fluid pressure in the reduction region of the die using DEFORM 2D. The geometry parameters of the die design were yielded from the die design approach in Section 3.3, and these parameters were considered for the experimental die that was fabricated.

2D axisymmetry was utilized to simplify the explicit dynamics simulation, and 6061-O aluminum, 6061-T6 aluminum, and AISI 1018 steel were the billet materials considered. As mentioned, two simulation models in ANSYS considered 1) die stresses and 2) drawing load for the hybrid die design. For both cases, the billet was prescribed with a displacement boundary condition on the bottom edge of the billet to simulate the drawing operation.
Multilinear isotropic hardening curves in Appendix A were utilized to define the billet material characteristics.

### 3.5.1 Die Stress Simulations for Drawing Die Design

The basic, meshed model for the die stress simulations is shown in Figure 3.16. For these simulations, six flexible bodies (billet, four die sections, and die container) were modeled to capture the physical die design for observing stress concentrations in the assembled die. To maintain consistency with extrusion die stress observation, a frictional condition with $\mu$ equal to 0.1 was prescribed between the billet and die sections. Frictionless contact was considered for the interaction between the die sections and the die container. Also, the bottom edge of the die container was fixed to contain the model and represent the bolted connection between the die container and the elevated die frame used for experimental work.

The die was modeled with hardened (60 HRC) A2 tool steel die sections, and the container was modeled with material characteristics of annealed A2 tool steel. These material parameters, along with the remaining billet parameters, are provided in Table 3.8. Also, since the billet was not the major concern of these simulations, mesh density was reduced (compared to the subsequent analysis) to reduce computation time for the simulation. The major concern was
to provide a sufficiently dense mesh for the die sections such that the small radius of each die section could be adequately captured for the analysis. The mesh density, as well as general geometry and simulation parameters, are provided in Table 3.9.

Table 3.8: Material characteristics for extrusion simulations.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>$E$ (ksi)</th>
<th>$v$</th>
<th>$\sigma_Y$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billet</td>
<td>6061-O</td>
<td>10,000</td>
<td>0.33</td>
<td>8,000</td>
</tr>
<tr>
<td>Billet</td>
<td>6061-T6</td>
<td>10,000</td>
<td>0.33</td>
<td>40,000</td>
</tr>
<tr>
<td>Billet</td>
<td>AISI 1018</td>
<td>30,000</td>
<td>0.29</td>
<td>54,000</td>
</tr>
<tr>
<td>Die Container</td>
<td>A2 (annealed)</td>
<td>30,000</td>
<td>0.29</td>
<td>52,000</td>
</tr>
<tr>
<td>Die Sections</td>
<td>A2 (60 HRC)</td>
<td>30,000</td>
<td>0.29</td>
<td>310,000</td>
</tr>
</tbody>
</table>

Table 3.9: Simulation parameters for hybrid die stress simulations.

<table>
<thead>
<tr>
<th>General Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billet $D_0$ (in)</td>
</tr>
<tr>
<td>Billet $D_f$ (in)</td>
</tr>
<tr>
<td>Final Die Half-Angle</td>
</tr>
<tr>
<td>Re%</td>
</tr>
<tr>
<td>$\mu$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billet</td>
</tr>
<tr>
<td>Container</td>
</tr>
<tr>
<td>Section 1</td>
</tr>
<tr>
<td>Section 2</td>
</tr>
<tr>
<td>Section 3</td>
</tr>
<tr>
<td>Section 4</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
The equivalent stress distribution in the die sections and the die container were observed with drawing simulations for the three billet materials considered. High stress concentrations exist on the small radii that are unsupported on each die section, and, due to the hardness of these components, excessive tensile stress on these components would result in die failure. Additionally, the stress in the die container also required careful consideration, as this component remained in the annealed condition for experimentation, which provided a much lower yield stress than the hardened die sections. The equivalent stress contours for each billet material considered are presented in Figure 3.17, Figure 3.18, and Figure 3.19.

Figure 3.17: Equivalent stress contour for die sections (left) and die container (right) for 6061-O aluminum (stress in psi).

Figure 3.18: Equivalent stress contour for die sections (left) and die container (right) for 6061-T6 aluminum (stress in psi).
Figure 3.19: Equivalent stress contour for die sections (left) and die container (right) for AISI 1018 steel (stress in psi).

The contours suggested high stress concentration at the unsupported radii on the die sections, as expected, and the maximum equivalent stresses are tabulated in Table 3.10.

<table>
<thead>
<tr>
<th>Material</th>
<th>Die Section $\sigma_{max}$ (psi)</th>
<th>Container $\sigma_{max}$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>112,180</td>
<td>12,240</td>
</tr>
<tr>
<td>6061-T6</td>
<td>187,420</td>
<td>32,059</td>
</tr>
<tr>
<td>AISI 1018</td>
<td>311,020</td>
<td>55,582</td>
</tr>
</tbody>
</table>

From these results, it was predicted that drawing AISI 1018 steel billets would cause die failure, as the maximum equivalent stress in the die sections exceeded the yield stress of the hardened die sections. Additionally, the stresses transmitted into the die container suggest possible yielding of the die container as well. While failure of the die container was less concerning, if the loading causes any excessive elastic yielding in the container, deflection of the hardened die sections could result, and tensile bending stresses could be experienced in the die sections, promoting die section failure. Results from the 6061-O and 6061-T6 aluminum suggested that the materials could be cold drawn with the considered design. The 6061-T6 aluminum billet material resulted in a factor of safety against failure of 1.65 for the drawing simulation, while the 6061-O aluminum billet predicted a conservative factor of safety of 2.76.
These observations, coupled with the previous extrusion simulations, justified the exclusion of the AISI 1018 steel billets from further numerical and experimental consideration. Also, while the factor of safety for drawing the 6061-T6 aluminum samples is likely sufficient for compressive loading considerations, unpredictable process conditions that could induce tensile stresses in the die arrangement that cannot be captured via numerical analysis may impact the success of subsequent experimental testing with this billet material. Next, the die design is evaluated further by predicting drawing load for the two remaining billet materials.

3.5.2 Simulation without Fluid Supply

The modified model for the drawing load analysis defeatured the hybrid drawing die as a single component. Additionally, the die was defined as a rigid component, and two frictional contact cases ($\mu = 0.05$ and $\mu = 0.15$) were considered between the billet and die. Additionally, the mesh density of the billet was slightly increased to 2,510 elements, and the die was modeled with considerably more elements (22,603) to define the small radii of the die sections since the rigid component did not affect the computation time of the simulation. Also, the general simulation parameters included an initial billet diameter ($D_0$) of 1.500", a final billet diameter ($D_f$) of 1.162", a percent area reduction of 40%, and a final die half-angle ($\alpha$) of 11°. The defeatured model used for drawing load analysis is depicted in Figure 3.20.

![Simulation model for hybrid die drawing load analysis.](image)

Figure 3.20: Simulation model for hybrid die drawing load analysis.
A force reaction was retrieved from the displacement boundary condition for the two materials considered, and the resulting drawing load prediction for the two frictional conditions considered are shown in Figure 3.21 and Figure 3.22 for 6061-O and 6061-T6 aluminum billet materials, respectively.

Figure 3.21: 6061-O hybrid die drawing load prediction for two friction cases.

Figure 3.22: 6061-T6 hybrid die drawing load prediction for two friction cases.
The average steady-state drawing load was obtained for these simulations for comparison, tabulated in Table 3.11.

Table 3.11: Steady-state drawing load data for hybrid drawing simulations for various materials and frictional conditions.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu$</th>
<th>SS Load (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>0.05</td>
<td>15,225</td>
<td>25.1</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>19,602</td>
<td></td>
</tr>
<tr>
<td>6061-T6</td>
<td>0.05</td>
<td>34,902</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>44,200</td>
<td></td>
</tr>
</tbody>
</table>

Expected trends, such as a load increase for a higher coefficient of friction, were noticed, with 25.1% and 23.5% difference in drawing load predicted for 6061-O and 6061-T6 aluminum, respectively. The comparison of these results to the conventional drawing case is considered in Section 3.6.2.

3.5.3 Simulation with Fluid Supply

Capturing the effect of high pressure fluid in the reduction area of the die was unachievable in ANSYS as there was no means to apply the pressure from the die onto the moving billet without introducing a fluid-structural interaction. In lieu of this restriction, DEFORM 2D was utilized to simulate an approximation of the fluid pressure for 6061-O aluminum billets. The implicit solver features a pressure window selection which allows the definition of a static region within the model which applies pressure on flexible bodies as the bodies pass through the region. Specifically, the pressure window acts on flexible surface element edges only, and the pressure acts normal to the surface of these elements.

The rigid-plastic simulation was conducted with the DEFORM 2D 6061-O aluminum material model, and two friction coefficients ($\mu = 0.05$ and $\mu = 0.15$) were considered for comparison to the ANSYS simulations. The general simulation parameters included an initial billet diameter ($D_o$) of 1.500", a final billet diameter ($D_f$) of 1.162", a percent area reduction of 40%, and a final die half-angle ($\alpha$) of 11°. Additionally, two approaches to the application of the pressure window boundary condition were observed as a means to bound the actual predicted drawing load. The pressure boundary condition acts on the surface of elements that pass through the
region, regardless of frictional contact with the rigid die, which reduces the accuracy of the model to predict the fluid interaction within the hybrid die. To capture this error, analysis was first conducted for a "Half Pressure Window" condition, where the pressure window was active on only the top half of the die sections that supplied fluid to the reduction region of the die. The second analysis considered a "Full Pressure Window", where the pressure window was active along the entire die section length. In total, four unique sets of simulations were obtained to couple the pressure boundary conditions and frictional conditions prescribed.

3.5.3.1 Half Pressure Window

The first analysis, which considered pressure acting on the billet over half of the die section height (for the three die sections where fluid was supplied), was conducted to establish an upper bound for the actual hybrid drawing operation. The active regions of the pressure window are denoted by red boxes in Figure 3.23. The windows which bounded the pressure boundary condition were depicted within the rigid die for clarity; however, the portions of the pressure windows which overlapped the rigid die did not contribute to the simulation.

Figure 3.23: Half pressure window utilized to simulate fluid pressure in hybrid die design.

The range of pressures simulated for the analysis bounded the yield stress of the 6061-O aluminum billet. Supplied pressures ranging from 5,000 psi to 10,000 psi were simulated in 1,000 psi increments to capture trends with pressures above and below the typical 8,000 psi.
psi yield stress of 6061-O aluminum. The predicted steady-state drawing load for the fluid pressures considered for 6061-O aluminum billets are depicted in Figure 3.24 and Figure 3.25 for $\mu = 0.05$ and $\mu = 0.15$, respectively.

Figure 3.24: Steady-state drawing load results for various supplied pressures ($\mu = 0.05$).

Figure 3.25: Steady-state drawing load results for various supplied pressures ($\mu = 0.15$).
The predicted drawing load suggested a clear trend of load reduction with increasing pressure supplied via the pressure window boundary condition. Additionally, the comparison between the two frictional conditions revealed an expected load increase for the higher coefficient of friction considered. Also, between the lowest pressure (5,000 psi) and highest pressure (10,000 psi) considered, the load reduction predicted was 11.9% and 21.8% for $\mu = 0.05$ and $\mu = 0.15$, respectively. Next, the full pressure window approached was considered, and the differences between the two approaches was determined.

### 3.5.3.2 Full Pressure Window

The full pressure window analysis considered pressure acting over the full height of the three die sections which supplied fluid pressure in the reduction region of the hybrid die in order to establish a lower bound numerical solution for the fluid pressure interaction of the hybrid drawing operation. The active regions of the full pressure window are described by red boxes in Figure 3.26.

![Figure 3.26: Full pressure window utilized to simulate fluid pressure in hybrid die design.](image)

The same pressure conditions were considered for the full pressure window analysis, and the steady-state drawing load was obtained for each pressure variation and friction condition in Figure 3.27 and Figure 3.28.
Reduction of drawing load was noticed with an increase in pressure, similar to the half pressure window analysis; however, a slightly larger reduction was observed with an increase in pressure due to the larger region of pressure acting to reduce die contact as compared to the half window analysis. Specifically, load reduction between the 5,000 psi and 10,000 psi simulations of 12.8% for $\mu = 0.05$ and 23.2% for $\mu = 0.15$ were predicted. A full comparison of these two pressure approaches is provided in Section 3.5.4.
3.5.4 Comparison of Hybrid Die Simulation Results

The pressure window approaches conducted in DEFORM 2D provide a reasonable approximation of the fluid pressure interaction in the physical hybrid drawing operation; however, since the actual die contact cannot be accurately predicted, it was necessary to bound the physical impact of the fluid pressure between the two pressure windows approaches considered. First, the load variation between the two approaches were considered for the various pressure and friction conditions to observe the relative drawing load bounds predicted by the different approaches, described in Table 3.12 and Table 3.13 for the two frictional conditions.

Table 3.12: Comparison of steady-state drawing load for half pressure (Half) and full pressure (Full) window approaches ($\mu = 0.05$).

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>SS Load, Half (lbs)</th>
<th>SS Load, Full (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>14,671</td>
<td>14,071</td>
<td>4.2</td>
</tr>
<tr>
<td>6,000</td>
<td>14,270</td>
<td>13,620</td>
<td>4.7</td>
</tr>
<tr>
<td>7,000</td>
<td>13,946</td>
<td>13,117</td>
<td>6.1</td>
</tr>
<tr>
<td>8,000</td>
<td>13,625</td>
<td>12,615</td>
<td>7.7</td>
</tr>
<tr>
<td>9,000</td>
<td>13,299</td>
<td>11,970</td>
<td>10.5</td>
</tr>
<tr>
<td>10,000</td>
<td>13,017</td>
<td>11,300</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Table 3.13: Comparison of steady-state drawing load for half pressure (Half) and full pressure (Full) window approaches ($\mu = 0.15$).

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>SS Load, Half (lbs)</th>
<th>SS Load, Full (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>16,366</td>
<td>15,699</td>
<td>4.2</td>
</tr>
<tr>
<td>6,000</td>
<td>15,922</td>
<td>15,112</td>
<td>5.2</td>
</tr>
<tr>
<td>7,000</td>
<td>15,499</td>
<td>14,540</td>
<td>6.4</td>
</tr>
<tr>
<td>8,000</td>
<td>15,131</td>
<td>13,899</td>
<td>8.5</td>
</tr>
<tr>
<td>9,000</td>
<td>14,787</td>
<td>13,107</td>
<td>12.0</td>
</tr>
<tr>
<td>10,000</td>
<td>14,390</td>
<td>12,436</td>
<td>14.6</td>
</tr>
</tbody>
</table>
The percent difference between the two approaches increases with an increase in fluid pressure, which creates a larger bound between the predicted drawing load solution for higher pressures. This result was expected due to the increasingly reduced surface contact between the die and the billet for an increase in pressure. Additionally, the disparity between the half and full pressure window analysis was slightly greater with the higher friction coefficient considered. This resulted from the additional load reduction that could be realized by reducing die-workpiece contact for the higher frictional interaction. Overall, the steady-state load predicted a decrease in load with an increase in pressure for both friction conditions considered, which mimics the expected physical nature of the process for varying fluid pressure supplied at the die-workpiece interface. Both pressure window approaches are considered in the comparison to experimental results in Chapter 6, and the more accurate approximation is suggested.

3.6 Conventional Drawing Die Simulations

Conventional drawing simulations were conducted in ANSYS to compare drawing load data to the hybrid drawing simulations. The drawing die used in the model features a $11^\circ$ die half-angle, identical to the final half-angle of the hybrid drawing die, and the dimensions match the conventional die that was fabricated for experimental testing. Similar to previous simulation approaches, a 2D axisymmetric model was used, and simulations for 6061-O aluminum and 6061-T6 aluminum billets with 2,485 elements were observed. The die was modeled as a rigid component with 403 elements, and two friction conditions with $\mu = 0.05$ and $\mu = 0.15$ between the die and billet was utilized in an effort to bound the actual expected friction condition. Multilinear isotropic hardening was utilized to predict the plastic flow of the billet materials, shown in Appendix A. The general simulation parameters included an initial billet diameter ($D_o$) of 1.500", a final billet diameter ($D_f$) of 1.162", a percent area reduction of 40%, and a die half-angle ($\alpha$) of 11°. Also, to eliminate unnecessary simulation time, the billet was modeled with a taper from the initial simulation step such that the billet component fit completely in the conventional die. The meshed simulation model is shown in Figure 3.29.
3.6.1 Drawing Load Prediction

A force reaction was captured from the displacement boundary condition for the two materials considered, and the resulting drawing load prediction for the two frictional conditions considered are shown in Figure 3.30 and Figure 3.31 for 6061-O and 6061-T6 aluminum billet materials, respectively.

Figure 3.30: 6061-O conventional die drawing load prediction for two friction cases.
Figure 3.31: 6061-T6 conventional die drawing load prediction for two friction cases.

The steady-state drawing load for each material and friction condition considered are tabulated in Table 3.14.

Table 3.14: Steady-state drawing load data for conventional drawing simulations for various materials and frictional conditions.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\mu$</th>
<th>SS Load (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>0.05</td>
<td>13,882</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>17,664</td>
<td></td>
</tr>
<tr>
<td>6061-T6</td>
<td>0.05</td>
<td>32,175</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>40,482</td>
<td></td>
</tr>
</tbody>
</table>

Clear increases in drawing load were predicted with an increase in friction from the simulation results. The percent difference between the two friction condition for the billet materials simulated was 24.0% (6061-O aluminum) and 22.9% (6061-T6 aluminum). These ranges provided bounds to compare the predicted numerical drawing load to the experimental results obtained.
3.6.2 Comparison of Hybrid and Conventional Die Drawing Load

To observe the novelty of the hybrid drawing operation in terms of overall energy reduction, comparison of the drawing load predictions between the hybrid drawing simulations from ANSYS and DEFORM 2D were compared to the steady-state drawing load obtained for the conventional drawing simulations. The zero pressure hybrid drawing load results were first compared to the conventional drawing load data for each friction case, presented in Table 3.15.

Table 3.15: Comparison of drawing load for hybrid die (no pressure) and conventional die for various friction cases.

<table>
<thead>
<tr>
<th>Material</th>
<th>SS Load, Hybrid (lbs)</th>
<th>SS Load, Conventional (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>15,225</td>
<td>13,882</td>
<td>9.2</td>
</tr>
<tr>
<td>6061-T6</td>
<td>34,902</td>
<td>32,175</td>
<td>8.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>SS Load, Hybrid (lbs)</th>
<th>SS Load, Conventional (lbs)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O</td>
<td>19,602</td>
<td>17,664</td>
<td>10.4</td>
</tr>
<tr>
<td>6061-T6</td>
<td>44,200</td>
<td>40,482</td>
<td>8.8</td>
</tr>
</tbody>
</table>

The comparison suggested an increase in drawing load for the hybrid drawing die without fluid pressure supplied, with percent difference values ranging from 8.1% to 10.4% for the two materials and friction conditions considered. The increase inferred that, without the influence of fluid pressure in the hybrid drawing die, this die design was less efficient than the conventional process. However, comparing the conventional drawing load results to the hybrid drawing load data from the DEFORM 2D simulations showed an improvement in drawing load for the 6061-O aluminum billet material.

Considering the more conservative half pressure window approach from the DEFORM 2D simulations, reduction in drawing load was predicted for supplied pressure greater than 8,000 psi for \( \mu = 0.05 \) compared to the conventional drawing results. For \( \mu = 0.15 \), improvements in drawing load were predicted for each supplied pressure considered.
3.7 Analysis Conclusions

The finite element approaches presented provided insight on a variety of design considerations and experimental predictions for the drawing operation. Initially, design parameters of the hybrid drawing die were analyzed with DEFORM 2D to determine the number of die sections, die section half-angle, and die offset radius that provided the most uniform stress and strain distribution in the resulting drawn billet. The four die section die design with a final die section half-angle of 11° was selected as the most ideal die geometry. Additionally, die stress analysis of the extrusion operation suggested the allowable billet parameters for higher strength materials to achieve an extruded billet while maintaining an acceptable factor of safety against die failure in the extrusion die, with a machined billet requirement of 1.45” and 1.25” for the 6061-T6 aluminum and AISI 1018 steel billets, respectively. Also, die stress analysis of the hybrid drawing die predicted die failure for the AISI 1018 steel billet material considered, which prompted the exclusion of this material for subsequent experimental work. Finally, detailed comparison of drawing load for a variety of hybrid drawing cases were compared to a conventional drawing operation in order to assert potential load improvements for the hybrid drawing process over the conventional operation. The comparison revealed that, without the incorporation of fluid pressure in the reduction region of the die, the hybrid die design was less effective than the conventional process; however, the fluid pressure supply enhanced the design and predicted lower steady-state drawing loads at several fluid pressures considered.
CHAPTER 4

HYBRID DRAWING DIE AND EXPERIMENTAL SET-UP DESIGN

4.1 Introduction

In order to realize a potential hybrid drawing metal forming operation, it was necessary to conceive a potential design prototype that would satisfy some basic criteria for the hybrid die. Many aspects were considered in an effort to improve on the current conventional drawing die, as described in the following sections. Additionally, the experimental set-up was developed to complement the hydraulic press available in the Advanced Metal Forming and Tribology Laboratory (AMTL). Several modifications to the original design conception of the experimental set-up were made to adapt to the limitations of this energy source.

4.2 Design Conception of Hybrid Die

There are many high-level design considerations that define the basic framework for the hybrid die design, including

1. Acceptable material flow to accept high pressure fluid in the reduction region of the die
2. Reliable fluid introduction at multiple locations in the reduction region of the die
3. Altered stress state in reduction region of the die to improve material formability
4. Feasible, modular die sections that are interchangeable and easily manufactured on a large scale
5. Robust container design able to handle drawing stresses for a variety of sample materials

The major components of the hybrid die design are illustrated in Figure 4.1. The modular, stepped die design conceived for the hybrid die creates small voids in the reduction region
in order to accept a "wedge" of fluid at different locations in the reduction region of the die. To introduce high pressure fluid into the reduction region of the die, a single fluid inlet was utilized, and die sealing is facilitated by die-workpiece contact and O-rings fitted within the die container. In order for the fluid to reach the sample in the reduction region, a series of channels in both the die container and die sections were incorporated in the design. The single fluid inlet concept was utilized as a simplification of a future design generation, where unique fluid inlets will be utilized for each die section to provide pressure variation at each die section.

![Figure 4.1: Hybrid die assembly section view.](image)

### 4.3 Unique Characteristics of the Hybrid Drawing Design

The unique design of the hybrid drawing die allows fluid to enter the reduction region of the die at high pressure, which generates major advantages over the conventional drawing operation. First, the tribological performance of the system is enhanced with the achievement of a hydrodynamic lubrication film in the reduction region of the die. Also, the combination of drawing load and high pressure fluid acting on the workpiece serves to alter the stress state of the workpiece compared to the current operation, which has the ability to improve formability.
Enhancement of Tribological Performance. The unique lubrication mechanism inherent in the hybrid drawing process motivated the research. As mentioned in greater detail in Section 2.3, many bulk metal forming operations require the use of conversion coatings and solid lubricants to maintain surface quality and minimize forming load. Specifically, fluid lubricants cannot be utilized in large reduction cold drawing operations with higher strength materials as a result of fluid starvation in the reduction region of the die. Failure to utilize the typical conversion coating lubrication technique in the conventional drawing operation for these higher strength materials would cause infinite drawing loads, rendering the process infeasible; thus, the incorporation of high pressure fluid via the hybrid drawing die provides a feasible fluid lubrication alternative that alleviates the necessity of environmentally harmful conversion coatings.

Therefore, by introducing hydraulic fluid at multiple locations in the reduction region of the die, as well as supplying this fluid at high pressure, it is possible to maintain proper fluid lubrication throughout the reduction. Additionally, a mixed lubrication region can be obtained by local surface deformation of the drawn sample due to the high pressure fluid supply. This localized "orange peel" surface generated by the high pressure fluid allows the material to trap pockets of fluid (micro-pooling) into the next die section, maintaining the surface finish of the drawn sample.

Altered Stress State in the Reduction Region. In addition to the tribological enhancements, another major advantages of the hybrid drawing process is the ability to alter the state of stress in the reduction region of the die. In typical metal forming operations, one of the initial observations involves the state of stress in the deformed sample. Plastic deformation is achieved by generating large shear stresses in the forming operation. To maximize the novelty of a hybrid metal forming operation, it is desired to alter the stress state in a conventional process such that the shear stress of the material can be increased by a hybrid forming element, thus increasing material formability.

Utilizing a 3-D Mohr’s circle (Figure 4.2), the principal stresses of the drawing operation are illustrated. In a conventional drawing operation, axial stress (σ₁) is generated in the workpiece due to the axial force acting on the sample. Indirect compressive stresses (σ₂ and σ₃) are generated by die-workpiece contact to reduce the cross-section of the sample. This stress state (observed by the principal stresses) creates shear stress in the sample to promote plastic deformation.

The hybrid drawing operation utilizes the hydroforming element to increase compressive stress in the reduction region of the die, as shown in Figure 4.2. If the fluid pressure can be generated in the reduction region such that the compressive stresses are increased and a
hydrodynamic fluid film is achieved, greater sample formability can be realized. Achieving
this increased formability can be utilized to cold draw stronger materials that were previously
unformable in cold forming operations.

Figure 4.2: (a) Principal stresses in drawing operation. (b) Mohr’s Circle representation for
stress state alteration.

These two major characteristics of the hybrid drawing die design suggest a possibility to draw
high strength materials with the use of a fluid lubrication mechanism that is not attainable
via a conventional drawing operation. For higher strength materials, a conventional drawing
operation using a fluid lubricant would not be feasible, as the drawing load would increase
indefinitely. By suggesting a novel approach to the lubrication mechanism with the high
pressure fluid supply, the necessity of the environmentally harmful conversion coatings used
for drawing higher strength materials is eliminated.

4.4 Hybrid Drawing Die Design

After identifying the design considerations highlighted in Section 4.2, a prototype design for
the hybrid drawing die was determined. Major aspects of the die design include the design of
the individual die sections, the sealing mechanism of the die, and the fluid supply routing into the reduction area of the die.

Generically, the major components of the hybrid drawing die were four unique die sections, a lower container to house the die sections, and a container lid. This modular set-up was utilized so that the sections could easily be replaced (if damaged or modified) or substituted for a conventional drawing die for experimental comparison. An exploded view of the die design is shown in Figure 4.3.

**Die Section Description.** Four die sections were utilized for the hybrid drawing experiments. The sections are composed of A2 tool steel hardened to 58-60 HRC. The outer diameter of the sections were established such that the die sections are slip fit into the lower container piece, while the inner features were tapered to impose a 40% area reduction on the drawn billet; specifically, 1.5'' diameter samples were reduced to 1.162'' diameter finished products. These surfaces that were in contact with the billet were prescribed with an 8 micron surface finish to
improve surface quality and reduce material galling on the dies.

The die section half-angle and height were determined from numerical simulations described in Section 3.3. The sections are all equivalent in height (0.357”), and, thus, the reduction half-angle of the die sections is increased in order to accommodate an offset between each die section. This offset, illustrated in Figure 4.4, was utilized to provide a small gap which would allow fluid to enter the reduction region of the die at the top of each die section.

As a means to reduce design variable complexity, the reduction half-angles of the die sections were increased by 1°, where the reduction half-angles are governed by the relationship $a_1 < a_2 < a_3 < a_4$ (see Figure 4.4). Therefore, with an 8° half-angle defined for the top section ($a_1$), the reduction half-angles for $a_2$, $a_3$, and $a_4$ were 9°, 10°, and 11°, respectively. This final half-angle ($a_4$ on the bottom die section) set the finished billet diameter of 1.162”. The final sizing is assisted by including a 0.125” die land on the bottom die section.

![Figure 4.4: Die section half-angle variation.](image)

**Fluid Supply.** In order to introduce high pressure fluid into the reduction region of the hybrid die, it was necessary to design features on both the die container and the die sections. As mentioned, a single fluid inlet in the die container was utilized. This fluid supply was then routed through both the die container and die sections to reach the reduction region of the die, illustrated previously by Figure 4.1. Specifically, the fluid inlet in the die container supplied
a small vertical channel in the void of the container bottom. This distributed fluid flowed vertically in the channel to reach each die section. Fluid then flowed circumferentially around each die section via small chamfers machined on the top corners of the die sections. Finally, 4, 0.040” x 0.040” slots were machined in the top face of each die section at 90° increments (see Figure 4.5). These slots provided the final fluid routing to reach the die-workpiece interface. The top section excluded these features since this section was not actively lubricated by the high pressure fluid supply. Also, based on the die section half-angle, the fluid that reached the reduction area creates a small fluid "wedge" in the reduction area in three places (defined by the three die sections that supply fluid) along the reduction.

![Figure 4.5: Stacked die sections.](image)

The fluid "wedge" created by the unique die section design is illustrated in Figure 4.6. The axial load imposed on the outlet side of the die, in conjunction with the offset of the die sections, allowed high pressure fluid to enter the reduction region of the die and create a small wedge that tapers in the drawing direction. With sufficient fluid pressure, it would be possible to generate a hydrodynamic fluid film, eliminating metal-to-metal contact.
Sealing Mechanisms. In order to build pressure in the reduction region of the die, it was imperative to achieve proper die sealing. The sealing considerations that were observed included the container sealing and the internal sealing between the billet and die-workpiece interface. The container was composed of a lower container that accepted the modular die sections, and the unit was assembled by attaching a container lid with a series of bolts. Using this strategy, O-rings were fitted in the upper and lower corners of the container void. These O-rings were compressed by the die sections when the container lid was tightened.

To provide internal sealing, the fluid supply strategy to the individual die sections is utilized, which allows two areas of die-workpiece contact in the reduction region of the die. As shown in Figure 4.6, the entry die section is not actively lubricated with high pressure fluid, which provides sealing on the inlet side of the internal region of the die. In addition, the die land on the bottom die section is utilized to seal the outlet end of the die. This sealing was critical to the success of the experiment since, without proper sealing, it would be impossible to build sufficient pressure to create the hydrodynamic lubrication regime in the reduction region of the die.
4.5 Experimental Set-up

All drawing experiments were carried out in the AMTL using laboratory equipment. Each of the drawing experiments required three major preliminary procedures: 1) sizing and heat treatment of raw samples, 2) extrusion to point the end of the sample, and 3) final drawing of the sample. The equipment and tooling necessary to complete these procedures as well as the drawing operation are discussed.

The hybrid drawing experiments required two main energy sources in order to satisfy the design intent of the die system, shown in Figure 4.7. A hydraulic press was utilized to supply the axial drawing load on the sample, and a hydroforming high pressure fluid control system was incorporated to supply high pressure hydraulic fluid in the reduction region of the hybrid die. The 150 ton Press Master hydraulic press was modified to incorporate custom punches that allowed the system to exert drawing force on the samples while still maintaining a typical extrusion configuration. To monitor the drawing load, a LabVIEW interface was utilized, which captured load data at 100 ms intervals during the experiment. To incorporate the hydroforming element of the hybrid process, a dynamically-controlled high pressure hydraulic fluid system was utilized. Using a custom, computer-controlled interface, this system was introduced by providing a user-input pressure profile during the drawing operation. Pressure was ramped to a final design pressure to allow adequate time to build pressure in the reduction region of the die while the press loaded the sample to seal the reduction region.

Figure 4.7: AMTL hydraulic press (left) and hydroforming control system (right).
To effectively incorporate the hydraulic press and fluid supply system, fabrication was necessary to modify the press. Specifically, an elevated die frame was fabricated in order to provide a gap between the base of the press and the drawing die to draw the sample. Additionally, drive punches were designed to load the chuck that was attached to the sample. The ideal design and function of these components are discussed in greater detail in subsequent sections, and the components are illustrated in Figure 4.8.

![Figure 4.8: Schematic of the full experimental set-up.](image)

### 4.5.1 Sample Preparation

Different materials were used to verify the hybrid die design, and varied methods were utilized to prepare the different samples. Originally, 6061-O aluminum samples were used as a means to achieve a number of samples quickly and reliably before moving to higher strength materials.

**6061-O Aluminum.** Processing the aluminum samples required four major operations: 1) Sizing, 2) Annealing, 3) Pointing, and 4) Cold Forging. The evolution of a typical sample is illustrated in Figure 4.9.
The billets are composed of 6061 aluminum alloy with a T6 temper, which necessitated an annealing process in order to restore the alloy to its annealed state, or -O temper. The samples were cut 5.7” in length (see Section 4.5.3 for determination of sample length), where facing of the billets using a lathe provided consistent billet length and smooth, flat faces. Following the sizing of the billet, samples were annealed in a furnace based on ASM annealing procedures for 6061 Aluminum alloys [33]. This procedure required the samples to remain at 775°F for 2-3 hours to remove the effects of solution treatment, followed by a cooling rate of 50°F/hr until 500°F as a means to limit distortion upon cooling. At this point, the samples were air-cooled to room temperature.

After receiving the heat treatment, samples were pointed, or swaged, a process where the originally cylindrical billets were extruded on the end, which allowed the sample to fit through the drawing die and to be pulled from the outlet side of the drawing die for the final experimental step. Additionally, by achieving this pointed feature via an extrusion operation, the material is work hardened, making it possible to sustain the drawing load without necking the material with the reduced cross-sectional area. In this procedure, an extrusion die with a 7° taper was constructed from A2 tool steel, and two case dies were bolted on top to constrain the extruded material from bulging during the extrusion process. The final diameter of the sample was 1.130”, as this provided a slightly smaller diameter that would fit easily into the drawing
die. Also, the 7° die allowed the tapered portion of the pointed billet to fit into the hybrid drawing die such that the pointed end reached the bottom of the drawing die. A punch was used to transmit the load into the billet supplied by the 150 ton press. In order to maximize the sample stroke available for the final drawing experiment, the billets were pointed such that a 2.375" long reduced diameter section remained.

Gripping the pointed samples was facilitated with the use of a forging operation on the end of the samples. Two A2 tool steel rectangular bars were fitted with a slightly tapered (~2°) hole that was machined with circumferential grooves (sec Section 4.5.4 for more details on the chuck design). The pointed sample was then placed inside of the grooved, tapered slot, and loading from the hydraulic press yielded the desired forged feature on the billets. Following some mild material removal, the samples were prepared for final experimentation.

6061-T6 Aluminum. In addition to the experiments that were conducted with the annealed 6061 samples, experiments were conducted with the tempered, T6 alloy. The raw material arrived in this tempering condition, so no further heat treatment was required to prepare the material for experimentation. For these samples, it was only necessary to machine the samples and point the ends of the samples to receive preparation for the drawing operation. Additionally, the forging operation was not needed due to the redesigned chuck that was utilized for the higher strength material. While some preparation procedures were eliminated for the 6061-T6 samples, additional machining time was required in order to limit the risk of die failure during the extrusion operation.

Two major considerations were made to determine the required machining on the 6061-T6 samples: 1) reduce the pointed cross-section such that no sustained die damage would be experienced and 2) ensure sufficient work hardening of the material to prevent the onset of necking during the drawing operation. This analysis was discussed in Section 3.4.2. It was determined that the sample should be prepared with an initial machined cross-section of 1.450", as shown in Figure 4.10, which would provide sufficient strength of the resulting extruded sample without causing damage to the extrusion die.
Since it was desired to maintain the 2.375" pointed sample length, as discussed in the previous section, a volume conservation calculation was conducted to determine the proper machined pointed length. With the final pointed length, final diameter, and original diameter known, the original machined pointed length was determined to be 2.640".

The extruded billet is shown in Figure 4.11. The dimensions prescribed for the machined pointed length were accurate to achieve the desired pointed geometry, as the extruded portion of the billet meets the end of the machined taper almost perfectly. Also, the dark marks on the extruded end of the sample were generated as a result of the solid lubricant embedding the surface of the sample. This was of no concern for the subsequent drawing operation. The lubrication technique used for the 6061-O samples was also utilized for the 6061-T6 samples, and the lubrication was not well maintained, based on the galling that resulted in the extrusion die following the operation (Figure 4.12).
Extrusion Set-up and Design. The extrusion set-up was developed to provide the work hardened, pointed end on the samples that would be used on the outlet end of the drawing die to allow the chuck to sufficiently grip the sample. With the hydraulic press in the AMTL, this procedure was simple in design due to the fact that the press directly provided the compressive loading needed to extrude the samples; however, the functionality of the press was limited since the maximum opening between the base of the press and the press plate (attached to the hydraulic cylinder) is only 14.375". To alleviate this height restriction, the set-up was designed modularly, and a multi-stage operation was conducted.

In general, an extrusion operation would consist of three tooling components: 1) a conical, converging extrusion die, 2) a case die to restrict material bulging during compression, and 3) a punch to drive the material through the extrusion die. It was not possible to machine a single case die and punch combination that could be fitted under the press plate, so it was necessary to fabricate a two-piece case die, accompanied by a shorter punch, to make the process feasible with the AMTL hydraulic press. The components of the extrusion set-up are depicted in Figure 4.13.

Figure 4.12: Galling on extrusion die following the 6061-T6 sample extrusion.

Figure 4.13: Extrusion operation tooling (l to r: punch, upper case die, lower case die, locking ring, extrusion die).
The modular extrusion tooling was initially assembled as shown in Figure 4.14 with the punch inserted. To fix the tooling together, the lower case die is attached to the extrusion die via a locking ring. The lower case featured a stepped feature which allowed the locking ring to tighten the lower case die to the extrusion die. Next, the upper case die was fitted into the lower case die. A stepped design was used to mate the two case die components to ensure concentric alignment, and bolts tightened the upper case die to the lower case die.

![Figure 4.14: Full extrusion set-up (left) and second extrusion operation (right).](image)

The extrusion operation required several steps to yield the pointed billet. First, the billet is lubricated and placed inside the two-piece case die. The punch was fitted on top of the billet and located by the case die. Using the hydraulic press, the punch drove the billet into the extrusion die until the top face of the punch was flush with the top of the upper case die. At this point, the upper case die and punch were removed, and the punch was relocated in the lower case die opening (see Figure 4.14). The press was used to load the punch again, and the billet was extruded to the final pointed length. The final pointed billet was shown previously in Figure 4.9.
4.5.2 Hybrid Drawing Set-up

The experimental set-up for the hybrid drawing operation was unconventionally designed in order to satisfy the geometry limitations presented by the hydraulic press. The assembled set-up is shown in Figure 4.15

![Figure 4.15: Hybrid drawing process experimental set-up.](image)

The elevated frame was rigidly mounted to the base of the hydraulic press, and the hybrid drawing die was fixed to the top plate. The punches, mounted to the press plate, served to provide the downward force on the chuck that generated the drawing load. Additionally, the fluid inlet was positioned such that the high pressure fluid line could be tightened without obstructing the drawing operation. During the operation, the punches were driven downward until they reached the bottom plate of the elevated frame. A time lapse of the operation is shown in Figure 4.16.
4.5.3 Stroke Limitations and Billet Sizing

In order to determine the allowable billet size and maximum stroke, the maximum height between the press plate and the base of the press were determined. Once this height was obtained, the drive punch length and the elevated frame height were optimized based on the conserved volumetric flow rate of the billet material on the inlet and outlet side of the die. The volume zones considered for the conservation analysis are illustrated in Figure 4.17.

Since there is a known drawing velocity, \( v \), a known final diameter, \( D_f \), and the volume between Zone 2 volume is constant, the volumetric flow rate at the outlet of the billet can be determined by
\[ \dot{V}_f = v \left( \frac{\pi D_f^2}{4} \right) \]

Since \( \dot{V}_f = \dot{V}_o \) due to the conservation of volumetric flow rate at the inlet and outlet of the die, the entry billet velocity can be determined, knowing the initial diameter, \( D_o \). The ratio of the velocities can be utilized to determine the maximum amount of the billet allowed to protrude from the top of the die without being contacted by the press plate relative to the stroke of the drawn billet. Referring to Figure 4.18, the stroke length of the billet on the drawn side, \( l_f \), and the distance between the press plate and the top of the die, \( l_o \), are illustrated.

![Figure 4.18: Schematic of stroke lengths to determine maximum billet length.](image)

The first geometry constraint required \( l_f \) to be less than \( l_o \) (neglecting the billet) so that the maximum stroke was defined by the actual drawing distance rather than the interference of the press plate and the top of the die. Also, the length of \( h \) was constrained such that the available stroke, \( l_f \), did not cause the press plate to contact the top of the undrawn billet, which was determined by observing the velocity ratio of the billet at the inlet and outlet of the die.

Maintaining these two constraints, an approximate deformed billet volume was determined to find the original billet length. Since \( h_3 \) is prescribed based on the gripping height of the chuck and \( h_2 \) is related to the die geometry, the volumes of Zone 1 and Zone 3 can be determined.
directly. The volume of Zone 2 is given by the volume of a circular cone frustum [34].

\[ V_2 = \frac{\pi h_2}{12} (D_0^2 + D_f^2 + D_0 D_f) \]  \hspace{1cm} (4.2)

The sum of the volumes was then utilized to determine the original length of the billet. These geometric relationships were incorporated in order to determine the longest raw billet length that could be drawn without interfering with the press plate or other components of the elevated base. The maximum length determined was 5.7".

### 4.5.4 Sample Chuck

As described in previous sections, it was necessary to design a chuck that could both transmit the load from the hydraulic press into axial drawing load as well as sufficiently grip the drawing sample without slipping. From the initial conception of the design, it was desired to design a low-profile chuck design that would not further impede the limited stroke of the hybrid drawing operation. The introduction of stronger billet materials during experimentation prompted a more robust chuck design for the completion of the experimental work for the 6061-T6 aluminum samples.

#### 4.5.4.1 Gripping Mechanism, Version One

The first sample chuck design utilized two A2 rectangular bars (1"x1.5"x12") that were bolted together to grip the pointed drawing samples (see Figure 4.19). As discussed in Section 4.5.1, this chuck was utilized to forge the end of the samples; thus, the grooves cold forged in the sample matched perfectly with the chuck when tightened.

![Figure 4.19: Exploded view of gripping chuck, version one.](image)
The gripping principle of this chuck design was proposed due to the limited space the chuck occupied in the axial drawing direction. With the two rectangular bars bolted together, a hole was machined with a small taper (\(\sim 2^\circ\)) where the largest diameter of the hole was slightly smaller than the pointed sample diameter. Additionally, circumferential slots were machined along the taper, which allowed material to flow into the recessed ridges during the cold forging operation. The material which occupied the ridges, coupled with the tapered design (shown in Figure 4.20), provided sufficient gripping of the drawn samples.

![Figure 4.20: Illustration of slots and taper machined in chuck (arrow indicates drawing direction).](image)

4.5.4.2 Gripping Mechanism, Version Two

Since the original chuck did not provide adequate robustness to draw the 6061-T6 aluminum samples, a second gripping mechanism was designed and verified with FEA. The cross-section of the new gripping mechanism was increased considerably, which sacrificed some stroke length, and the component was hardened to increase strength. Also, the gripping mechanism was revised to utilize a collet-style design which would serve to grip the sample more tightly with increasing axial load in the drawing direction.

**Numerical Simulations.** The chuck design was observed via numerical simulations in ANSYS Workbench 14.5 to ensure that the strength was adequate for drawing the 6061-T6 aluminum samples. The highest predicted drawing load for the 6061-T6 samples was observed for the hybrid drawing simulations with a friction coefficient of 0.15 applied between the die sections and the workpiece (see Section 3.5.2 for details of the drawing load results). The steady-state drawing force was around 44,000 lbs, which equated to a pressure of 14,000 psi acting on the chuck surface over the contact area created by the punch.

Quarter symmetry was incorporated for the static structural analysis. Additionally, the model was defeatured to focus on critical regions of the gripping mechanism. Namely, the collet was model as a single component, the gripping grooves on the collet were excluded, and the nut (which fixed the collet pieces in the chuck housing) was also excluded, as this component was
removed during the drawing operation to increase the available stroke. Contact was modeled between the billet and the collet as well as the collet and the main chuck component with a frictional interaction ($\mu = 0.2$). Lastly, the billet was modeled rigidly as a fixed support, similar to the previous simulation for the first gripping mechanism. The material parameters for the hardened A2 components included a yield stress of 195,000 psi, a Young’s modulus of 30,000 ksi, a Poisson’s ratio of 0.29, and a density of 0.284 lb/in$^3$.

Symmetry boundary conditions were applied for the quarter model, and the pressure load was applied in the region where the drive punch would contact the chuck component. These conditions are described in Figure 4.21.

![Figure 4.21: Gripping mechanism, version two simulation boundary conditions.](image)

Body sizing was applied to all components in the simulation, with a starting element edge size of 0.1”. Stress convergence was utilized on the main chuck component to refine the mesh on this component only, as this was the major concern for potential failure. The convergence tool was configured to have a percentage change less than 1% for satisfactory convergence. The element refinement, along with the maximum equivalent stress in the main chuck component, are shown in Table 4.1.
Table 4.1: Stress convergence results.

<table>
<thead>
<tr>
<th>$\sigma_{\text{max}}$ (psi)</th>
<th>% Change</th>
<th>Element Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>178600</td>
<td></td>
<td>113666</td>
</tr>
<tr>
<td>170690</td>
<td>-4.53</td>
<td>130635</td>
</tr>
</tbody>
</table>

The convergence tool could only refine the component mesh once before the remeshing caused the simulation to become unstable. Based on this, the simulation was accepted after one remesh, where elements were concentrated at the top of the component (where the maximum load was located) and towards the bottom of the tapered hole where the main chuck component was in contact with the collet. The equivalent stress contour plot, showing the main chuck component only, is described in Figure 4.22.

Figure 4.22: Equivalent stress contour for revised chuck design simulation.

Comparing with the tensile yield strength of the hardened A2 component, the maximum stress in the chuck was slightly below the yield stress, with a factor of safety of 1.14. From a design perspective, a higher factor of safety would have been ideal, but the limited area
where the chuck was housed restricted any additional design modifications to strengthen the component. Additionally, stresses in the collet were satisfactory, and, since all of this stress was compressive, there was little concern for any failure in the collet.

**Gripping Mechanism Design.** The assembled gripping mechanism is depicted in Figure 4.23. The A2 tool steel collet pieces were machined with multiple shallow grooves that provided gripping strength on the pointed end of the drawn samples. These grooves were achieved by a turning operation on a machined, tapered cylinder; following this operation, the collet pieces were cut into six individual pieces, as shown in Figure 4.24. These pieces were then arranged in the larger chuck housing, which featured a matching female taper which allowed the collet pieces to lock inside when loaded.

![Figure 4.23: Gripping mechanism, version two.](image-url)
To install the chuck on the pointed end of the sample, the sample was loosely fitted within the chuck and surrounded by the collet pieces. A large nut was machined to tighten the collet pieces from the bottom of the chuck such that the collet pieces would provide gripping pressure on the sample prior to press loading. Once the chuck was loaded by the punches from the press, the collet grooves engaged the sample tightly, and the nut was removed to increase the possible drawing stroke.

The large chuck component, which housed the collet and tapered locking mechanism, was heat treated to 50 HRC by a heat treatment facility since the laboratory furnace was not large enough to contain the component. This hardness was intuitively selected to provide sufficient strength for drawing higher strength samples as well as maintain toughness under tensile loading that resulted from bending during the drawing operation.

The collet pieces were hardened to 60 HRC based on the ASM handbook hardening procedure [33]. Since A2 tool steels are typically provided in the annealed condition (around 20 HRC) from suppliers, this procedure was necessary to achieve the necessary strength to resist permanent deformation during the drawing operation. In this procedure, the collet pieces were wrapped in stainless steel foil to prevent decarburizing and oxidation of the material surface and preheated slowly to 1455°F. The pieces were soaked for 30 minutes to achieve a uniform temperature distribution. Heating slowly is critical since 1) tool steels are sensitive to thermal shock, which could lead to cracking with sudden temperature increases and 2) volume changes (distortion) can occur as the annealed microstructure transitions to the high temperature, austenite structure. The samples were then austenized at 1750°F for 20 minutes to diffuse carbide particles in the microstructure. The pieces were then air-cooled evenly to
around 120°F, resulting in a brittle, martensite microstructure. To make use of this hardness, it was necessary to temper the pieces to stress-relieve the martensite microstructure. The tempering procedure required reheating to 450°F and soaking for 30 minutes to achieve a hardness of 60 HRC (see Figure 4.25 to determine tempering temperature). The samples were then air-cooled to room temperature.

![Figure 4.25: Hardness vs. tempering temperature for A2 tool steel [33].](image)

This gripping mechanism was utilized for several of the the 6061-O aluminum samples as well as all of the tempered aluminum (6061-T6) samples. To ensure that the design was adequate for the higher loads experienced for the 6061-T6 aluminum drawing experiments, numerical simulations were conducted.

### 4.6 Conclusion

Creating a die design and experimental set-up that would both prove the concept of a hybrid drawing operation as well as coordinate with the existing laboratory equipment required extensive consideration. Importantly, all of the major aspects of the hybrid drawing die
design were evaluated, including the sealing mechanism, die section design, and fluid supply strategy. Billet preparation was also considered for the operation, and the experimental set-up was optimized to maximize the potential of the experimental equipment in the AMTL. The experimental set-up design is capable of drawing a variety of high strength materials, as the final design components satisfy strength requirements for the desired billet materials. High pressure fluid up to 20,000 psi can be supplied to the die reduction region, and the 150 ton press capacity is suitable to draw a variety of materials. Good variability is possible with the experimental set-up and die design to accommodate for various materials and design considerations.
CHAPTER 5

EXPERIMENTAL RESULTS

5.1 Introduction

In order to assess the novelty of the hybrid drawing design, it was necessary to conduct experiments with a hybrid die prototype in the AMTL capable of supplying high pressure fluid into the reduction region of the die. 6061-O and 6061-T6 aluminum samples were cold drawn using the hybrid drawing die with varying fluid pressure levels supplied in the reduction region of the die. Samples of both materials were also drawn using a conventional drawing die to compare to the hybrid drawn samples. Also, while these experiments provided insight on the capability of the hybrid drawing operation, drawing high strength billet materials is ultimately required to exemplify the novelty of the hybrid drawing die design; thus, the observation of the experimental billet materials cannot fully describe the enhancement of the drawing operation via the hybrid drawing process since these materials do not produce the severe tribological conditions that exist with higher strength alloys.

The experimental results were observed initially by obtaining surface characteristics using Scanning Electron Microscope (SEM) and Optical Microscope (OM) imaging to assess tribological conditions of the hybrid drawing operation. Also, microhardness testing was conducted on portions of drawn billets to compare hardness distribution and assess material flow characteristics in the experimental drawing operations. Lastly, drawing load was captured for each of the drawing samples for comparison of energy requirements for varying pressure levels and die designs.

5.2 Experimental Procedure Overview

Since the optimal fluid pressure level was not known explicitly for the hybrid drawing operation, samples were drawn using pressure variations between 5,000 and 10,000 psi in...
1,000 psi increments. For comparison, samples were drawn with the conventional die using the same hydraulic fluid which pressurized the hybrid die as a comparable lubricant. The two drawing die sets used for experimental work are shown in Figure 5.1.

Two samples were obtained for 6061-O aluminum samples at each of the fluid pressure levels. Also, two conventional drawing samples were obtained for comparison. The higher strength of the 6061-T6 aluminum samples raised potential concerns for die failure; thus, these samples were drawn following the completion of all of the annealed sample experiments. One 6061-T6 aluminum sample was drawn using the hybrid die set at a supplied pressure of 10,000 psi, and a second sample was drawn using the conventional die for load and surface comparisons.

5.3 Hybrid Drawing Samples

First, the hybrid drawing samples were compared for a variety of supplied fluid pressures. Drawing load, macro surface features, and micro surface topography were observed for comparison between the samples. These observations served to assert the achievement of a hydrodynamic fluid film in the reduction region of the hybrid drawing die for the various fluid pressures that were selected for experimentation.
5.3.1 Surface Topography

Macro and micro surface observations were exhausted for the 6061-O aluminum samples via visual inspection, OM images, and SEM images to determine the effect of various fluid pressure supplied on the resulting drawn sample.

5.3.1.1 Macro Surface Observations

A sample drawn via the hybrid die is shown in Figure 5.2. Major macro observations were made by comparing both the steady-state drawn portion of the sample as well the conical feature that remained from the portion of the sample that was not completely drawn through the drawing die.

![Figure 5.2: 6061-O aluminum sample drawn with hybrid die at 5,000 psi fluid pressure.](image)

From a visual inspection of the steady-state drawn region of the samples, there was little evidence of surface improvement with varying fluid pressure, as the surface of all of the drawn samples was excellent, shown in Figure 5.3.

![Figure 5.3: Comparison of high quality steady-state surface finish for various fluid pressures.](image)

The major visual difference that was notable was the resulting conical region that remained in the hybrid die at the conclusion of the drawing experiment. In practice, samples would be drawn completely through the drawing die; however, the limited stroke available with the hydraulic press in the AMTL coupled with the desire to inspect the region of the drawn sample within the reduction region of the hybrid die resulted in a final sample that was not completely drawn through the outlet of the hybrid die.
The unique regions of the sample related to the die sections in the reduction region are described as: (1) initial reduction region (not subject to high pressure), (2) first fluid inlet region, (3) first reduction region, (4) second fluid inlet region, (5) second reduction region, (6) final fluid inlet region, and (7) final reduction region. These labels are depicted in Figure 5.4.

![Figure 5.4: Features of the hybrid drawn billet due to the reduction region.](image)

The metal-to-metal contact regions (regions 1, 3, 5, and 7 from Figure 5.4) are more vibrant due to the ironing of the surface from the contact with the die sections. For the various fluid pressures supplied, it was desired to reduce the appearance of these regions, which would indicate larger regions where there was a fluid film generated between the die and the workpiece (regions 2, 4, and 6 from Figure 5.4). From the experiments at various pressures, it was observed that the 9,000 psi samples exhibited the largest achievement of a hydrodynamic fluid film in the reduction area of the die, as depicted by Figure 5.5.

![Figure 5.5: Comparison of 9,000 psi sample (left) and 5,000 psi sample (right).](image)
From Figure 5.5, the regions denoted by $H$ indicate the regions of the sample within the die that were not in metal-to-metal contact with the die sections. Clearly, a full, hydrodynamic fluid film was generated between the bottom two die sections in the 9,000 psi sample, as there was no visual indication that metal-to-metal contact existed between these two die sections. Also, the remaining fluid region created was much larger than the corresponding fluid region shown for the 5,000 psi sample. The die section contact in this region was minimal, and the sample was nearly under the influence of a hydrodynamic lubrication condition for all three fluid-supplied die sections. All of the remaining fluid pressures observed mimicked the results of the 5,000 psi sample shown in Figure 5.5 in terms of the macro observation of the reduction region.

5.3.1.2 SEM and OM Surface Observations

Details of the billet surface at the microscopic level were revealed via SEM images. For these observations, three 6061-O samples were observed. One of the samples was a portion of the original billet that had not been drawn, and the remaining two samples were taken from steady-state portions drawn with fluid pressure supplied at 5,000 psi and 10,000 psi. Figure 5.6 shows SEM images for two magnification levels of the 5,000 psi sample versus the 10,000 psi sample. The 5,000 psi sample featured small transverse imperfections, while the 10,000 psi sample was very smooth in the steady-state region. The onset of surface cracks present on the finished product for the 5,000 psi samples suggested a minor starvation of lubrication in the finished product. The control images from the original, undrawn billet validated the improvement in surface finish on the hybrid drawing samples compared to the original billet surface.

Additionally, the area of the drawn billet within the reduction region of the die was observed with OM images to assess the surface alteration of the billet due to the fluid pressure. Figure 5.7 shows macro surface topographical features of the reduction area for the hybrid drawing process (using the numbering convention from Figure 5.4). From visual inspection, the surface finish for the 10,000 psi sample featured some "orange peel" surface characteristics, which suggested local plastic deformation at fluid inlet regions 2, 4, and 6 due to the higher supplied pressure. The 5,000 psi sample appeared more uniform and smooth at each location with some minimal scratching. The OM images also showed that the density of rippled features increased as the drawn billet approached the exit section. These results demonstrated that the change in fluid pressure had the propensity to alter the surface topography which, in turn, altered the lubrication mechanism. The formed surface asperities at the interface suggested that micro-pool lubrication was exhibited at the interface, which explained the absence of surface scratches on the drawn specimens at 10,000 psi.
Figure 5.6: SEM images for 5,000 psi, 10,000 psi, and undrawn (control) samples.

Figure 5.7: OM images for 5,000 psi and 10,000 psi samples at fluid inlet locations in the reduction die.
5.3.2 Drawing Load Data

Drawing load data was captured from the load cell on the hydraulic press for each experiment. In order to allow the fluid pressure to build in the reduction region of the die, the sample was partially drawn to establish sealing between the sample and the upper/lower die sections. In some cases, the load on the sample was increased to allow the fluid pressure to build to the prescribed level. As a result, the drawing load data was stepped as the sample was loaded to build pressure; thus, the graphical results shown in the following sections were conditioned without these plateaus where the fluid pressure was generated prior to the full drawing stroke. The full, unconditioned drawing load results for the 6061-O aluminum drawing samples are shown in Appendix B. Once the steady-state pressure was reached, the stroke was uninterrupted until the available drawing stroke was completed (Figure 5.8).

Figure 5.8: Completed drawing operation.

5.3.2.1 6061-O Aluminum Samples

In order to capture the drawing load data visually, the drawing load results from the most favorable (lowest steady-state drawing load) sample at each pressure level were plotted, as shown in Figure 5.9, and the steady-state drawing load was tabulated in Table 5.1.
Figure 5.9: Experimental drawing load curves for various pressure levels.

Table 5.1: Average steady-state drawing load for various experiment configurations.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>SS Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>13,628</td>
</tr>
<tr>
<td>6,000</td>
<td>14,046</td>
</tr>
<tr>
<td>7,000</td>
<td>13,139</td>
</tr>
<tr>
<td>8,000</td>
<td>15,537</td>
</tr>
<tr>
<td>9,000</td>
<td>15,574</td>
</tr>
<tr>
<td>10,000</td>
<td>11,401</td>
</tr>
</tbody>
</table>

Since the samples originally featured a conical, reduced region, or frustum, from the extrusion operation, only the load corresponding to the final, steady-state portion was considered for the average drawing load. The samples clearly show the regions that correspond to the pointed end from the extrusion operation, the frustum from the extrusion operation, and the
steady-state drawn portion of the sample, as shown in Figure 5.10. The extrusion frustum was identified by the remaining solid lubricant that existed on the sample from the extrusion operation, and, from a volume calculation, the ideal length of this region in the final drawn sample was determined to be around 2”.

![Image](image.png)

Figure 5.10: Regions of drawn sample to determine steady-state region.

Referring to the raw experimental load results presented in Appendix B, repeatability of the experiments was observed for drawing sample pairs at several of the supplied fluid pressures. Specifically, the repeated samples drawn at 6,000 psi, 7,000 psi, and 8,000 psi achieved steady-state drawing loads that were nearly identical. These results concluded that the experimental conditions were closely replicated by the strong correlation of drawing load data obtained at these respective pressure levels. The sample pairs that were drawn at both 5,000 psi and 10,000 psi showed some variability, however, with a percent difference of 8.9% for the 5,000 psi samples and 19.2% for the 10,000 psi samples. The lack of correlation between the repeated experiments at these two supplied pressures suggested the need for further experimentation of these pressures to achieve a more repeatable result.

Also, trends were not well defined when comparing the samples drawn at various supplied pressures. As predicted, the 10,000 psi sample resulted in the lowest drawing load, which was due to the enhanced lubrication mechanism created by the micro-pool lubrication suggested from the OM images. In contrast, the sample drawn with a 9,000 psi fluid pressure produced the highest drawing load, even with evidence of a hydrodynamic fluid film generated in the reduction region of the die (see Figure 5.5). With the reduced metal-to-metal contact in the reduction region, it was expected that the frictional characteristics at the die-workpiece
interface for this fluid pressure were more ideal than any other condition; however, the resulting drawing load does not support this assertion. Further considerations of the drawing load increase are presented in the Section 5.5.3 comparison to the samples drawn with the conventional die.

### 5.3.2.2 6061-T6 Aluminum Sample

A single 6061-T6 aluminum sample was drawn with the hybrid die at a supplied fluid pressure of 10,000 psi. The full sample (shown in Figure 5.11) was drawn with a steady-state load of 32,786 lbs, and the load curve is depicted in Figure 5.12.

![Figure 5.11: 6061-T6 aluminum sample drawn with hybrid die at 10,000 psi fluid pressure.](image)

![Figure 5.12: 6061-T6 aluminum sample drawing load curve at 10,000 psi fluid pressure.](image)
5.4 Conventional Drawing Samples

To further assess the novelty of the hybrid die design, conventional drawing samples were obtained for both 6061-O and 6061-T6 aluminum samples. For consistency, this die was designed with the same area reduction (40%), and the die angle was equivalent to the final die angle of the hybrid drawing die (11°). Drawing load data was obtained for these samples to compare the load variation with the hybrid drawn samples.

5.4.1 Drawing Load Data

Three samples were drawn with the conventional drawing die. Two of these samples were 6061-O aluminum, and the other drawn sample was 6061-T6 aluminum. The results are presented in the following sections.

5.4.1.1 6061-O Aluminum Samples

One of the resulting samples that was obtained from the conventional drawing operation for the 6061-O aluminum samples is shown in Figure 5.13, and the corresponding load curve is depicted in Figure 5.14. Note that the torn area at the gripped end of the sample was created due to ejecting the sample from the drawing die.

Figure 5.13: 6061-O aluminum sample drawn with conventional drawing die.
Figure 5.14: Drawing load curves for samples drawn with the conventional drawing die.

5.4.1.2 6061-T6 Aluminum Sample

The 6061-T6 aluminum sample (Figure 5.15) was drawn using the conventional drawing die with a steady-state drawing load of 28,734 lbs. The load data is shown graphically in Figure 5.16.

Figure 5.15: 6061-T6 aluminum sample drawn with conventional drawing die.
Figure 5.16: Drawing load curve for 6061-T6 aluminum sample drawn with the conventional drawing die.

5.5 Discussion of Hybrid vs. Conventional Samples

Comparisons gathered between the samples drawn using the hybrid and conventional drawings dies included surface characteristics, hardness measurements of the steady-state drawn billet, and drawing load data. The results presented in the subsequent sections provided unique information regarding the novelty of the hybrid drawing process as compared to the conventional drawing operation.

5.5.1 Surface Comparison

5.5.1.1 6061-O Aluminum Samples

Surface finish between the 6061-O aluminum samples using the hybrid and conventional die configurations were very similar, as both drawing procedures produced a high quality surface finish on the steady-state drawn portion of the sample. Comparison of a hybrid drawn sample versus a conventional drawn sample is shown in Figure 5.17.
While some slight lubrication breakdown was discussed between variations in supplied pressure for the hybrid drawn sample in Section 5.3.1.2, the high relative surface quality between the conventional and hybrid drawn samples did not prompt further micro-surface analysis.

5.5.1.2 6061-T6 Aluminum Samples

Observation of the two 6061-T6 aluminum samples provided some indication of lubrication starvation for the sample drawn with the conventional die as compared to the hybrid drawn sample. From a visual inspection, small surface variations were noticed on the sample drawn with the conventional drawing die; thus, magnified images of the steady-state drawing region were obtained for the hybrid and conventional samples, shown in Figure 5.18.
In order to capture the surface variations in the sample drawn with the conventional die, a magnified, low light image was obtained at the radial edge of the sample in the steady-state region to prevent excessive reflection off of the billet surface. Clear surface cracking is visible for this sample as compared to the sample drawn with the hybrid drawing die, which indicated a starvation of fluid lubricant in the conventional drawing operation.

5.5.2 Knoop Hardness Comparison

Knoop microhardness tests were conducted to compare the hardness of steady-state drawn samples in the radial direction to assert the quality of strain distribution and final product strength. Steady-state portions were cut from two 6061-O and 6061-T6 aluminum samples for testing. One sample was drawn using the conventional drawing die, and the other sample was drawn with the hybrid die at a supplied pressure of 10,000 psi in both cases. Also, a control sample was measured in comparison for each material.

Knoop microhardness testing is typically performed on materials that are either too brittle or too small to be tested with higher load testing methods. For these samples, microhardness testing was ideal since many microindentations were achievable along the radial direction of the steady-state drawn portions. This provided multiple sampling points where hardness variation could be measured to predict hardness gradients in the drawn sample. The testing was carried out in accordance to ASTM Standard E384-11 [35] within the limitations of available equipment and testing environment.

A Knoop indenter is a rhombic-based, pyramidal-shaped indenter with a 7:1 ratio between the length of the long and short diagonal, shown in Figure 5.19.

![Figure 5.19: Knoop hardness indentation profile][1]

To calculate the Knoop Hardness Number (KHN), the applied load, \( P \) (grams force, or g\( f \)), and the long diagonal length, \( d \) (\( \mu \text{m} \)), were determined. While the applied load was prescribed for the testing, the diagonal length was measured under a microscope. Knowing these values, an indenter constant, \( c_p \), relating the projected area of the indentation to the square of the...
length of the long diagonal was used to complete the calculation, given by [35]

\[ HKN = 14229 \left( \frac{P}{d^2} \right) \]  
(5.1)

where 14229 is the value of \(1/c_p\) with built-in conversion values to measure \(P\) and \(d\) in the typical units (gf and \(\mu\)m, respectively).

To prepare the samples, portions of the steady-state drawn billet were cut and machined to ensure that the faces of the cylindrical portion were perfectly parallel. Next, the samples were polished using a lapping machine to produce a mirror-finish that would be sufficient to generate crisp micro-indentations on the sample for accurate measurement. In the testing machine, the center of the sample was located, and indentations were made at 0.040” increments in the radial direction.

5.5.2.1 6061-O Aluminum Samples

The hardness comparison of the 6061-O aluminum samples, measured radially from the center of the sample, is shown in Figure 5.20.

![Figure 5.20: Knoop hardness values for 6061-O aluminum samples drawn using a conventional die and the hybrid drawing die at a supplied pressure of 10,000 psi. An annealed, undrawn sample is the control.](image-url)
The measured HKN values for the 10,000 psi sample and the conventional sample were very similar, and there was little discernible difference that could be exploited via this test; however, the hardness values, compared to the annealed control sample, showed that the percentage difference of the average HKN for the 10,000 psi sample and the conventional sample, compared to the control sample, was 43.4% and 42.9%, respectively. The measured hardness was relatively low for the cold drawn materials due to the very low annealed hardness.

Also, the uniformity of the hardness values in the radial direction for both the hybrid drawn sample and the conventional sample was favorable, as compared to the strain variation observed from the numerical analysis. It may be difficult to discern the strain variation since the variation is quite small, but the hardness uniformity confirmed that the die section half-angle design was ideal.

### 5.5.2.2 6061-T6 Aluminum Samples

Knoop hardness results obtained for 6061-T6 aluminum samples are expressed graphically in Figure 5.21.

![Figure 5.21: Knoop hardness values for 6061-T6 aluminum samples drawn using a conventional die and the hybrid drawing die at a supplied pressure of 10,000 psi. An undrawn sample is the control.](image)
Similar to the 6061-O aluminum results, the hardness distribution for the 6061-T6 aluminum samples produced very uniform results. Additionally, the variation along the radial direction was minimal, which confirmed that the die half-angle proposed was also adequate for the higher strength aluminum. Increases in hardness relative to the control sample (undrawn 6061-T6) suggested an increase in hardness, but the effect was less drastic compared to the annealed drawing samples. Percent differences between the drawn samples compared to the control material were around 11%.

5.5.3 Drawing Load Comparison

Hybrid drawing load data was compared to conventional drawing load data for both cold drawn materials considered as a measure of the obtainable load reduction via the hybrid drawing operation; however, since these materials have proven to be easily drawn with simple fluid lubrication in a conventional drawing process, shown in Section 5.4, the resulting comparison does not fully highlight the novelty of the hybrid drawing operation. Specifically, in order for the hybrid drawing load results to fully exhibit the enhancement of the unique lubrication mechanism, materials that cannot be drawn with fluid lubrication techniques should be observed.

Additionally, while the incorporation of high pressure fluid in the reduction region of the die provides a means to reduce the frictional interaction between the die and the workpiece, a vertical component due to this supplied pressure acts against the drawing direction, which inherently increases the resulting drawing load. In order to isolate the effective drawing load present for the various fluid pressures supplied, an approximation was utilized to subtract the vertical component of pressure that opposed the drawing direction for comparison to the conventional drawing load data obtained for each aluminum billet.

Since the fluid pressure was applied normal to the oblique billet surface in the reduction region, it was possible to extract a force component for each fluid pressure considered to obtain the effective drawing load. By assuming that the billet was subjected to a full hydrodynamic lubrication condition, the area of the billet surface under the hydrodynamic condition was multiplied by the supplied pressure value, which produced a force acting normal to the billet surface. The vertical component of this force was then determined and subtracted from the overall drawing load to produce an effective drawing load, illustrated by Figure 5.22.
The opposing load, $F_{opp}$, that was obtained from the vertical component of the extracted normal force was approximated by

$$F_{opp} = \sum_{i=1}^{3} p l_{ci} \pi (r_i + R_i) \sin \theta_i$$

(5.2)

where $p$ is the supplied fluid pressure, $l_{ci}$ is the relative die section contact length, $r_i$ is the exit radius of the die section, $R_i$ is the entry radius of the die section, and $\theta_i$ is the die section half-angle. This approximation was extended to the drawing load data for each fluid pressure, and the resulting effective drawing load was compared to the conventional drawing load data.

5.5.3.1 6061-O Aluminum Samples

The most favorable raw drawing load data from the hybrid die design for various fluid pressures was plotted alongside the best conventional drawing sample in Figure 5.23. Additionally,
the effective drawing load was determined for each of the fluid pressures for comparison to the conventional load data, shown in Figure 5.24.

Figure 5.23: Experimental drawing load curves for various experiment configurations.

Figure 5.24: Effective drawing load curves for various experiment configurations.
Table 5.2: Average steady-state drawing load (raw and effective) for various experiment configurations (sorted by increasing raw and effective drawing load, respectively).

<table>
<thead>
<tr>
<th>Raw Drawing Load</th>
<th>Effective Drawing Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Configuration</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>11,336</td>
</tr>
<tr>
<td>10,000 psi</td>
<td>11,401</td>
</tr>
<tr>
<td>7,000 psi</td>
<td>13,139</td>
</tr>
<tr>
<td>5,000 psi</td>
<td>13,628</td>
</tr>
<tr>
<td>6,000 psi</td>
<td>14,046</td>
</tr>
<tr>
<td>8,000 psi</td>
<td>15,537</td>
</tr>
<tr>
<td>9,000 psi</td>
<td>15,574</td>
</tr>
<tr>
<td>10,000 psi</td>
<td>11,336</td>
</tr>
<tr>
<td>7,000 psi</td>
<td>9,321</td>
</tr>
<tr>
<td>9,000 psi</td>
<td>10,665</td>
</tr>
<tr>
<td>5,000 psi</td>
<td>10,773</td>
</tr>
<tr>
<td>6,000 psi</td>
<td>10,901</td>
</tr>
<tr>
<td>8,000 psi</td>
<td>11,174</td>
</tr>
<tr>
<td>Conventional</td>
<td>11,336</td>
</tr>
</tbody>
</table>

As evidenced by the raw load data, the sample drawn using the conventional drawing die produced the lowest steady-state drawing load; however, the 10,000 psi hybrid drawing sample produced a similar result. In comparison, the effective drawing load results from Figure 5.24 suggested a reduction in the load contributing only to the drawing load for each of the hybrid drawing samples. The average steady-state drawing load for each of the samples compared in Figure 5.23 and Figure 5.24 are tabulated, in increasing order, in Table 5.2. The results presented for the effective drawing load provide interesting insight to the novelty of the hybrid drawing operation. While the overall energy supplied to the system is greater than the conventional operation, the effective energy that is consumed to draw the sample is reduced as compared to the conventional operation.

While the effective drawing load provides a rationalization for the increased raw drawing load experienced in the hybrid drawing operation, other process and material characteristics potentially contributed to the lack of drawing load improvements and repeatability shown by the hybrid drawn, 6061-O aluminum billets. Specifically, there is less merit to the hybrid process using softer, more formable materials, such as the aluminum billets considered for the experimental work. Ultimately, the intended application of the hybrid drawing die design applies to harder materials, where more severe tribological conditions exist. These materials, which require the use of a conversion coating for adequate lubrication, must be observed experimentally to obtain the added drawing load reduction potential of the hybrid drawing die design. Due to the favorable formability of the experimental billet materials utilized in the
conventional operation, the altered stress state and lubrication mechanism benefits from the hybrid drawing operation are not able to sufficiently exploit the limitations of the conventional operation. Other considerations that may have contributed to the disparity of the experimental results included the variation in die surface preparation, sample material variations, and inconsistencies in the extrusion operation.

**Die Surface Preparation.** Maintaining proper tribological conditions between the die and workpiece were critical to maintaining accurate drawing load measurements for the drawn samples. Specifically, the top die section, which was not exposed to the high pressure fluid supply, experienced some material galling on the die surface. While this die section, and each of the other die sections, were inspected and cleaned between drawing experiments, there could have been some material pick-up on the die sections that adversely affected the resulting drawing load data captured for the drawn samples. This result may have also inhibited repeatable drawing load results shown in the 5,000 psi and 10,000 psi sample pairs.

**Sample Material Variations.** The drawn samples were not produced from identical raw material, and variations in the materials properties of the raw material may have contributed to unexpected variations in drawing load for the various fluid pressure levels considered. Additionally, material uniformity during the annealing procedure could have affected the resulting material characteristics prior to the drawing operation. While this procedure was programmed with the furnace controller, which controlled the temperature set points and time duration at each step, there were variations in the number of samples annealed during the annealing process which could have had minor affects on the resulting material properties of the annealed samples.

**Inconsistent Pointed Samples.** Some of the expected load variations in the hybrid drawn samples could also be attributed to the inconsistency of the extruded samples that were prepared for the drawing operation. In some cases, the pointed end of the sample did not remain concentric to the raw billet region, shown in Figure 5.25. The curved samples that were produced resulted from inconsistent lubrication or lubrication break-down in the reduction area of the extrusion die. This caused material to become intermittently restricted in one area, and the free material flowed away from the cylindrical axis of the billet.
When the gripping mechanism was attached to samples to prepare for the drawing operation, there were perpendicularity errors between the sample and the surface of the gripping mechanism that was in contact with the punches. While the punches only traveled in a single axis, the correction of the gripping mechanism, when loaded, caused slightly asymmetric material flow during the drawing operation. Evidence of this error is illustrated by Figure 5.26.

The altered material flow of the sample during the drawing operation ultimately led to the sample contacting the top of the die container, which sheared a region of the undrawn material. Drawing load increases were noticeable from the resulting drawing load. Clearly, this sample was not considered for analysis, but there were several drawing samples that exhibited slightly asymmetric drawing characteristics that could have contributed to the unexpected load variation.

5.5.3.2 6061-T6 Aluminum Samples

In addition to the load results presented for the 6061-O aluminum billets, raw drawing load comparisons for the hybrid drawing and conventional drawing experiments using 6061-T6
aluminum samples are shown in Figure 5.27. The effective drawing load for the hybrid drawn billet is also depicted in comparison to the conventional drawing data in Figure 5.28.

Figure 5.27: 6061-T6 aluminum experimental drawing load curves for hybrid and conventional drawing samples.

Figure 5.28: Comparison of effective drawing load curve to conventional drawing load for 6061-T6 aluminum samples.
An increase in the raw drawing load was shown for the hybrid drawing sample as compared to the conventional drawing sample, with a steady-state drawing load percent difference of 14.7%. Since there were only two samples drawn using the 6061-T6 aluminum material, drawing load trends were difficult to determine; however, improvement in the raw drawing load for the hybrid drawing operation could possibly be obtained with a higher fluid pressure near the yield point of the higher strength 6061-T6 aluminum billet. Observation of the effective drawing load predicted similar results from the 6061-O aluminum billets, and the comparison of this effective load compared to the conventional drawing load suggested a load reduction of 4.7% for the hybrid operation.

5.6 Conclusion

The experimental results presented valuable information regarding the achievement of a hydrodynamic fluid film in the reduction region of the hybrid die, and comparisons to samples drawn using a conventional drawing die were established to determine relative surface finish and drawing load for each billet material considered. Inspection of the samples drawn with the hybrid die, particularly in the region of the billet that remained in the die at the conclusion of the drawing operation, showed clear alteration of the lubrication mechanism by achievement of a nearly complete hydrodynamic fluid film for the 9,000 psi 6061-O aluminum sample discussed. Also, 6061-O aluminum samples drawn at 10,000 psi fluid pressure exhibited surface asperities due to local plastic deformation from the high pressure fluid, which provided a mixed lubrication region in the drawing operation which enhanced the surface finish of the steady-state billet.

Also, the observation of both the raw and effective drawing load results for the hybrid drawn samples suggested some unique conclusions regarding the effectiveness of the hybrid drawing die. As mentioned, the experimental materials drawn in this study were not able to exemplify the novelty of the hybrid die design due to the fact that these materials did not exhibit a severe tribological condition in the hybrid and conventional drawing operations. Furthermore, while the total energy consumed in the drawing process is increased in the hybrid drawing operation due to the addition of the high pressure fluid component, the effective drawing load results showed the potential of the hybrid operation for the billet materials utilized in this study. Specifically, by omitting the contribution of the raw drawing load due the effect of high pressure fluid, the results indicated that the amount of energy consumed for only the drawing component was more ideal than the conventional operation.
6.1 Introduction

Determination of steady-state drawing load expectations in the drawing operation via FEA is useful for die design by providing a means to predict energy consumption, determine proper die geometry, and prevent die failure. The analysis conducted in Section 3.5 and Section 3.6 provided drawing load predictions that were utilized to compare to the raw experimental load results obtained from drawn samples using the conventional and hybrid drawing dies.

6.2 Numerical Analysis vs. Hybrid Drawing Experiments

Raw experimental load data obtained for the 6061-O aluminum hybrid drawing samples were compared to the drawing load results predicted by the various simulations cases conducted in DEFORM 2D. Since these simulations were not performed for the 6061-T6 aluminum samples, numerical drawing load results from the ANSYS hybrid drawing simulations were utilized to contrast the experimental drawing load for the 6061-T6 aluminum sample drawn with the hybrid drawing die.

6.2.1 DEFORM 2D vs. Hybrid Drawing Load Prediction

The 6061-O aluminum experimental results were compared to the DEFORM 2D simulations, described in Section 3.5.3, to determine the error predicted between the simulated drawing load results and the experimental drawing load over the steady-state load range. As mentioned in Section 3.5.3, the DEFORM 2D analysis was conducted in order to bound the expected experimental drawing load by utilizing four simulation cases that combined the two pressure window approaches along with the two friction conditions considered. For each experimental pressure observed, the steady-state drawing load prediction for the four simulation cases was
compared graphically to the experimental drawing load data. The half pressure window and full pressure window approaches are denoted as "Half" and "Full", respectively, in the graphic legend of the following figures.

Figure 6.1: DEFORM 2D and experimental drawing load comparison for 5,000 psi fluid pressure.

Figure 6.2: DEFORM 2D and experimental drawing load comparison for 6,000 psi fluid pressure.
Figure 6.3: DEFORM 2D and experimental drawing load comparison for 7,000 psi fluid pressure.

Figure 6.4: DEFORM 2D and experimental drawing load comparison for 8,000 psi fluid pressure.
Figure 6.5: DEFORM 2D and experimental drawing load comparison for 9,000 psi fluid pressure.

Figure 6.6: DEFORM 2D and experimental drawing load comparison for 10,000 psi fluid pressure.
The graphical comparisons revealed some inconsistency regarding the accuracy of the finite element prediction of the drawing load experienced in the hybrid drawing operation; however, limited replication of experimental testing and poor repeatability for some of the fluid pressures considered prevented the ability to quantify the drawing load variation between the supplied pressures; thus, experimental data does not trend similarly to the numerical results. To categorize the data for error determination, the average steady-state drawing load obtained from the four simulation cases were tabulated alongside average experimental steady-state drawing load data. The data comparison for \( \mu = 0.05 \) is first considered in Table 6.1.

Table 6.1: Comparison of experimental and numerical steady-state drawing load for \( \mu = 0.05 \).

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Case</th>
<th>Load, FEA (lbs)</th>
<th>Load, exp. (lbs)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>Half</td>
<td>14,671</td>
<td>13,628</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>14,071</td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>6,000</td>
<td>Half</td>
<td>14,270</td>
<td>14,046</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>13,620</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>7,000</td>
<td>Half</td>
<td>13,946</td>
<td>13,139</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>13,116</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>8,000</td>
<td>Half</td>
<td>13,625</td>
<td>15,537</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>12,615</td>
<td></td>
<td>18.8</td>
</tr>
<tr>
<td>9,000</td>
<td>Half</td>
<td>13,299</td>
<td>15,574</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>11,970</td>
<td></td>
<td>23.1</td>
</tr>
<tr>
<td>10,000</td>
<td>Half</td>
<td>13,017</td>
<td>11,401</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>11,300</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>

The DEFORM simulations with \( \mu = 0.05 \) predicted reasonable error (less than 8%) for experimental drawing loads at 5,000 psi, 6,000 psi, and 7,000 psi fluid pressures. The error was magnified for the higher pressure values, with the exception of the 10,000 psi data comparison to the full pressure window analysis, which predicted the steady-state drawing load with a percent error of 0.9%. Next, the percent error results between the experimental steady-state drawing load and the full pressure window analysis were tabulated in Table 6.2.
Table 6.2: Comparison of experimental and numerical steady-state drawing load for $\mu = 0.15$.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Case</th>
<th>Load, FEA (lbs)</th>
<th>Load, exp. (lbs)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>Half</td>
<td>16,366</td>
<td>13,628</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>15,699</td>
<td></td>
<td>15.2</td>
</tr>
<tr>
<td>6,000</td>
<td>Half</td>
<td>15,922</td>
<td>14,046</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>15,112</td>
<td></td>
<td>7.6</td>
</tr>
<tr>
<td>7,000</td>
<td>Half</td>
<td>15,499</td>
<td>13,139</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>14,540</td>
<td></td>
<td>10.7</td>
</tr>
<tr>
<td>8,000</td>
<td>Half</td>
<td>15,132</td>
<td>15,537</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>13,899</td>
<td></td>
<td>10.5</td>
</tr>
<tr>
<td>9,000</td>
<td>Half</td>
<td>14,787</td>
<td>15,574</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>13,107</td>
<td></td>
<td>15.8</td>
</tr>
<tr>
<td>10,000</td>
<td>Half</td>
<td>14,390</td>
<td>11,401</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>12,436</td>
<td></td>
<td>9.1</td>
</tr>
</tbody>
</table>

Generally, the percent error is large for the higher friction coefficient simulation cases, with only three predictions within 10% error of the experimental result. Few trends are observable from these results, as both the half and full pressure window approaches were better predictions of the drawing load for different fluid pressures.

The simulated results were not able to predict definitive trends in the experimental steady-state drawing load data for any of the four simulation cases considered. The 5,000 psi results revealed that the simulation over-predicted the steady-state drawing load for each simulation case. In contrast, the 8,000 psi and 9,000 psi results under-predicted the experimental load for each simulation case. The 6,000 psi, 7,000 psi, and 10,000 psi results were bounded by the full pressure window simulation cases, which provided some validity for the simulation strategy. Ultimately, some of the unknown trends in the experimental results prevented any solidified trends to develop in the simulation comparison.
6.2.2 ANSYS vs. Hybrid Drawing Drawing Load Prediction

Since the DEFORM 2D simulations cases were not observed for the 6061-T6 aluminum billet material, the experimental steady-state drawing load for the sample drawn at 10,000 psi fluid pressure was compared to the hybrid drawing simulations conducted in ANSYS (Section 3.5.2). The experimental drawing load was compared graphically to the ANSYS simulations for both friction conditions in Figure 6.7.

![Figure 6.7: ANSYS and experimental drawing load comparison for 6061-T6 aluminum hybrid drawing sample.](image)

The percent error between the experimental and numerical average steady-state drawing load data was 6.2% and 34.4% for friction coefficients of 0.05 and 0.15, respectively. The lower friction condition was a marginal estimation of the drawing load realized in the hybrid drawing experiment, but, with the absence of fluid pressure, this analysis could not be translated to predict the drawing load for a variety of fluid pressures. The results predicted that, in the hybrid drawing sample with 10,000 psi supplied fluid pressure, the friction was less than what was considered to be a lower bound coefficient of friction ($\mu = 0.05$).

6.3 ANSYS vs. Conventional Drawing Experiments

The experimental steady-state drawing load for the 6061-O and 6061-T6 aluminum samples drawn with the conventional die was observed against the conventional drawing simulations.
completed in ANSYS (Section 3.6). The comparison for the two materials is shown in Figure 6.8 and Figure 6.9.

Figure 6.8: ANSYS and experimental drawing load comparison for conventionally drawn 6061-O aluminum samples.

Figure 6.9: ANSYS and experimental drawing load comparison for conventionally drawn 6061-T6 aluminum sample.
Each of the conventional drawing samples produced steady-state drawing loads less than the predicted load for both friction conditions. While an exact friction coefficient was unknown, the fluid lubrication used for the experiments was expected to produce a friction coefficient that fell within the range of the simulated results; however, the graphical comparisons suggested that the friction was less than these predicted values. The error between the experimental and numerical results is tabulated in Table 6.3.

Table 6.3: Comparison of experimental and numerical steady-state drawing load for conventional drawing samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>μ</th>
<th>Load, FEA (lbs)</th>
<th>Load, exp. (lbs)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-O, Conventional 1</td>
<td>0.05</td>
<td>13,882</td>
<td>11,336</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>17,664</td>
<td></td>
<td>55.8</td>
</tr>
<tr>
<td>6061-O, Conventional 2</td>
<td>0.05</td>
<td>15,922</td>
<td>13,152</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>15,112</td>
<td></td>
<td>34.3</td>
</tr>
<tr>
<td>6061-T6</td>
<td>0.05</td>
<td>32,175</td>
<td>28,734</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>40,482</td>
<td></td>
<td>40.9</td>
</tr>
</tbody>
</table>

While the second conventional sample drawn using the 6061-O aluminum sample yielded a percent error of 5.6% compared to the low friction simulation, all of the other numerical results over-predicted the expected steady-state drawing load by more than 12%. Further experimentation to determine the actual friction characteristics of the fluid lubricant could improve these predictions, as a more reasonable friction value could be obtained.

### 6.4 Conclusion

Three comparisons were observed between the numerical and experimental steady-state drawing loads obtained to assert the predictability of the experimental hybrid and conventional drawing operation for the considered billet materials. The first comparison between the hybrid drawing experiments and DEFORM 2D simulations for 6061-O aluminum samples suggested that some novelty of the simulation results was evident; however, the lack of trending experimental drawing load data prevented clear comparisons at different pressure levels. Additionally, the 6061-T6 aluminum sample drawn with the hybrid drawing die
was compared with ANSYS simulations of the same material without pressure influence. The results suggested that a reduced friction interaction was present as compared to the numerical results, but, without consideration of pressure in the numerical analysis, it would be unreasonable to use this finite element simulation over a wide range of experimental pressures. Finally, conventional drawing comparisons were made for both materials, and, while the simulations captured the physical process well, the numerical drawing load over-predicted the experimental load. This suggested that a reduced friction condition was experienced at the die-workpiece interface; thus, further investigation of the friction effects should be considered to approximate the drawing load more closely.
The approaches presented for this research have shown, numerically and experimentally, that the realization of a hybrid drawing process is achievable. Die design characteristics were optimized via FEA, and the resulting design provided positive material characteristics in experimentally drawn samples. Also, comparisons between simulation results suggested drawing load reduction for a variety of supplied fluid pressures as compared to the conventional process. Experimental testing showed the achievement of a hydrodynamic fluid film for a cold drawn, 6061-O aluminum sample, and materials testing revealed improvements in surface quality over the conventional process. With further optimization and analysis of the design, it may be possible to integrate the design into manufacturing as a viable, novel substitute of the conventional operation, thereby eliminating the harmful conversion coatings that are used currently.

**Future Work for Hybrid Drawing Design.** While several positive outcomes were realized in this research effort, the hybrid die design is still a prototype, at this time, and several aspects of the analytical and experimental approach to the research could be explored to further develop the design.

To capture the physical nature of the hybrid drawing operation, a fluid-structural interaction could be modeled numerically in order to simulate the evolution of the fluid wedge in the reduction region of the die. This would allow the process to be modeled much more closely to the actual operation, and optimal fluid pressure levels could be determined with reduced error.

Furthermore, an analytical approach could be explored as a means to predict a critical design pressure that would promote the achievement of a hydrodynamic fluid film. Adaptation of analytical models presented in Section 2.6 could be utilized to define the hybrid die geometry and predict the process parameters required to generate a full film lubrication process.
From an experimental standpoint, one of the difficulties with the experimental work revolved around the limited drawing stroke available with the current hydraulic press, which reduced the amount of steady-state drawing region achievable in a single sample. The design and fabrication of a draw bench dedicated to the drawing process has been developed in the AMTL. With this apparatus, the drawing operation can be carried out for much longer samples, which would provide a longer steady-state region for further evaluation of drawing load and surface characteristics.

Additionally, replication of the current materials drawn with the hybrid drawing design should be investigated to improve repeatability in the resulting steady-state drawing load realized for various fluid pressures. Also, it is imperative to examine the novelty of the hybrid die design using billet materials that produce a much more severe tribological condition at the die-workpiece interface in the drawing operation. While the billet materials in this study provided clear insight regarding the unique lubrication mechanism of the hybrid die design, the true novelty of the design can be observed by successfully drawing higher strength materials that cannot be drawn via the conventional drawing operation without the use of a conversion coating lubrication technique. In order for these experiments to be possible, a redesign of the drawing die should be conducted to increase robustness for the higher die stresses expected with these materials. Finally, investigation of multiple fluid inlets with varying fluid pressure could improve the drawing load reduction. Since there was only a single high pressure fluid source, this could not be investigated with the current die prototype.

Overall, the hybrid drawing process has exhibited potential as a substitute for the current cold drawing operation as a means to eliminate environmentally harmful lubrication techniques, and further investigation into the design could provide the necessary validation to incorporate the process into mass manufacturing environments.
REFERENCES


Figure A.1: Multilinear isotropic hardening curve for 6061-O aluminum.
Figure A.2: Multilinear isotropic hardening curve for 6061-T6 aluminum.

Figure A.3: Multilinear isotropic hardening curve for AISI 1018 steel.
Figure B.1: Drawing load for 6061-O samples using conventional die.
Figure B.2: Drawing load for 6061-O samples using hybrid die at 5,000 psi fluid pressure.

Figure B.3: Drawing load for 6061-O samples using hybrid die at 6,000 psi fluid pressure.
Figure B.4: Drawing load for 6061-O samples using hybrid die at 7,000 psi fluid pressure.

Figure B.5: Drawing load for 6061-O samples using hybrid die at 8,000 psi fluid pressure.
Figure B.6: Drawing load for 6061-O samples using hybrid die at 9,000 psi fluid pressure.

Figure B.7: Drawing load for 6061-O samples using hybrid die at 10,000 psi fluid pressure.