Title
Extrusion Die Machine for the Grain Refinement of Soft Metals

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Publication Date
2019-04-01

EXTRUSION DIE MACHINE FOR THE GRAIN REFINEMENT OF SOFT METALS

By

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A capstone project submitted for
Graduation with University Honors

June 6, 2019

University Honors
University of California, Riverside

APPROVED

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Abstract

Dr. Suveen Mathaudhu's research group at the University of California, Riverside, focuses on the strengthening of metal alloys for aerospace and defense applications. A project that the group is currently working on is designing magnesium alloys that feature nanocrystalline grains within the material. In structural applications, magnesium alloys are becoming a promising alternative material due to their lightweight properties. However, magnesium alloys still do not serve as adequate structural materials due to their relatively weak mechanical properties. One solution for the improvement of the mechanical properties of magnesium alloys is grain refinement. Through the incorporation of nanocrystalline grain refinement, Dr. Mathaudhu's research group aims to improve the mechanical properties of a magnesium alloy. The research group plans to achieve grain refinement through the use of extrusion on bulk material samples. For the extrusion process to be successful, an extrusion machine must be able to successfully reduce the diameter of the bulk material while maintaining a constant extrusion ratio. In the extrusion process, nanocrystalline grains are created once the material is put under high strain rates and plastic deformation. The research group currently does not have an extrusion machine, so one must be designed and built to fit their specifications. This machine will be able to achieve an extrusion ratio of fourteen and be strong enough to withstand multiple uses without failure. The extrusion die machine will provide Dr. Mathaudhu's group with an effective method for the grain refinement of bulk magnesium and aluminum samples. Points of focus for this report will be on the design of the extrusion dies, the Solidworks modeling and simulations, heat treatment, and the results of the viability of the machine.

Acknowledgements

I would like to show my thanks and appreciation to my team mentor, Dr. Davil Garcia, and my design team Olivia Brandt, Albert Gomez, Christopher Lee, and Raymond Nguyen. This project would not have been possible without the guidance and support from Dr. Garcia and the cooperation and teamwork exhibited by my team. I would also like to thank the following individuals and companies for their support in our project: Mr. Matt McCormick, Dr. Perry Cheung, Mr. Christian Roach, Ms. Yiwei Sun, Mr. Amir-Ali Akhavi, Dr. Suveen Mathaudhu, University of California Riverside, UCR Machine Shop, and Valley Heat Treat.

Table of Contents

Introduction

Magnesium alloys have potential for many applications as structural materials. However, many magnesium alloys currently still do not exhibit adequate mechanical properties. Low yield strengths and hardness leave magnesium alloys mechanically weak.[1] A common method to improve the strengths and mechanical properties of materials is through grain refinement. One such method is incorporating nanocrystalline grains into materials. Nanocrystalline materials are polycrystalline with grains that are less than 100nm in size. Typically speaking, the smaller the grains are within a material the stronger the material is. When materials have smaller grains, there are lower chances for dislocations to propagate in a material under stress. As the lengths of the dislocations decrease, the higher the activation stress needed to begin plastic deformation becomes. Since smaller grain materials demonstrate higher mechanical strengths, incorporating nanocrystalline grains looks to be an effective method for improving magnesium alloys.[2]

Dr. Suveen Mathaudhu's research group has successfully synthesized nanocrystalline grains within structural materials in the past by mechanically alloying powdered metals. However, the group does not currently have any methods for preparing bulk samples of materials with nanocrystalline grains. A common method of incorporating nanocrystalline grains within materials is through extrusion. When the materials are subjected to severe plastic deformation, grain boundaries within the material become nanosized through the rearrangement of the crystal lattice defects.[3] Extrusion is a process commonly used for the strengthening and grain refinement of metallic materials. Furthermore, extrusion is one of the few processes that is able to provide strain rates high enough to produce the plastic deformation necessary to achieve nanocrystalline grain refinement. As such, using extrusion for the grain refinement of the magnesium alloys is ideal.

The research group is looking to use an extrusion machine to achieve development of nanocrystalline grains within bulk material samples. Since the group does not have an extrusion die machine, one must be designed and built to meet the needs of the group. Some of the specifications set by the group are that the machine must utilize a hydraulic press, a variety of dies, and a ram and punch head. In addition, the machine must be designed to handle and withstand significant wear. Further, the extrusion machine must also be able to achieve a 14:1 cross-sectional extrusion ratio between the original cross-sectional area of the billet and the cross-sectional area of the extruded billet respectively. The assembly must also be made to fit on a Dynamo hydraulic press supplied by the group. Additionally, the extrusion machine must also produce extrudates in compliance with the ASTM B221 and B107 standards for extruded aluminum and magnesium billets. [4-5] This machine shall also be simple enough for most users to be able to safely use it without specialized training.

Literature Review

The method of extrusion used for this machine is direct extrusion, which is when a ram is used to push a billet of material into a mold that contains a die at the end of a housing or chamber. In direct extrusion, the extruded material flows in the same direction of the force of the hydraulic press on the ram. When the billet is pushed into the die it expands to fill any excess space until it has filled the volume of the space between the die and ram. At this point in the extrusion process the pressure from the ram will cause a pressure build up within the billet as it pushes against the die. This pressure will accumulate until the billet is then extruded through the die into its final shape. The force applied in direct extrusion is one of the largest out of the different extrusion methods due to the accumulation of pressure from the hydraulic press on the ram and the frictional forces within the extrusion machine. In an effort to preserve some of the machinery, some iterations of direct extrusion machines use dummy blocks or punch heads as an additional barrier between the ram and billet. This additional barrier helps to prolong the life of the machine by being easily detachable from the ram and replaceable.[6]

Another aspect of extrusion to consider is the extrusion ratio. The ratio used in extrusion helps to predict the changes in the grain boundaries that are re-formed once extrusion is complete. Since the change in the microstructures and grain boundaries are what lead to the changes in mechanical properties, it is important to be able to accurately predict the extrusion results. Some of the mechanical properties changed through extrusion are the yield strength, hardness, ductility, and strength of a material. In general, the better the mechanical properties of a material are prior to extrusion the lower the extrusion ratio needed is. Additionally, using a lower extrusion ratio with an extrudable material will provide greater improved mechanical properties compared to a high extrusion ratio.[7]

Another aspect of the extrusion machine to consider is the longevity of the different components. In this design the extrusion die machine is comprised of a ram, punch head, ram guide, extrusion die, housing, and a base. Although this design is not used for every extrusion machine, the durability of the dies, punch head, and ram are a constant concern across many different designs. In most cases the common cause of failure in the machine is die failure. Extrusion dies typically fail through fatigue, wear, and/or plastic deformation. Out of the different types of potential failure the most common cause is brittle fracture of the die, which originates from directional forces causing chipping or crack propagation in the dies.[8] The causes of failure in the dies can be attributed to the high-stress nature of extrusion along with the high degree of friction between the billet and die. The combination of these forces leads to wear on the die that then causes failure. In some examples asymmetrical die profiles could also lead to imbalances in the forces and high stress concentrations on varying parts of the die, thus leading to further plastic deformation and failure.[8] Due to this, die designs must be as symmetrical as possible to limit this possibility of failure.

When considering the longevity of the die, it is important to design a die that effectively distributes and withstands the forces it is subjected to. Extrusion dies can be simple or complex, depending on the desired effect on the extruded product. Some simple die designs just decrease the cross-sectional area of a billet to a desired cross-sectional area, which can then be interpreted as an extrusion ratio. As the dies become more complex, they can include tapers for greater material utilization, different shapes to change the extrudate shape, or multi-hole designs to produce more than one extrudate from larger billets.[9]

Methodology

Initial designs for the extrusion die machine were made by the Mathaudhu research group, which were comprised of a ram, ram guide, punch head, housing, die, and base. In use, the extrusion die machine will be powered by a 40-ton Dynamo hydraulic press. The hydraulic press is manually driven, which causes the press to apply a force to the ram of the extrusion die machine for direct extrusion. Materials were purchased from Hudson Tool Steel and provided to the team by the Mathaudhu research group, including O6, O1, and H13 tool steel. Further material selections and designs were made by the senior design team. The materials initially provided include a 3.5” x 4” O1 steel cylinder, a 2.5” x 9” O6 cylinder, a 3/4” x 17.5” O6 rod, a 5/8” x 14.5” O6 rod, and a 3/4" x 17.5” H13 rod. The last material chosen was a 1.22” x 5” aluminum cylinder. Each material was allocated to their part based on their mechanical and thermal properties. The extrusion die machine will also work in compliance with ASTM standards B221 and B107, which outline the expected mechanical properties of extruded aluminum and magnesium respectively. In order to determine the validity of the machine, samples must be extruded and tested to determine their similarity to expected results.

Material Selection

The senior design team was provided with O1, O6, and H13 tool steel to use for the extrusion die machine. Since the O1 tool steel has the largest diameter of the materials, it was designated to serve as the base for the extrusion die machine since the base needs to be large enough to hold the rest of the assembly. During the extrusion process the forces that will occur are compressive, shear, and frictional forces. To minimize the frictional forces the O6 and H13 tool steels will be used for the ram, punch head, housing, and die respectively. Additionally, the ram will be smaller than the punch head in diameter so that only the punch head and housing are in contact. To further maximize durability, the two-part ram and punch head design is also used to make either part easily replaceable in the event that one part fails during extrusion. In this design, the ram sits within an identically shaped recess in the punch head. As a result of this design, frictional forces will be highest in the punch head and housing during extrusion. In order to further minimize friction, O6 tool steel will be used for the punch head and housing since it features suspended graphite particles. The graphite particles within the steel allow for easy sliding and self-lubrication as the particles flake off. For further friction reduction, a boron nitride lubrication will also be added to parts of the extrusion die machine prior to use.

The 3/4" O6 rod will be used for the punch head while the 3/4” H13 rod will be used for the dies since they have the same diameter. The 5/8” O6 rod will be used for the ram so it will easily fit within the pocket of the punch head. For the housing, the 2.5” O6 cylinder will be used since it is the second largest piece. Out of the materials provided the H13 tool steel is the strongest so it will be used for the dies since it features the best mechanical properties, such as superior yield strength, hardness, and impact toughness, compared to O1 and O6 tool steels. The ram guide will be made from the 1.22” aluminum cylinder since it will only be used to help steady the ram during extrusion.

Die Design

Simple extrusion dies are commonly broken up into three components; the approach zone, bearing zone, and back relief. An example from a United States Patent for an extrusion die featuring all three components can be seen in Figure 1. In extrusion dies, back relief is used to help guide the billet out of the die while limiting friction and chipping of the die. The bearing zone is where the billet is in contact with the die and is extruded and the approach zone is where the billet is guided into the bearing zone and deformation is initiated.[10]

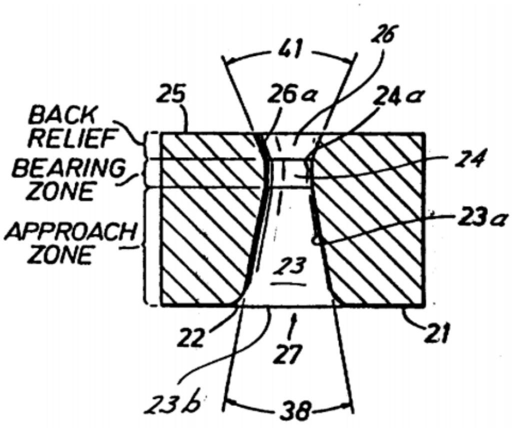


Figure 1: *United States Patent ceramic die.[10]*

Some designs do not use an approach zone or back relief, so it is only a bearing zone that the material is extruded through. These dies are typically flat and have a 90° angle between the surface in contact with the billet and the bearing zone. However, one drawback is that these flat dies cause material loss. When there is no taper in the die or an approach zone, the billet develops a dead-metal zone. A dead-metal zone in extrusion is the lost material that does not flow through the die and builds up along the face of the die.[11] Figure 2 depicts an example of an extrusion machine that uses a flat 90° die and builds up a dead-metal zone during extrusion. In order to minimize the loss of material, it is necessary to introduce an approach zone that takes the place of the dead-metal zone to allow for further flow of the billet through the extrusion die.

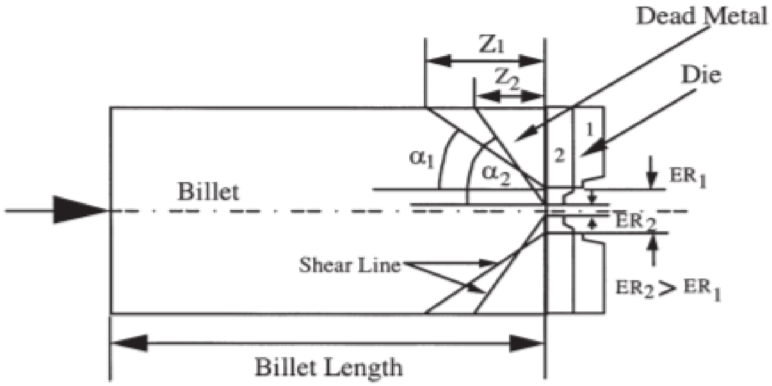


Figure 2: *Extrusion Machine diagram that shows the relationship between the extrusion ratio and dead-metal zone angles.*[11]

Another component to consider when designing the extrusion die was the length of the bearing zone, also known as the land length. The land length of the die influences the change in mechanical properties that result from extrusion. For soft metal extrusion with a low extrusion ratio, it is ideal to use longer die land lengths. A study comparing 3mm, 10mm, and 15mm land lengths was conducted to determine the length that optimizes the mechanical properties of the extrudates. It was found that the improved surface roughness and hardness produced by the 3mm and 10mm lengths are the most similar, while the 15mm length provides further improved results.[12] Although the 15mm lengths are expected to produce more friction, they could still provide the best results for improved mechanical properties.

The final component considered was the inclusion of back relief in the extrusion die. Back relief helps to reduce friction and preserve the durability of an extrusion die. When using back relief in a die, it is optimal to use a small angle to minimize damage in the die. The angle correlates with the friction in extrusion by decreasing as the friction increases. In instances where metal parts are to be extruded without additional lubrication, it is best to use a very low angle for the back relief.[13] For extrusion of soft metals like magnesium and aluminum, with a low extrusion ratio of 14, an optimal angle to use is 3°.

The main die design to be used for the extrusion die machine is a die with a 45° angle in the approach zone, a 15mm land length, and no back relief. This design minimizes material loss during extrusion while also optimizing the mechanical properties of the material that is extruded. Although the friction in the die will be high, the back relief was excluded to optimize the mechanical properties of the extrudates. The final design for the 45° die can be seen in Figure 3a. In addition to the 45° die, two other dies were designed to be tested and compared. Figure 3b shows a 90° die which features a 15mm land length. A flat 90° die is one of the most common dies used in extrusion, so it can be used to compare extrusion results with the 45° dies. The final die design features a 45° angle in the approach zone, a 3mm land length, and a 3° angle for the back relief. This die design can be seen in Figure 3c. Since 3mm and 10mm die land lengths are expected to produce similar mechanical properties, the 3mm land length was chosen to allow for significant back relief in the extrusion process. The extrusion die machine is designed to allow for die interchangeability, so any of these dies can be loaded into the machine for extrusion and testing.

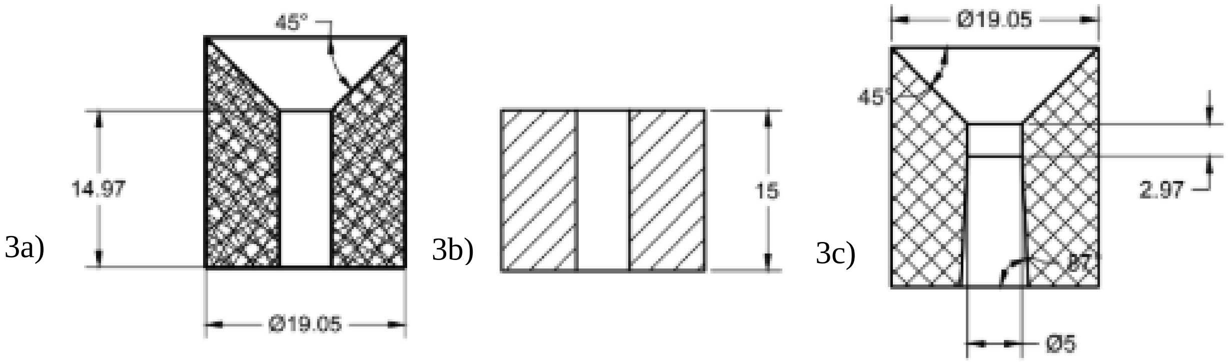
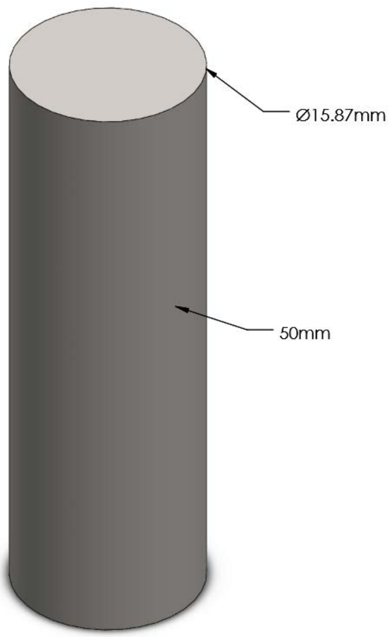


Figure 3: *a) 45° die with no back relief. b) Flat 90° die. c) 45° die with 1° back relief.*

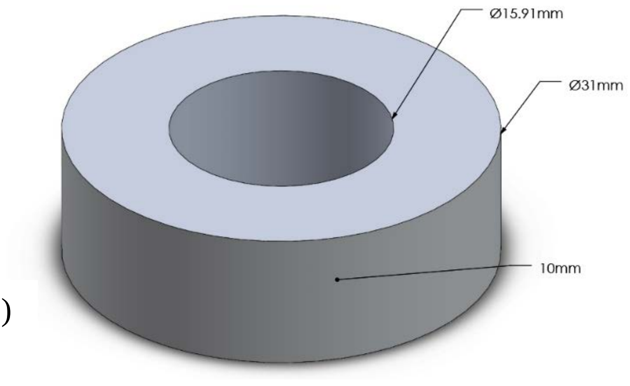
Solidwork Modeling and Simulation

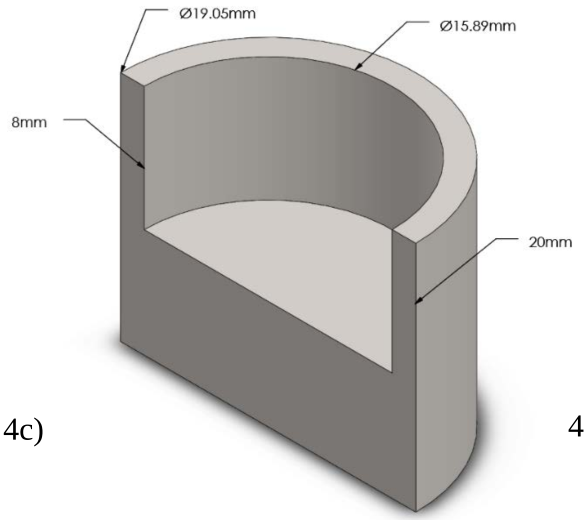
During the design phase a 3D model of the extrusion die machine was constructed using Solidworks. This 3D model was then subjected to compression simulations to anticipate deformation and/or failure during the extrusion process. Compression simulations were completed on the extrusion die machine with the 45° die, 90° die, and the 45° die with back relief. The results of the simulations were used to determine if dimensions needed to be changed or if materials needed to be improved. Each part of the extrusion die machine was drafted using the dimensions determined upon by the senior design team. Figure 4 contains 3D models created in Solidworks for each component of the extrusion die machine. Once each part was modeled, an assembly was created in Solidworks to model what the extrusion die machine would look like once it is assembled. Figure 5 depicts a cross-sectional and regular view of the extrusion die machine assembly.

4a)

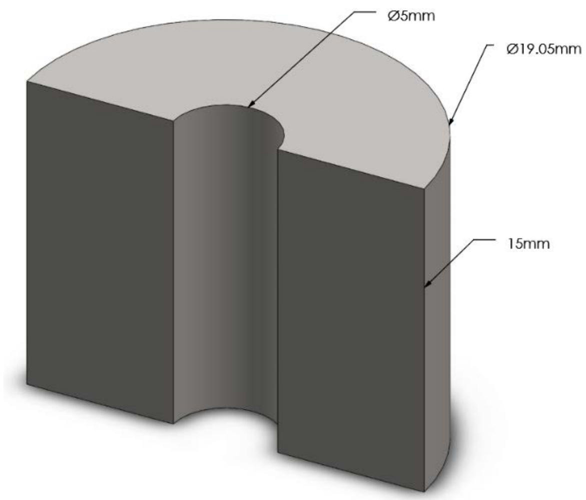


4b)

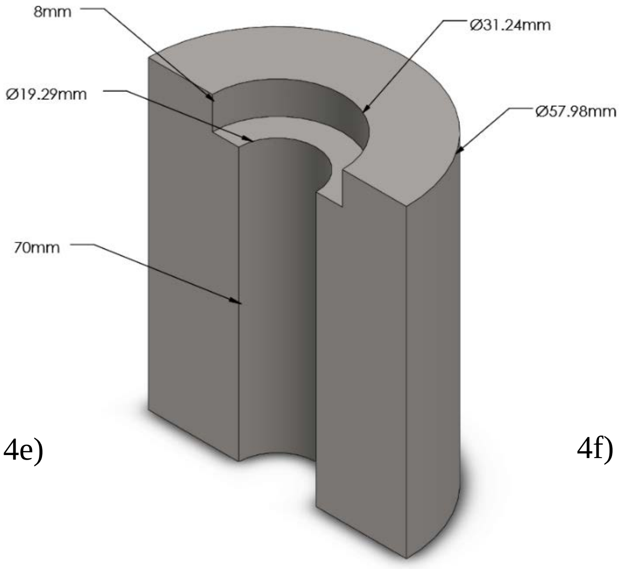



Ø19.05mm
Ø15.89mm
8mm
20mm

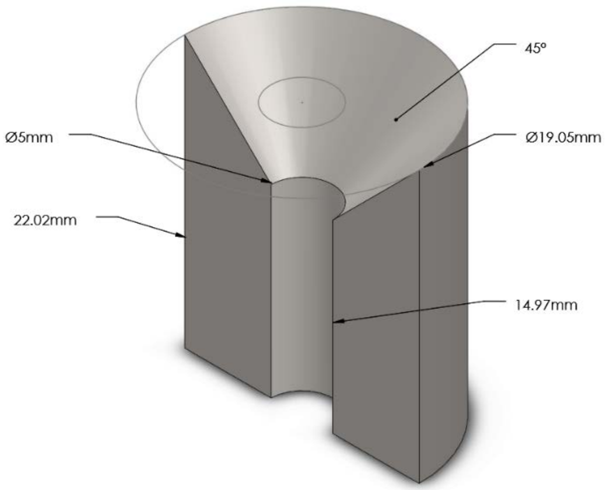
4c)


Ø5mm
Ø19.05mm
15mm

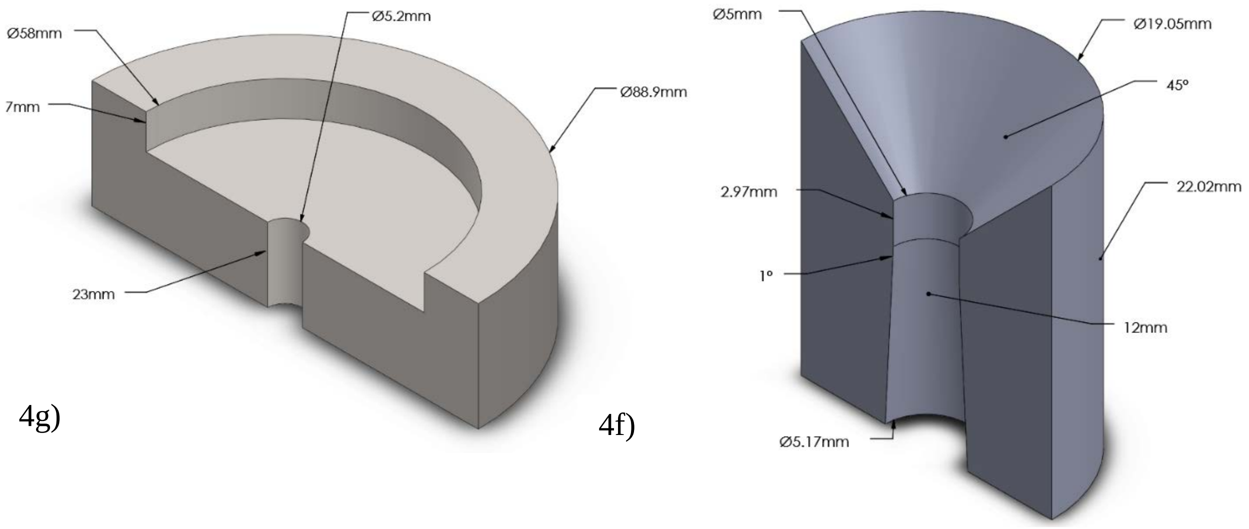
4d)


8mm
Ø31.24mm
Ø19.29mm
Ø57.98mm
70mm

4e)

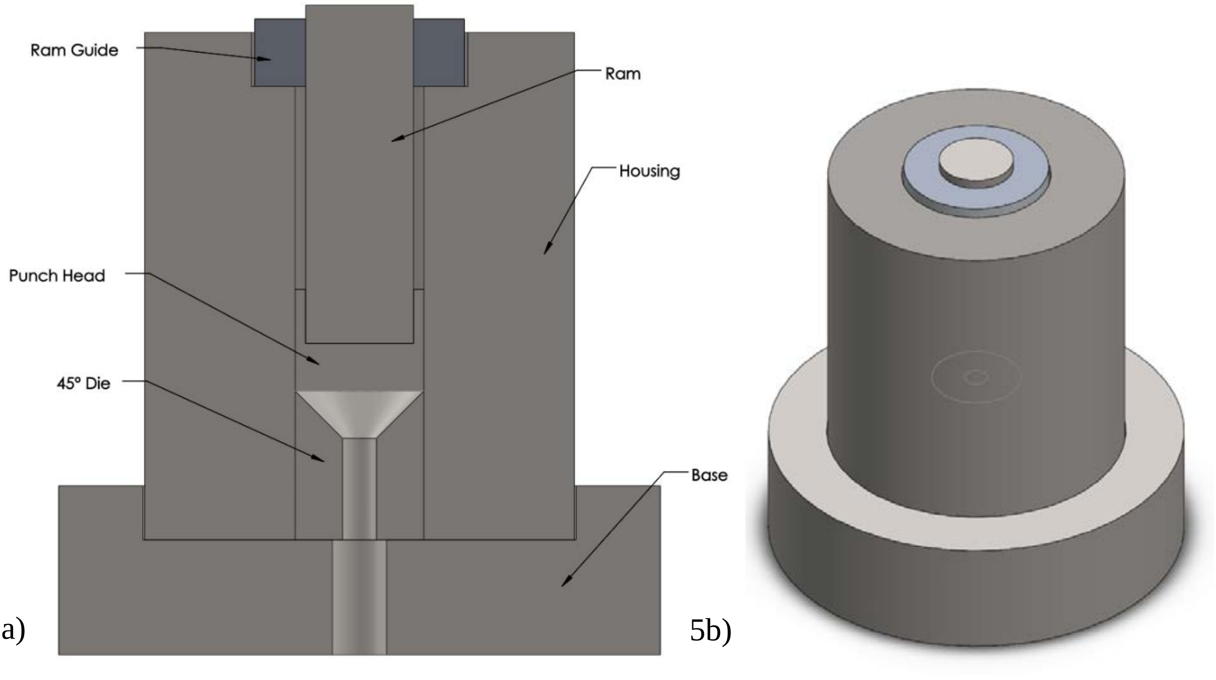

45°
Ø5mm
Ø19.05mm
22.02mm
14.97mm

4f)



4g) 4f)

Figure 4: *Solidworks models of Extrusion Die Machine components with labeled dimensions. a) Ram. b) Ram Guide. c) Punch Head cross-section. d) 90° Flat Die cross-section. e) Housing cross-section. f) 45° Die cross-section. g) Base cross-section. f) 45° Die with Back Relief cross-section.*



5a) 5b)

Figure 5: *Solidworks model of Extrusion Die Machine assembly.*
a) Extrusion Die Machine labeled cross-section. b) Extrusion Die Machine assembly.

Solidworks compression simulations were used to predict deformation and failure in the extrusion die machine at the end of extrusion. For these simulations no billet was modeled or used. Instead, the compression simulations were run on the assembly when the ram and punch head were in contact with the extrusion die. Simulations were run at this point of the extrusion process to see if the die, punch head, and ram could withstand the maximum compressive forces needed for extrusion. Following the completion of the simulation Solidworks provides a data report that estimates stress, strain, and displacement in the assembly. The data provided can then be interpreted to determine if the materials would experience plastic deformation or fracture. In the data, high-stress points can also be seen to predict where fracture or deformation would specifically be expected to occur.

For these compression simulations, a maximum force of 35-36 metric tons is expected to be needed for extrusion of magnesium or aluminum. When designing the simulation parameters, the parts of the extrusion die machine that were going to sit on a surface needed to be assigned a fixed geometry in Solidworks. Other components in the assembly needed to be given rigid body connections. Rigid body connections in Solidworks provide a stiffness and connection between components in a 3D assembly. Using these connections allows forces on one component of the assembly to travel to the other components. This creates a realistic force distribution across the assembly to simulate how the machine would react to the compressive forces of the hydraulic press. The force to be used in the simulations is a pressure, which is a calculation of the force from the hydraulic press distributed over the are of the ram.

Pressure Calculation

Max Load:

- 36 Metric Tons = 353039.401 N

Ram Area:

- Area = $\pi(7.935 \text{ mm})^2 = 0.000198 \text{ mm}^2$

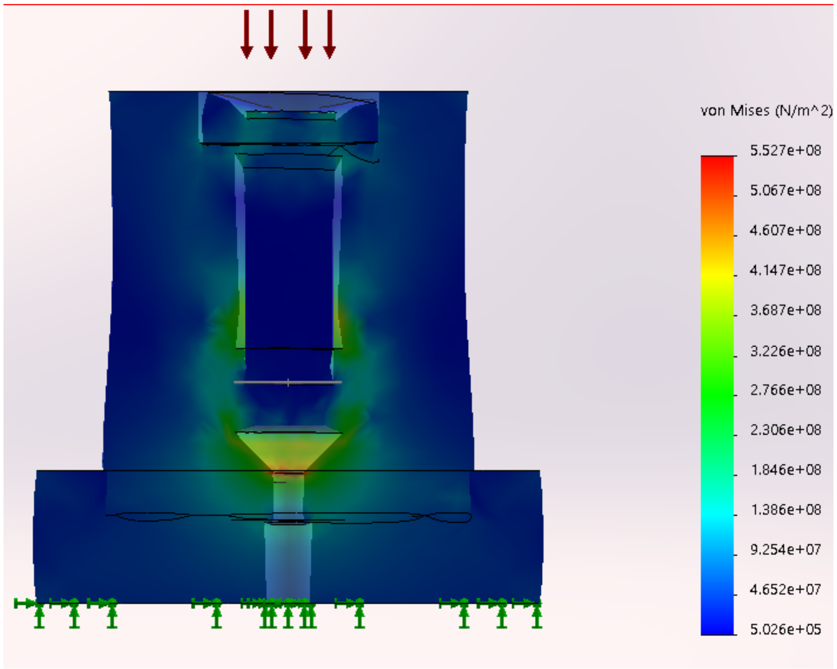
Pressure:

- Pressure = Force / Area = 353039.401 / 0.000198 Pa = 1.783×10^9 Pa = 1.783 GPa

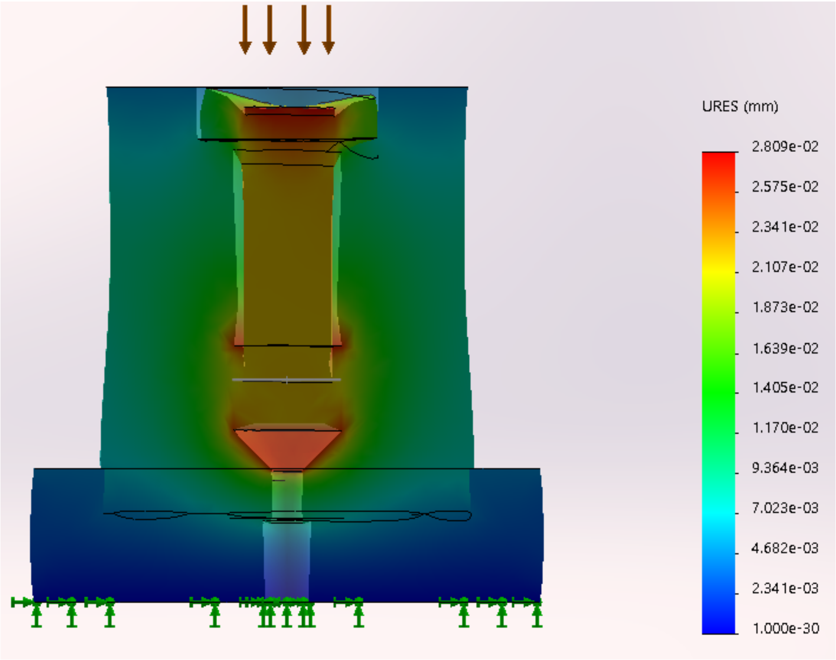
Simulation: 45° Die

The first simulation was run on the extrusion die machine with the 45° die that has no back relief. Figure 6 shows the stress and displacement results for the compression simulation. For both sets of results the amount of stress or deformation present in the machine increases as the colors change from blue to red. Locations in red have the highest concentrations of stress and are where deformation or fracture is likely to occur. For the stress results in Figure 6a the highest point of stress is located in the inner radius of the 45° die. The rest of the stress is regionalized around the die and punch head. Carbon steels such as H13 and O6 have yield strengths around 220 MPa, so locations in red, yellow, and green are beyond the estimated yield strengths of the material. The inner radius of the die has stress values ranging from 460 MPa to 500 MPa, going well beyond the yield strength of the material. With this information it is likely that deformation or fracture would occur in the die originating at the inner radius. Additional deformation could be expected to be seen in the housing around the contact point between the die and punch head.

For the deformation results in Figure 6b the largest points of deformation are consistent with the highest points of stress. The most deformation would be expected in the die, likely originating from the inner radius. The compression simulations show that if fracture or deformation were to occur with this assembly, it would likely begin in the die and then continue to cause deformation throughout the rest of the housing. Other points of interest are in the ram guide and base, which deform as the ram is pushed down into the assembly. This could likely be due to friction from the ram for the ram guide and from the force of the hydraulic press in the base. It is important to note that the results in the software may be overexaggerated by the software, so the extent of deformation in practice could yield different results.



6a)



6b)

Figure 6: *Solidworks compression simulations for the Extrusion Die Machine with the 45° die. a) Von Mises stress results in the assembly. b) Deformation results in the assembly.*

Simulation: 90° Die

Compression simulations were also completed for the extrusion die machine with a 90° flat die. For these simulations the ram was slightly extended to account for the decrease in die size. This change in dimensions should not drastically alter the expected results for the simulations. In this compression simulation a pressure of 1.783 GPa was again used. Although the length of the ram was changed the radius stayed the same, so the pressure from the 36 metric ton force stayed constant. Figure 7a shows the stress results from the simulations. With the 90° die there are significantly less high-stress areas in the assembly, with the highest concentration of stress only reaching around 400 MPa. This is due to the flat surface of the die and even distribution of the forces. In the angled die designs the forces are highly concentrated on the perimeter of the dies since the approach zone limits the surface for contact with the punch head. For the 90° die design the forces are below the 220 MPa yield strength, so fracture and plastic deformation are less likely to occur. Figure 7b contains the deformation of the assembly resulting from the compression simulations. Much like the deformation in the assembly with the angled die, there are still some high-stress concentrations around the punch head and housing. There is likely to be some slight deformation in the housing around the punch head and possibly towards the base of the extrusion die machine. Running extrusion tests with the flat die will likely not cause the die to fracture, and it will at most cause some minor deformation in the housing.

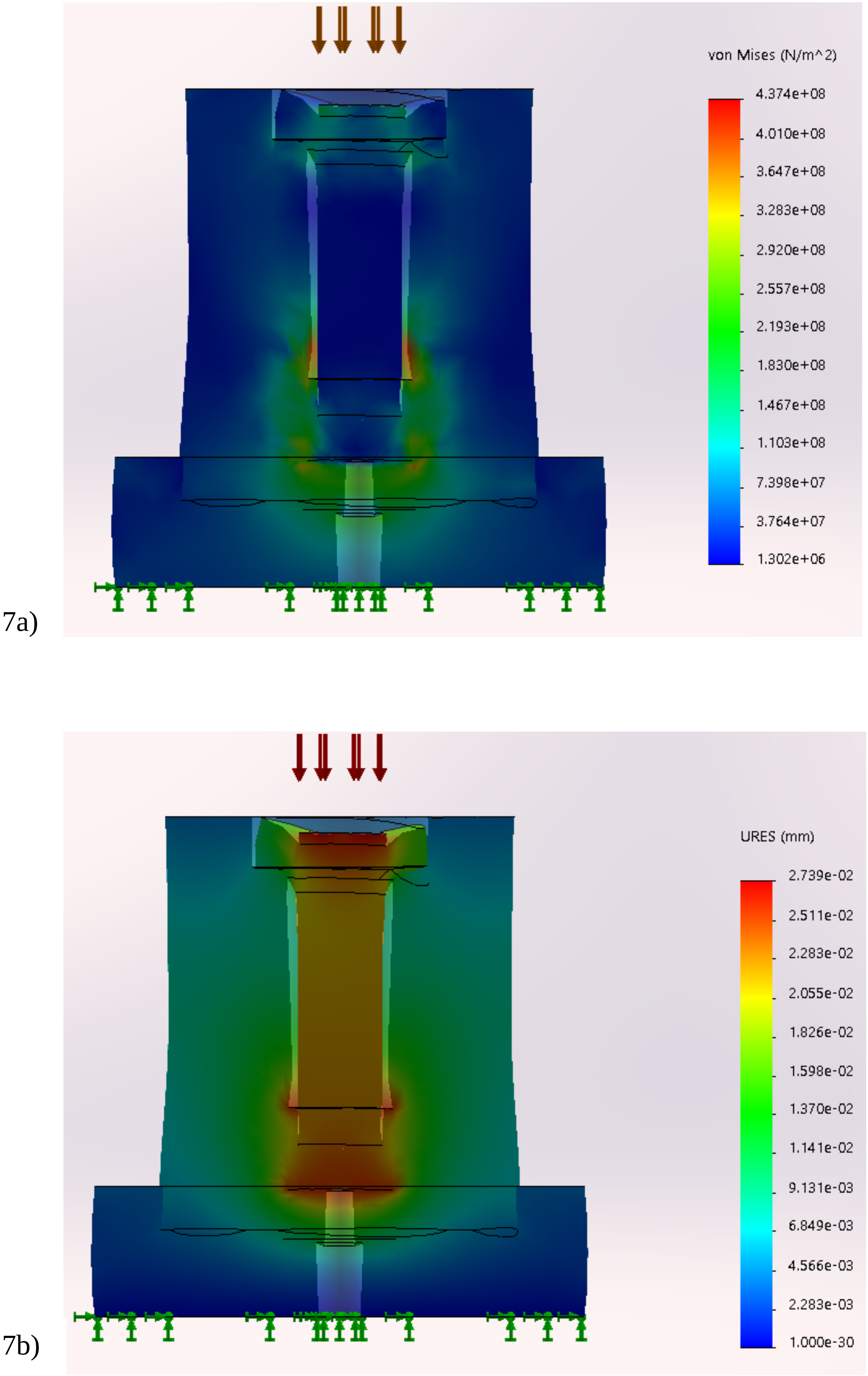
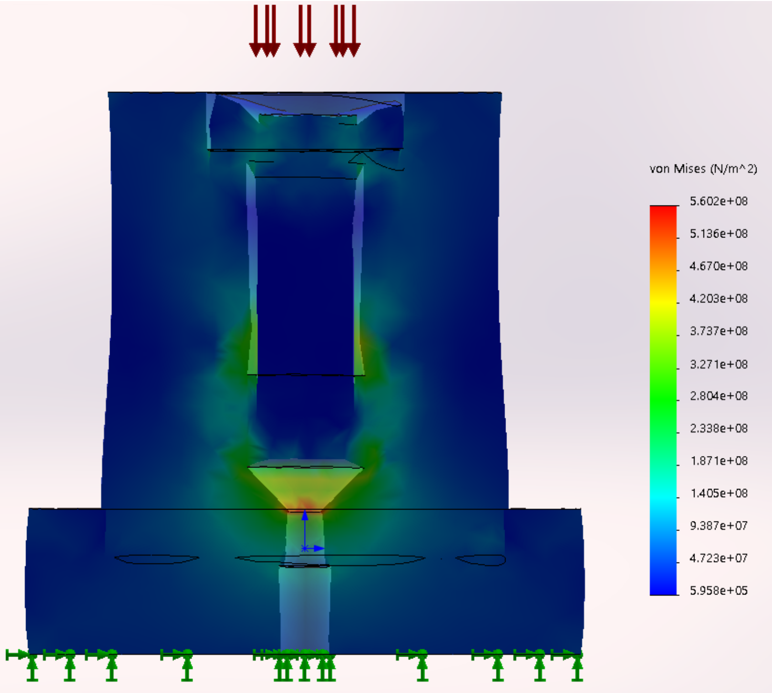


Figure 7: *Solidworks compression simulations for the Extrusion Die Machine with a 90° die. a) Von Mises stress results in the assembly. b) Deformation results in the assembly.*

Simulation: 45° Die with Back Relief

The final simulation was run on the extrusion die machine with the 45° die that has back relief. Like that last two simulations the pressure used was 1.783 GPa. Stress and deformation results for this simulation on the extrusion die machine can be seen in Figure 8. The stress results for this simulation in Figure 8a are very similar to the results present in the simulation with the 45° die that has no back relief. This is expected since both dies only come into contact with the punch head on the top perimeters of the dies. The highest concentration of stress is again within the inner radius of the die around 460 MPa to 500 MPa, so if deformation or fracture are to occur it would be expected to begin there. Additional concentrations of stress are again around the die and punch head ranging above the yield strength of 220 MPa. The deformation results in Figure 8b are consistent with the concentrations of stress and are also similar to the deformation present in the assembly which the regular 45° die. Most deformation in the assembly is likely to occur around the die, punch head, and the housing surrounding their contact point.



8a)

8b)

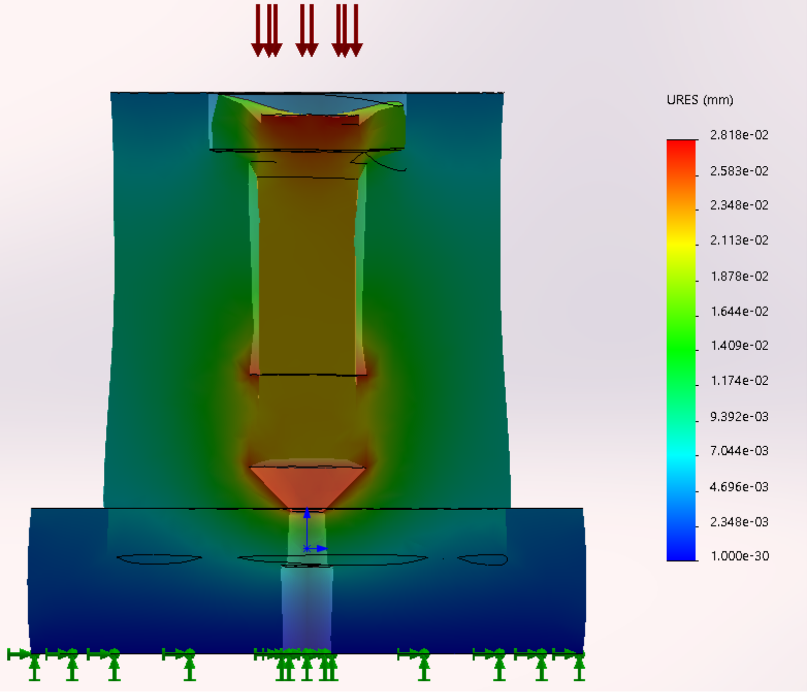


Figure 8: *Solidworks simulation for the Extrusion Die Machine with a 45° die that has back relief. a) Von Mises stress results in the assembly. b) Deformation results in the assembly.*

Heat Treatment

Solidworks simulations presented the possibility that the dies, ram, or punch head could deform or fracture during extrusion. Since the stresses are so high in these components it is necessary to make improvements to the designs to ensure durability. Rather than use different materials, it was determined that heat treating and tempering the materials would be the best option. Heat treatment of metals is a common practice that allows a materials physical and chemical properties to be altered. The material is brought up to a critical temperature, which changes the microstructure of the material, and is then rapidly cooled through quenching. Tempering, which is an additional round of heating and cooling, is also included in the process to further improve a material's mechanical properties. When H13 or O6 steels are heat treated correctly, mechanical properties such as the hardness and toughness can be significantly improved.[14] When preparing final designs for the extrusion die machine, it was necessary to consider potential changes in dimensions of the heat-treated parts. Although heat treatment can improve the mechanical properties of a material, it can also introduce some deformation. These changes in dimensions had to be accounted for when preparing tolerances between these parts.

Heat Treatment Calculations

The thermal expansion equation was used to calculate the potential changes in dimensions for the extrusion die machine parts. For the design the ram, punch head, and all of the extrusion dies were chosen to be heat treated. These parts experience the most forces during extrusion, so heat treatment was needed to ensure that the parts would be durable enough to withstand multiple uses. Thermal coefficients for both O6 and H13 were found on the Hudson Tool Steel website and used in the thermal expansion equation.[15-16] The expected dimensional changes for the parts are relatively small, but were still considered when determining clearances and tolerances for the final dimensions. Following the completion of the calculations and the finalizing of the designs, the heat treatment was then outsourced to Valley Heat Treat to be completed.

Linear Coefficients of Thermal Expansion

H13: $\alpha_L = 13.5 \text{ x } 10^{-6}\ {}^{\text{mm}}/_{\text{mm C°}}$

O6: $\alpha_L = 12.64 \text{ x } 10^{-6}\ {}^{\text{mm}}/_{\text{mm C°}}$

Thermal Expansion Equation

$$\frac{\Delta L}{L} = \alpha_L \Delta T$$

O6 Parts

Ram Length:

$$\frac{\Delta L}{50\text{mm}} = 12.64 \text{ x } 10^{-6}\ {}^{\text{mm}}/_{\text{mm C°}} *(427\text{-}21\text{C°})$$

$\Delta L = 0.231mm$

Ram Diameter:

$\Delta L = 0.081mm$

Punch Head Length:

$\Delta L = 0.103mm$

Punch Head Outer Diameter:

$\Delta L = 0.098mm$

Punch Head Inner Diameter:

$\Delta L = 0.082mm$

H13 Parts

Die Outer Diameter:

$$\frac{\Delta L}{22.03mm} = 13.5 \times 10^{-6}\, {}^{mm}/_{mm\ C^{\circ}} * (538\text{-}21C^{\circ})$$

$\Delta L = 0.133mm$

Die Inner Diameter:

$\Delta L = 0.035mm$

45° Die Length:

$\Delta L = 0.154mm$

90° Die Length:

$\Delta L = 0.105mm$

Testing

Testing with the extrusion die machine was completed using the Dynamo 40 ton hydraulic press in Dr. Mathaudhu's laboratory. A Mg-3wt%Al alloy billet was used for each extrusion test, meaning the billet was comprised of magnesium and by weight 3% aluminum. Five tests were set up to test the 45° die, the 90° die, and the 45° die with back relief. Prior to each test the die, ram, and punch head were cleaned using an acetone solution to remove any contaminants. Following the cleaning, a boron nitride lubrication was sprayed onto the parts to reduce friction and make disassembly easier. Tests 1, 2, and 3 used the 45° dies with back relief, test 4 used the 45° die, and test 5 used the 90° die. For each test a maximum force of 36 metric tons was used to extrude the billet. The hydraulic press was also required to be hand cranked so there was less control over the rate of extrusion.

Results

Test 1

Test 1 used a 45° die with back relief and no boron nitride lubrication. During the test, loud metallic pops were made by the extrusion machine. The test was ended early at 22 metric tons so the components of the extrusion die machine could be inspected. Upon disassembly there was an early formation of an extrudate in the billet and a crack running down the side of the die. An image of the die after the test can be seen in Figure 9. The crack in the die was determined to be the source of the crack heard during extrusion. Test 1 was determined to be unsuccessful.

Figure 9: *Crack running alongside of the 45° die found after test 1.*

Test 2

Figure 10: *45° die with back relief coated in boron nitride spray. Further crack propagation present in the side of the die.*

Test 2 was conducted using the die previously used in test 1. In this test the boron nitride lubrication was added to the die, punch head, and housing. During test 1 the billet experienced deformation and needed to be sanded down to fit in the housing again. For this test 35 metric tons was reached with the hydraulic press, but the test had to be ended due to an oil leak from the press’s gas assembly. Upon disassembly and inspection, it was found that the die created an indentation in the base of the extrusion die machine. Additionally, the material from the billet began to fill in the crack of the die which can be seen in Figure 10. Test 2 was also determined to be unsuccessful.

Test 3

Figure 11: *Fracture 45° die with back relief. Scraps of billet and die surround the fractured*

For test 3 a new 45° die with back relief was used in the extrusion die machine. The boron nitride lubrication was sprayed onto the die, punch head, and housing for this test. During extrusion there were cracks heard at 18, 19, and 35 metric tons before the test was ended at 36 metric tons. After this test it was found that the billet began to extrude but stopped due to the fracturing of the die. As seen in Figure 11, the die fractured down the center and caused additional deformation in the housing. Following this test, the dies no longer had a snug fit in the housing. Although the billet was somewhat extruded, the die fractured, so test 3 was determined to be unsuccessful.

Test 4

In test 4 a 45° die was used with a shim to help tighten the fit in the housing. Deformation from the past test has deformed the housing where the die sits, so shims are now needed to fill in the additional space. For this test a stainless-steel foil was wrapped around the die twice. During this test cracks were heard before the end of the test at 35 metric tons. Upon inspection there were two cracks found in the die. The die with the two cracks can be seen in Figure 12. Fortunately, the cracks did not propagate in this test likely due to the additional tightness provided by the shim. The billet did not extrude any further in this test, so test 4 was also deemed unsuccessful.

Figure 12: *45° die with cracks in the body of the die.*

Test 5

The final test was competed using a 90° die and boron nitride lubrication. From the previous tests the billet had begun to develop a conical region, which was the first part to be in contact with the die. Throughout the extrusion process no cracks were heard, and the test completed after reaching a force of 36 metric tons. After disassembly the die was found to be intact and without any visible cracks. Additionally, a 3.5mm extrudate was found inside the die. Figure 13 shows the die after extrusion and the billet alongside a scale bar. Although the full billet was not extruded there was still extrudate produced without damaging the die, thus making test 5 successful.

13a)

13b)

Figure 13: *Test 5 extrusion results.*
a) 90° die after extrusion.
b) 3.5mm extrudate with scale bar.

Discussion

Tests 1-4 provided valuable information about the design of the extrusion die machine that could be used for further improvements to the project. Failure of the dies in these tests could be attributed mainly to the design of the dies. Although the 45° taper in two of the designs helps prevent materials loss, it makes the dies unusable in direct extrusion. Another point to consider is that the deformation and fractures could be due to the heat treatment of the dies. Even though the heat treatment improves the hardness of the material, the material in turn is subject to brittle failure during certain loadings. In these instances, the billet being pushed into the conical sides of the die provided an unexpected radial force that causes the dies to fracture. Similar to the Solidworks simulations, fracture of the dies originated in the inner radius and propagated throughout the die. With this information, changing the die design to either have a shorter taper or removing the taper altogether could provide more efficient dies. Deformation throughout the rest of the extrusion die machine was located primarily in the housing where the die, billet, and punch head collide, similar to the results in the Solidworks simulations. Additional deformation was also found in the base, where an indent was produced from the dies.

Although most of the tests were unsuccessful test 5 proves that the extrusion die machine has potential as a viable product. A 3.5mm extrudate was produced from test 5 while the 90° die remained intact. With the success of the test, the extrusion die machine now has proof of concept. However, there are some additional alterations that could be made to the design to improve its efficacy. The first improvement could be in the die design, which caused most of the tests to fail. If a 90° die, or a die that distributes the force across a larger surface than the surface of the 45° die, is used then the machine would provide better extrusion results. Additionally, a hydraulic press rated beyond 40 tons would also make extrusion easier. The extrusion process became difficult as the press reached it’s 40 ton capacity, so using a higher rated press would make reaching 36 metric tons easier. Heat treating the housing is another option that could improve the durability of the extrusion machine. The housing experienced more deformation than expected, so heat treating the housing to provide additional resistance to the forces could help improve the durability of the machine. However, another option could be to introduce a heating element to the extrusion die machine. By heating the components of the machine and the billet, the force needed to extrude the material is lowered. Any of these alterations could easily be made to the extrusion die machine to provide a more viable product for the Mathaudhu research group to use.

Conclusion

A senior design team was tasked with designing and building an extrusion die machine for the Mathaudhu research group at the University of California, Riverside. After being provided with some initial designs and materials, the team worked to prepare an extrusion machine capable of extruding aluminum and magnesium alloys. Following a literature review, parts such as the extrusion dies were drafted and designed. For this machine, three different dies were designed to be used interchangeably with the extrusion machine. Two 45° dies were designed, one with and one without back relief, to minimize material loss. Additionally, a third 90° die was designed to compare extrusion results with. Solidworks compression simulations were ran to determine potential points of deformation or failure in the design. These simulations identified locations of potential deformation or failure that could occur within the extrusion machine. In the 45° dies deformation or failure was likely to occur at the inner radius of the dies. For the rest of the assembly deformation was expected to occur in the housing surrounding the die, the ram and punch head, and in the housing surrounding the punch head. Out of the three simulations ran, the only test that showed low chances of deformation was in the simulation with the 90° die in the assembly. Following finalizing of the designs and production of the parts, the high-stress components of the assembly were subjected to heat treatment in an effort to improve durability. Thermal expansion calculations were necessary to anticipate deformation that could be produced by heat treatment. The potential deformation was then considered when making clearances and tolerances for the space between the machine’s parts. Once the high-stress parts were heat treated, testing was performed with the extrusion die machine to determine the viability of the product.

Testing of the extrusion die machine had varying results that could be used to expand on in the development of an improved extruder. Extrusion test results were consistent with the expected deformation and fracture from the Solidworks simulation. However, the extrusion test results were ultimately unfavorable. During the testing extrusion dies cracked and fractured, the housing experienced plastic deformation, and the base was indented. However, even though many of the extrusion tests were unsuccessful a proof of concept was achieved following the success of the extrusion through the 90° die. A 3.5mm Mg-3wt%Al extrudate was produced as a result of the final extrusion test. In an effort to improve the design, many different alterations could be made to the extrusion die machine to increase its viability. Some of these changes include heat treating the housing to minimize its deformation, making a tighter fit between the die and housing, using a heating element to lower the required extrusion force, or using a higher rated hydraulic press for extrusion. With the completion of this project, the Mathaudhu research group now has plans for an extrusion die machine that could be used with minor alterations to successfully extrude aluminum and magnesium.

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