MODELING THE INFLUENCE OF DESIGN GEOMETRY ON THE COINING PROCESS

By

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Abstract

A number of aspects of the coining process are investigated, both through experimentation using several types of tooling using blanks made of copper 110 or brass 260, and by developing and using a FEA model. Several relationships have been found which describe the effects of changing the type of coin blank or the geometry of the coining tooling on how much volume of the coin is formed at different forces.

The open-die bulk upsetting test was used to find the true stress and strain curves of both materials, and the ring test was used to determine the coefficient of friction. Coins were made over a large range of forces in order to test the general nature of how the diameter and design of a coin are formed. While the diameter begins to increase, the thickness of the coin reduces and material is pushed into the punch cavity, filling the design’s volume up rather linearly.

 Tests on the effects of changes in the wall angle were inconclusive. As the punch design depth increased the force requirement went down in a manner roughly inverse to the ratio of the increase in depth. Effects of coining with a punch on one side versus two sides were tested. Effects of the perimeter of the punch design showed that a longer perimeter actually reduced the forces required for thinner coins, a difference that got smaller as the coin blanks got thicker.

Blanks required 1.4 times the force to form than a coin half its thickness. A direct correlation of forming force to the yield stress of the material was expected but rather appeared to be related to the full nature of the true stress-strain curves.
The FEA model was able to match experimental results relatively closely, but only up to about 333.3 kN, the lowest force used for the bulk of the experimental samples. The FEA model provided a good look into what happens to the coin while it is under load and the mysteries of ghost coining were unveiled.
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Chapter 1

Introduction

Coining is an important metalworking process in which surface patterns are imprinted on to a metal part under compression. There are no accurate models of the coining process in the literature that can be used by a designer to estimate required forces, energy consumption, and greenhouse gas emissions associated with the process. Two models describing coining have been presented by Kalpakjian & Schmid [1] and Heinz Tschaetch [2], but are only capable of calculating a large range for the required forming forces based almost solely on the yield stress of the material and a coefficient related to whether the pattern is deep or shallow. Models of various other metal forming processes such as bulk upset forming and open and closed die forging have been developed in the past using methods such as the slab model, but nothing gives a comprehensive model based on the material properties and the specific geometry of the tooling.

The coining process is very well known as the process by which coins are made for use as money and has been the case for nearly three thousand years. However, especially in modern times, coining is just another metal forming process which can be used to create the final shape or finish on a wide range of products such as badges and other very small or delicate parts for the mechanical and electrical engineering industry. An example of a non-monetary coined product is shown in Figure 1-1.
The sizing of parts to give higher dimensional accuracy to an already pre-formed blank also falls under the category of coining, such as final drop-forging internal combustion engine connecting rods. The modern definition of coining is a precision stamping, cold-working, closed-die process which is used to put a final finish on metal surfaces. Typically three dies are used, two dies to form either of the faces (from here-on referred to as punches) and one die to form the edge. Preformed blanks (also known as planchets or flans) which are very near the finished size of the coin are used rather than randomly shaped scraps, meaning that the process only deforms small quantities of material near the surface of the part. Figure 1-2 shows two examples of some of the earliest known coins which were made by hammering scrap metal between two dies. These are on display in Watson Hall at Queen’s University, Kingston, ON.
Since the definition of coining has changed over time from simply a process used to make coins, the ancient Lydian coins shown in Figure 1-2 are not coins by the modern definition since they are made by open-die forging. Figure 1-3 shows an example of a modern copper coin made in our laboratory during my fourth year thesis project.
Note that compared to the ancient coins, the modern coins are round and formed very closely to the shape of the dies used, even showing marks near the word “Engineering” where the die was dropped prior to heat treating.

The primary objective of this work is to develop a reliable and comprehensive model for the coining process, based upon experimental work and a finite element analysis model, and to see how the model performs when applied to a process involving more complex parameters. Greater understanding of the coining process will allow further work to be conducted which could improve and optimize the process. Secondary objectives of this work are to develop a reliable system of sensors and controls for the hydraulic coin press which can easily be altered and used with similar processes on the same press, and to investigate the viability of using liquid lubrication in the coining process since it is not used due to technical limitations.

Performing this work and developing this model of the coining process will allow us to understand the process more completely and will allow designers to determine required forces, energy consumption, and greenhouse gas emissions in order to make the process more economical and environmentally friendly. Making an effort to reduce greenhouse gas emissions in relation to manufacturing processes is a continuing practice in our lab.
Chapter 2

Literature Review

The coining process has its origins in ancient Greece with the earliest examples coming from the Ephesus in the Anatolian Kingdom of Lydia, from around 700 B.C. Some other of the earliest coins have been found on Aegina Island and also made by the Mahajanapadas in of the Indo-Gangetic Plain in India. Both of these other findings date from around 700 B.C. so there is some debate about where coining was invented first. The first use of coins for money dates back to the 11th Century B.C. in ancient China, but these coins were cast rather than stamped.

Ancient coins were made from a small, sometimes heated, scrap of metal which was then placed between two dies on an anvil and struck with a hammer. Each die had carved into its end the inverse of the image that was to be struck into one face of the coin. By the modern definition of the coining process these ancient coins were not actually coins from a manufacturing point of view, since this ancient process used two open dies and was sometimes done hot.

As stated previously, very few published works on the topic of coining can be found, since research performed by mints is proprietary and kept secret. Notable published examples are Chapter 8 of “Metal Forming practice” by Heinz Tschaetsch [2], Chapter 17 of “Mechanics of Plastic Deformation in Metal Processing” by Erich G. Thomsen, Charles T. Yang, and Shiro Kobayashi [3], and Section 14.4 of “Manufacturing Engineering and Technology” by Serope Kalpakjian and Steven R. Schmid [1].
2.1 Method of Coining

In the modern coining process, three close fitting dies are used, no material is allowed to escape, and no burr is created on the edges of the part. A pre-formed blank which fits snugly within the dies is typically used in order to obtain higher dimensional accuracy on the finished part.

Initially hammers and anvils were used to manually form coins using hand carved dies, then around the 18th century the screw press came into use which allowed higher forming forces and a more controlled application of force. Modern coin presses are either electric, or more commonly, hydraulic and are fully controlled for excellent quality control.

To form a coin, a blank is placed within the die and between the two punches. The punches are then squeezed together until the full forming force is reached and the coin is fully formed to the dies, then the finished coin is ejected from the die with its final surface finish. Typically, to produce coins for use as money, a fairly high strain rate is used. The effects of strain rate on the coining process will not be studied here but it will be kept consistent between different tests.

Although it can reduce the required force to produce a coin [3], lubrication is not used for coining. When a coin is being formed, the metal is compressed until the impression of the die is fully imprinted onto the blank. Since any liquid lubrication is incompressible it will fill up cavities in the die, preventing the metal from flowing there, and introduce defects to the formed surface giving the coin a mottled or pitted surface. However, as will be discussed in Section
Chapter 5, this work shows that liquid lubrication in coining may be feasible if a small amount of liquid lubricant is finely atomized onto the surface of the punches beforehand. Another study suggests that superimposed vibration during the coining process may be useful for decreasing surface friction without introducing the defects caused by liquid lubricants [3], although with an increase in equipment costs. An interesting phenomenon was observed in these experiments where a considerable depression was made on the face which was being acted upon by a flat-faced die. This “coring defect” very pronounced with the samples affected with vibrations, and even more so on blanks with a lower ratio of initial thickness to diameter.

2.2 Forming Force

Although material displacement is relatively small, coining typically requires very high forming forces, primarily as “the result of friction between the blank and the forming tools in restraining the metal from conforming to the surface irregularities of punch and die” [3]. The forming force is what is required in order to fill 100% of the die cavities with the blank material. Studying the manner in which different geometry and materials affect the forming force is the major focus of this thesis.

Very little work is published that can help predict required forming forces, and when there is, usually coefficients are listed for a handful of materials with no explanation of their meaning or derivation. Kalpakjian & Schmid [1] give the required forging force as:

\[ F = k \cdot Y_f \cdot A \]  

(2-1)
Where \( Y_f \) is the flow stress of the material at the forming temperature, \( A \) is the projected area of the forging, and \( k \) is a coefficient obtained from a given table. For the coefficient \( k \), coining falls under the category of “simple shapes, without flash” and has a range of values from 3 to 5.

Tschaetch [2] gives a similar explanation where the max coining force is:

\[
F = k_r \cdot A
\]  

(2-2)

This force is based solely on the coefficient \( k_r \), a value range given for various metals, and punch area. It was found that forming forces calculated using Equation 2-2 will generally be lower than those calculated using Equation 2-1 because of the different coefficients used. For example, using values from Equation 2-1, the required forming force range at the start of forming (it will increase because the flow stress increases with strain) found for annealed copper using Equation 2-1 is (945 to 1575)A, while for Equation 2-2 the max coining force is given to be (800-1000)A for soft copper, where \( A \) is the coin cross-sectional area.

Additionally, Tschaetsch suggests that the work required to form a coin is:

\[
W = F \cdot h \cdot x
\]

Where \( x \) is a process factor, equal to about 0.5, and the punch displacement, \( h \), is:

\[
h = \frac{V_t}{A_{proj}}\frac{1}{8}
\]
Where \( V_i \) is the volume of the impression and \( A_{proj} \) is the projected area of the coined part. This relationship was found empirically.

2.3 Effects of Material and Geometry

Besides coefficients given for different materials in a table, the only material property that is mentioned as having an effect on the forming force is the flow stress of the material. Since the flow stress is the instantaneous stress which is required to continue deforming a strain hardening material, there is good reason to believe it plays an important role in the required forming force for coining, up until at least the point where the blank material is 100% fully formed to the dies. At this point the material is incompressible.

As mentioned in [3], experiments by Pugh used blanks made of commercially pure lead as well as commercially pure aluminum and found that as the ratio of the initial blank thickness to diameter \( (h_0/d_0) \) decreased, the forming force required increased significantly. The test blanks were all 1 inch in diameter and consisted of three initial thicknesses. Figure 2-1 shows Bocharov’s results for the pure lead samples, clearly demonstrating that to achieve a 100% degree of coining the 0.250”, 0.125”, and 0.062” thick samples require 13000 psi, 17500 psi, and 34500 psi, respectively. Each thickness sample set showed the same trends, in that a great deal of pressure is required to form about the first 25%, and that not much more pressure is needed until about 80%, where the amount of pressure required to get to 100% rises dramatically. The same trends were also seen with the commercially pure aluminum samples. Figure 2-1 also shows what is expected
to be a typical load-stroke curve for the coining process; as the applied force begins to increase, the deformation of the blank progresses slowly until the material begins to yield, the coin then deforms quicker as the force increases a bit more until the force finally starts to increase rapidly as the coin approaches being fully formed.

Figure 2-1: Average coining pressures as a function of degree of coining $b/b_0$ for commercially pure lead. After Bocharov et al. [3]
The areas in Figure 2-1 which are filled in with a zig-zag pattern indicate the amplitude of a superimposed low-frequency alternation in the applied load as previously discussed in Section 2.1.

2.4 Finite Element Analysis

Finite element analysis (FEA) is a useful tool used for finding numerical solutions for field problems, which are described by the spatial distribution of one or more dependant variables. Field problems are mathematically described by differential equations or integral expressions and thus are typically very complicated to solve for even the simplest of shapes, and outright impossible for more complicated problems.

FEA provides an approximate solution to a field problem by breaking it up into many small, easier to solve, elements. Each element of the structure has a finite size and has only one value for the field quantity associated with each dependant variable, such as temperature or stress. This makes the problem much easier to solve than with calculus which would use infinitesimally sized elements and have a more complicated variation in the field quantity. Elements are connected at points called nodes which each will have spatial quantities associated with it, such as displacement. The assembly of all the elements into the defined body of the field problem is called a mesh.
In the simplest form, each element is a square (2D problems) or a cube (3D problems) all of which are connected at their corners by nodes. Each node and element has equations associated with it which must be calculated simultaneously and iteratively until steady state is reached. With the smallest of problems there can easily be hundreds or thousands of equations, which means that computers are a necessity for even the most basic of FEA and that considerable computation time is needed. More complex problems (such as non-linear problems where there is transient loading, large deformations, or plasticity) require more steady state steps to be calculated between the initial and final conditions, thus requiring even more computational time.

The finite element mesh is numerically represented by a system of algebraic equations which is solved for values of the field quantity at each node. Then, using assumptions about the element, the nodal solutions are used to determine the field quantity of the element. Since FEA is used to solve a complicated variation in the field quantity by representing it as several individual values, each occupying a finite space, this means that FEA inherently contains errors and thus is only able to find an approximation of the actual solution. However, with careful planning and execution of FEA, this approximation can be extremely close to the reality.

A visualization of FEA being applied to open-die upset forming for solid structural analysis is shown in Figure 2-2.
Figure 2-2 shows a finite element mesh in the initial and final configurations corresponding to a 26.67% height reduction and showing contours of effective plastic strain. The first image shows the undeformed finite mesh made up of quadrilateral elements; the second image shows the final deformed shape of the elements along with an outline of the original mesh for reference; the third image shows the outline of the final deformed shape containing contours of the Von Mises stress associated with each element using Gaussian quadrature curve fitting. The mesh utilizes symmetry about the horizontal axis, and is axisymmetric about the vertical axis as shown on the initial mesh configuration. Contours of the effective plastic strain are also displayed. One quarter of the specimen is actually modeled and the mesh consists of 100 elements. The information obtained from FEA solutions can be used to aid the engineer in altering a design or improving the process.
FEA is very useful because it is easily multidisciplinary; it can be applied to any field problem such as heat transfer and stress analysis while only requiring the nodal equations changed to suit the problem. FEA also has no restrictions on field geometry, boundary conditions, material properties, or combinations of components such as bars, beams, or cables. The approximate solution can be improved by creating meshes with greater mesh densities and by refining the mesh even further around areas of interest, that is, areas with steeper changes in field quantities.

FEA is a useful tool which can be used to analyze and better understand a real-world problem. The model can be validated by comparing the model results to real-world experimental results, and then the model can be used to predict the real-world system response due to different inputs. FEA is also extremely useful in the development of new products. Product concepts may first be developed using a computer aided design (CAD) package, then can be analyzed using FEA to virtually test the product to see if it performs as designed. Virtual FEA tests of solid structures allow detailed visualization of deformations and stresses in the product, allowing problems with the design to be spotted early and safely. This also allows an effective design process to happen faster because the design can iteratively be constructed, tested, and refined many more times, thus reducing the need to manufacture several prototypes for testing, and saving wasted time and resources as well.

By connecting several elements together by their edges (or faces in 3D) we can construct a much larger and more complicated geometry of a real-world problem. This only requires that the same equations need to be solved for each element, but they must be performed simultaneously.
Advantages of FEA are that it can readily handle very complex geometries, a wide variety of engineering problems (solid mechanics, dynamics, heat problems, fluids, electrostatic problems), can handle complex restraints, and can handle complex loading (nodal load (point load), element loading (pressure force), time or frequency dependant loading.

Disadvantages are that a general closed-form solution is not produced, which would allow examination of the system response to changes in various parameters, FEA only obtains “approximate” solutions due to its discretization nature as well as calculation errors, and mistakes by users can be fatal and difficult to identify. It is the responsibility of the user to fully understand the problem they are trying to solve as well as the FEA technology in order to produce results with confidence. Fancy graphs can easily be produced by any model no matter if it is good or bad.

To study coining using FEA, the metal blank (considered a continuum on the scale we are operating at) is broken down into elements and assigned the non-linear properties of the metal such as the true stress-strain curves under compression. Elements capable of dealing with a change in contact status are applied at contact boundaries, then the applied force is increased to an amount where an intermediate steady state step solution is found, then repeated until the full force is applied then released and final solution is reached. From this solution the field quantities of stress and displacement distributions are found and utilized.
Chapter 3

Design of Experimental Equipment

The coining press being used consists of a hydraulic press fitted with hardened steel tooling. Sensors for force and position are connected to a computer running LabVIEW which controls the operation of the press as well as logs experimental data. Standalone data logging sensors are used to obtain the current and voltage usage of the press during the tests.

A considerable amount of time was spent on designing and installing a new control system for the coining press. The press had previously been used for research into power metallurgy; hence the sensors and control system characteristics were different. The new press control system which was developed is described in Section 3.5.1.

The existing press was originally designed using imperial units, as was the load cell used for force calibration. For this project, the new parts, control system, and measurement will also use imperial units for simplicity’s sake, but all results are presented using SI units.

3.1 Hydraulic Press and Support Structure

The experimental setup uses a dual-action type of hydraulic press which features two linear hydraulic actuators mounted with a vertical axis of motion, with one hydraulic cylinder on the top and an opposing cylinder on the bottom. The cylinders are bolted to rigid steel substructures,
designed with a minimum safety factor of 5 against yielding, and constructed from welded 3”x3”x3/8” and 6”x4”x3/8” rectangular sections and 1” flat plate. The flat plate provides the mounting of a hydraulic cylinder, and holes through the rectangular sections provide the mounting for the strain posts. The upper and lower press substructures provide negligible deflection due to bending between the mounted cylinders and the strain posts.

The four strain posts, making up the mechanical core of the press load cell, are made from standard 2¾” diameter 1045 carbon steel. No machining was needed apart from threading the ends.

Figure 3-1 shows the main assembly of the press structure, showing the upper and lower hydraulic cylinders (and their piston rods to which tooling is attached), the upper and lower press substructures, and the four strain posts.
The lower press substructure also attaches the press assembly on to a wheeled cart to support the press as well as allowing it to be semi-portable. The wheeled cart and its attachment is not shown in Figure 3-2 for clarity.

The press is powered by a 25 hp (18.65 kW) electric motor driving a hydraulic vane pump which gives the press a total maximum capacity of approximately 70 tons (624 kN). Hydraulic fluid
flow to either ram is managed by two Moog series 172 servo valves. A schematic of the press’s hydraulic circuit is shown in Figure 3-2.

![Figure 3-2: Schematic of the hydraulic circuit used.](image)

### 3.2 Tooling

The coining process requires non-deformable tooling which make up the three forming faces; a top punch which forms the top side of the coin, a bottom punch which forms the bottom side of the coin, and a die which contains and forms the sides of the coin. Each coining punch is made up of three parts in order to allow quick and easy changes in the design geometry as well as making
the punch easier and cheaper to make. Each punch consists of the main punch body, a collar which allows fastening of the main punch body to a hydraulic piston, and an interchangeable punch head which is pressed on by the punch. Examples of these parts are shown in Figure 3-3. All tooling for the coin press is designed in inches because the die, other existing tooling, and all tooling tolerances was originally designed and specified in inches. Conversion to SI units for various calculations is performed at the end.

![Figure 3-3: Coin tooling: upper punch with collar and 2 punch heads.](image)

The main punch body has a conical flange at the base which mates with a conical surface on the inside of the collar. Previous punches used with this press have either been one solid punch, or made up of a punch and a collar which have rectangular flanges. Previously, after several loading
cycles, the previous punch designs have shown a tendency to loosen the collar’s bolts as well as shifting laterally, potentially causing the punch to contact the edge of the die with great force.

The new, two part conical flange design was chosen to address the issues of loosening bolts and lateral shifting. While the main punch body is under compression force is transferred directly to the hydraulic ram, ensuring no force transfers through the bolted collar, deforming it and loosening the bolts over time. The cone shape then helps the punch to remain centered when the compression force is removed, as long and the collar bolts are pre-tensioned.

Interchangeable punch heads are used so that several different design geometries can quickly and easily be switched out between experimental runs. The punch heads are designed so each set is able to vary one single geometry design variable, while keeping all other design parameters identical, in order to properly develop an experimental model. The punch heads are created from every combination of the options outlined in Table 3-1.

Table 3-1: Punch head design geometry options.

<table>
<thead>
<tr>
<th>Geometry Category</th>
<th>Option #1</th>
<th>Option #2</th>
<th>Option #3</th>
<th>Option #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>0.005”</td>
<td>0.010”</td>
<td>0.015”</td>
<td>0.020”</td>
</tr>
<tr>
<td>Wall Angle</td>
<td>0°</td>
<td>15°</td>
<td>30°</td>
<td>45°</td>
</tr>
<tr>
<td>Shape</td>
<td>Circle</td>
<td>Ring</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The design, dimensions, and variables of the punch heads are shown in Figure 3-4 for the circle shaped punch heads, and in Figure 3-5 for the ring shaped punch heads.
Figure 3-4: Dimensions and variables for Circle shaped punch heads.
The design dimensions of the punch heads are sized so all heads of equal depth also have equal design volumes, independent of the wall angle and design shape. The punch heads design variables “wall angle” and “depth” are created according to Table 3-1, d2 is kept constant at 0.250 inches, while D1 is sized appropriately in order to maintain the same volume between punches. Different sets of punch heads are used to isolate the effects on forming force caused by design depth, design wall angle, and design perimeter (using two design shapes, circle and ring).
Plain, flat-ground punches are also used to test the effects of having a punch with a design on one side or both.

Each set of punch heads consists of a single option which is constant for the set, and one punch head for all possible combinations of the remaining choices, yielding a total of 32 punch heads each with a unique geometry. Wall angles apart from 0° are not used on punches with a depth of 0.005” due to difficulty in machining the designs and the possibility that effects from different wall angles would be too small to measure. Flat punches and matching pairs of punch heads 0.010” and 0.020” deep were made to add the option of using one or two punch heads.

M2 tool steel was chosen as for the punch material in consultation with a machine shop (Kingston Heading Service) which specializes in designing and manufacturing tools for heading. All punches and punch heads are heat treated to maximum hardness (Rockwell C61-63) by preheating to 1450° F, then heating rapidly from 1450° F to 2200° F, holding for 3 – 5 minutes and followed by quenching. Punch heads are finished off by grinding to a diameter of 0.9967 ± 0.0002”.

The previously manufactured die provides the cylindrical surface for the coining process as well as guidance and support for the punches and punch heads. The die is made from steel with a shrink fitted hollow-cylinder insert which forms the surface which contacts the coin material. The insert is made from C11 tungsten carbide, with a wall thickness 0.250”, and ground to an inside diameter of 0.9980 ± 0.0002”. The insert also has a slight radius on the inner edge of both ends to aid the punches in entering the die in the case of a slight misalignment.
The assembly of the coining tooling is shown in Figure 3-6. One coining punch (shown in red in Figure 3-6) is affixed to the face of each hydraulic piston and the die (yellow) is bolted to the flat table part of the press’s lower substructure. 3/16” thick steel plate displacement arms (blue) are bolted to each punch collar so they move along with the hydraulic ram, and aligned to press against the end of either spring-loaded displacement sensor to communicate the axial positions of each ram. Two punch heads (green) are inserted into the die between the punches with the coin blank between the heads.

Figure 3-6: Cross section of assembled coining tooling and press.
3.3 Sensors and Calibration

3.3.1 Position Measurement

The positions of the top and bottom punches are measured using linear potentiometers which are actuated upon by the steel plate displacement arms attached to either hydraulic piston as seen in Figure 3-6. A potentiometer with a 10mm range measures the top ram when it is in place during coining and a 100mm range linear potentiometer is used to measure the position of the bottom punch at all times since it must move over a large range and in a controlled manner during the process. Linear variable differential transformers (LVDTs) were also evaluated as possible linear position sensors due to their repeatability and lack of friction but were turned down because the length of sensor needed would not fit easily inside the press, so more compact linear potentiometers were selected. Previous experiments using this hydraulic press used large LVDTs mounted outside of the press structure and connected to either ram by long steel arms. These arms would vibrate significantly while moving and were unsuitable for the fine measurements required for coining.

Calibration of the linear potentiometers and their signal conditioners (Novotechnik model MUP 100-1) was performed by mounting a linear potentiometer and a micrometer head to a stiff steel plate while LabVIEW was used to monitor the potentiometer’s voltage output. As per the instructions for the MUP-100-1 signal conditioners, the potentiometer is set to a position of 0.000 mm using the micrometer head followed by adjusting the signal conditioner’s low setting using a screwdriver until the output from the linear potentiometer is as close to 0.000 V as easily possible. The position of the sensor is then increased exactly to the potentiometers maximum
throw (10 mm or 100 mm) and the signal conditioner’s high setting is then adjusted until the sensor output is as close to 10.000 V as possible. This process is repeated until the linear potentiometer gives an output with repeatability to 0.000 V and 10.000 V within 0.001 V.

With both signal conditioners adjusted to their specific linear potentiometer sensor, a reading of the voltage output is taken at several positions throughout the sensor’s throw in order to get the full calibration curves between voltage output and position which will be used in the LabVIEW controller. The calibration curves for the 10 mm and 100 mm linear position sensors are shown in Figure 3-7 and Figure 3-9.

\[
y = -0.002x^2 + 1.0204x + 0.0015
\]
\[
R^2 = 1
\]

Figure 3-7: Data and calibration curve for 10 mm sensor.

The resolution of the linear potentiometers is 1 mV; using a 10 V signal this corresponds to position resolutions of 0.001 mm for the 10 mm sensor, and 0.01 mm for the 100 mm sensor.
Regression analysis performed on the calibration data produced a linear as well as a second-order polynomial curve, each with a “perfect” fit of $R^2 = 1$. A graph of the difference (residual data) between the sensor output and the linear and polynomial calibration curves, with respect to the displacement of the sensor itself, is shown in Figure 3-8.

![Figure 3-8: Residual position data for 10 mm sensor.](image)

This graph shows that the polynomial curve is actually a better fit to the sensor output than the linear calibration curve, thus, the 2nd order polynomial curve was chosen as the 10 mm sensor’s calibration curve. Residuals from the polynomial curve are less overall as well as more random. The residuals from the linear relationship form a definite curve, indicating possible irregularities in the sensor system which cause the voltage output to be lower than expected at either position extreme and higher than expected in the mid position range. The same was found for the 100 mm sensor as shown below.
Figure 3-9 shows the calibration curve and data relevant to the 100 mm linear displacement sensor. Just as with the 10 mm sensor, a linear as well as a 2\textsuperscript{nd} order polynomial relationship were found, both with a perfect fit of $R^2 = 1$.

![Calibration Curve](image)

Figure 3-9: Data and calibration curve for 100 mm sensor.

Residuals using linear and polynomial relationships found for the 100 mm sensor are shown in Figure 3-10. The same trend in the residual data using a linear relationship that was found with the 10 mm sensor is also found with the 100 mm sensor (although reversed) therefore the 2\textsuperscript{nd} order polynomial relationship which was found is used as the calibration curve.
Three of the five residuals measured are less than the sensors resolution of 0.01 mm. The calibration curves to be used in LabVIEW for the linear sensors are thus:

\[
10 \text{ mm Sensor: } \text{Position (mm)} = -0.002V^2 + 1.0204V + 0.0015 \quad (3-1)
\]

\[
100 \text{ mm Sensor: } \text{Position (mm)} = 0.002V^2 + 9.9784V + 0.002 \quad (3-2)
\]

### 3.3.2 Force Measurement

During the original construction of the press [5], it was decided to go with a design which integrated a load cell into the load bearing posts of the press. This design was chosen because traditional load cells are quite bulky and expensive, especially ones which are high capacity.
Their physical size would be problematic due to the size limitation within the press, and they would not allow different tooling to be easily attached. The alternative chosen was to attach strain gauges onto the four posts connecting the press upper and lower substructures in order to make the whole press a load cell in itself, this technique for force measurement is similar to that used by Jeswiet [6] in the measurement of normal force during rolling. This method has the advantage that it is very compact and does not take away any space within the small confines of the press, and that it is integral to the press so it allows for great freedom in the design and accessibility of any tooling installed. However, it does have the disadvantage that it requires calibration after installation of the strain gauges, whereas conventional load cells usually come professionally calibrated.

The physical mounting and electrical configuration of the strain gauges is such that only the axial force in the posts is measured, bending forces are cancelled out and the wiring negates sensitivity to temperature. This also results in the same magnitude of force being measured independent of where within the press it is applied, thus, alignment of the force with the center of the press is not necessary.

Force measurement within the press is measured with strain gauges mounted to each of the four strain posts. Each post has two pairs of strain gauges mounted midway up the post, with two mounted on the innermost surface of the post facing the center of the press, and two mounted on the opposite side facing away from the center, as shown in Figure 3-11 where each pair of gauges represented by a black rectangle.
Each pair of strain gauges consists of a strain gauge aligned parallel to the axis of the post and one perpendicular to the axis. The positioning, orientation, and numbering of the strain gauges on the posts are illustrated in Figure 3-12.
The only load we are concerned with for force measurement in the press is the axial load, so some way of eliminating the effects caused by any bending in the posts or temperature change is required. This is achieved by connecting the strain gauges in a normal full Wheatstone bridge configuration, shown in Figure 3-13.
Figure 3-13: Full Wheatstone bridge configuration used for axial force measurement.

Four strain gauges wired in series make up each leg of the Wheatstone bridge, one strain gauge from each post, each with matching physical position and orientation on the post. The reference $R_{ij}$ refers to each strain gauge number where $i$ is the position of the strain gauges on the post (as well as the bridge leg it belongs to), and $j$ is the post number.
The bridge illustrated in Figure 3-13 has the following relationship:

\[ e_0 = \frac{V_i}{4R} (\Delta R_1 - \nu \Delta R_1 + \Delta R_3 - \nu \Delta R_3) \]  

(3-3)

Where:

- \( e_0 \) = bridge output voltage
- \( V_i \) = bridge excitation voltage
- \( R \) = single unstressed strain gauge resistance
- \( \Delta R_i \) = total change in resistance in bridge leg \( i \)
- \( \nu \) = Poisson’s ratio of the post material

Gauge factor, \( F \), is defined as:

\[ F = \frac{\Delta R_a}{R} \frac{1}{\varepsilon} \]

Now, expanding Equation 3-3 and rewriting it in terms of the gauge factor we get:

\[ e_0 = \frac{V_i (1-\nu)F}{2} (\varepsilon_{11} + \varepsilon_{12} + \varepsilon_{13} + \varepsilon_{14}) \]  

(3-4)

Twelve strain terms cancel each other out, leaving four strain terms corresponding to four specific strain gauges using the numbering system shown in Figure 3-13. Equation 3-4 indicates that the bridge output voltage is linearly proportional to strain. This allows a relationship between press
force and voltage to be easily formed when the bridge is calibrated with another load cell of lower capacity. The mechanical relationship between press force and strain is also assumed to be linear since strains in the posts are relatively small.

The strain gauge bridge is connected to a Measurements Group model 2310 signal conditioning amplifier which supplies an excitation of 1.4 V and also receives, amplifies, and filters the output voltage before passing it to the LabVIEW DAQ. A gain of 4 and a gain factor of 1000 are applied to the bridge output voltage as well as passing through a 10,000 Hz filter.

The press strain gauge bridge was calibrated using a 5 ton (10 000lb_f) conventional, pre-made and pre-calibrated load cell. The relationship between the load cell and applied force is known to be 2 \( \mu \text{V} / \text{lb}_f \). The load cell was placed between the hydraulic pistons and the piston force applied to the load cell was slowly increased from 0 \( \text{lb}_f \) to a maximum of 10000 \( \text{lb}_f \) while the load cell’s output voltage and the press’s strain gauge bridge output voltage were logged using LabVIEW.

![Figure 3-14: Voltage data and calibration curve of post load cell.](image)
This was repeated three times, the 2 $\mu$V / lb$f$ load cell relationship was substituted, and the press’s relationship between press force and bridge output voltage was found to be:

\[ V_{Posts} = 5.2149V_{Load\;Cell} \]  \hspace{1cm} (3-5)

\[ V_{Load\;Cell} = Force \times \frac{2\mu V}{lb_f} \]  \hspace{1cm} (3-6)

\[ V_{Posts} = 1.04298 \times 10^{-5}Force \]  \hspace{1cm} (3-7)

\[ Force = 95879.1 \times V_{Posts} \pm 156.1\;lb_f \; (95\%) \]  \hspace{1cm} (3-8)

\[ Force = 426491.4 \times V_{Posts} \pm 694.6\;N \; (95\%) \]  \hspace{1cm} (3-9)

Error was found using regression analysis of a steady force signal.

### 3.4 AC Current and Voltage

The AC current and voltage consumed by the press during operation was measured using three Omega OM-PLCV AC power data loggers which measure real power. The data loggers were set to their maximum logging rate of 1 data point per second with one data logger dedicated to each phase of the supply power. Each data logger uses a current clamp around the supply wire for one phase, and a pair of alligator clips to measure the voltage between the phase’s fuse and ground.
With this setup we can measure the ancillary power required by the press, that is, the power which is consumed by the press while it is idle and not supplying flow to either hydraulic cylinder. In addition, real power use is measured during the coining process. The ancillary power is subtracted out to find the electrical power requirements for different coining setups, and can be compared to corresponding power requirements calculated based upon position and force measurements collected from the LabVIEW DAQ.

Measurements of these power requirements allow a model to be made which could be used to predict the greenhouse gas emissions associated with the process of making coins and run the machinery. Ultimately lowering greenhouse gas emissions is always a goal in our lab which we aim to apply to all forms of metal forming.

3.5 Press Controller and DAQ

The operation of the coin press is controlled by a laptop running LabVIEW which also serves to log data for press force as well as the position of the upper and lower rams. National Instruments LabVIEW 8.6.1 software package is used in conjunction with National Instruments DAQ hardware (Multifunction DAQ USB-6225 and Shielded Connector Block BNC-2110). Although initially it was planned to use a double-rejection negative feedback controller, control of the press was achieved using a PID controller. For further information, a brief discussion of control theory and LabVIEW are included in Appendix A.
3.5.1 Hydraulic Press Control System

A new control system has been designed using LabVIEW and installed on the press. Previously, the press had been used for experiments in power metallurgy, was mainly human-operated, and had no precise control over the individual rams. The new control system adds the ability to continuously measure the position of both rams, uses position feedback to control ram position, and has nearly all of the process automated so the process is easily controlled and repeatable.

The control system for the press is based on the software package LabVIEW 8.6. The system both controls the press and functions as the data acquisition system during experiments. User inputs include the maximum force goal to be used for each test, as well as controls to progress through the pressing cycle. The LabVIEW system controls the hydraulic ram movements using analog voltage outputs to either servo valve, uses feedback from the linear potentiometers to control ram position, and controls press force based on feedback from the strain gauges on the posts. During experimenting, LabVIEW collects the upper and lower ram positions as well as press force and writes this data to text files for later analysis. Data logs of AC current and voltage are acquired separately due to the nature of the sensors.

The hydraulic coin press control system uses ram position and force inputs (voltage), as well as minimal user inputs, to execute six distinct stages of the coining process by outputting analog voltage signals to either rams servo-valves. Figure 3-15 shows the control system’s overall architecture, visualizing inputs, outputs, data flow, and logic organization.
Figure 3-15: Overall control system architecture.
The dashed box represents the continuous loop system which runs to make each coin, indicating the initial state and desired maximum coining force are set each time before the loop runs. Blue boxes are DAQ voltage inputs or outputs, green boxes indicate user inputs, and the grey box is the controller’s logic center, a “state machine”. The logic contained and used in the state machine switches between the six possible states based upon a state signal output from the previous state, causing the press to move through several very distinct phases, from being ready for the user to insert a coin blank, to pressing the coin, to finally ejecting the coin out of the die for the user to remove, until the continuous loop is stopped. Three user inputs are included: “Go to next state” allows the user to change the state manually for certain coining phases (such as after loading a blank by hand), “abort operation” skips to the retract state in the case that an unforeseen or dangerous situation arises, and “speed up” will increase the speed at which top ram travels during certain states. Data is recorded each time the loop is started until it is stopped, and then is saved as a text file under a unique coin ID. Figure 3-16 shows the LabVIEW block diagram which was represented simply in Figure 3-15.
Figure 3-16 (Part 1): LabVIEW coin press controller block diagram. (“Position” button appears on both parts for reference).
Figure 3-16 (Part 2): LabVIEW coin press controller block diagram.
The six states of the coining process are: Ready, Position, Coin, Deforce, Retract, and Eject. From Figure 3-17 to Figure 3-22a diagrams of each state of the state machine, one visualizing its basic architecture (left side of all Figures) and one the LabVIEW block diagram (right side of all Figures). Each architecture diagram and block diagram can be inserted into Figure 3-15 and Figure 3-16 to visualize the entire control program during each state.

The “Eject” State uses a negative feedback PID controller to hold the lower punch in position sticking slightly out the top of the die, ready to accept a blank. Inputs to the PID are position feedback from the 100 mm linear potentiometer, and the “eject position” set point. A zero voltage is sent to the upper ram so it does not move during this state, and a button allows the user to change to the “Ready” state after a coin blank is loaded by hand. The initial state of the continuous loop is always automatically set to “Eject” since it is the state the coin press is left in at the end of a standard coining phase, meaning no physical movement of the press should take place on startup.

Figure 3-17: “Eject” state. Architecture (L), LabVIEW Block Diagram (R).
When the user advances the controller to the “Ready” state, the lower punch is drawn down into the die along with the blank, and held there with a PID controller using the inputs of position feedback from the 100 mm linear potentiometer, and the “coining position” set point. As in the “Eject” state, a zero voltage is sent to the upper ram to keep it still, and a button allows the user to change to the “Position” state.

Figure 3-18: “Ready” state. Architecture (L), LabVIEW Block Diagram (R).

When the user advances to the “Position” state the upper punch moves downward into the die to initialize contact with the blank. A PID controller continues to hold the lower punch at the “coining position” set point. A small positive signal (0.2 V) is sent to the upper ram to move it downward, while the user input “Speed Up” increases the upper ram’s speed by sending a larger voltage (0.75 V). Once the force feedback reaches 500 lb, indicating the upper punch has contacted the blank, the controller automatically advances to the “Coin” state.
Using the controller to switch to the “Coin” phase automates the process of increasing the force applied to the coin, eliminating human error to ensure factors such as strain rate and maximum force are consistent across all samples. To continually increase applied force, a linearly increasing voltage signal is sent to both rams; directly to the top ram to push downwards, and multiplied by a negative factor to push the lower ram upwards. Strain rate is unable to be directly controlled with the current controller but can be altered indirectly by changing the manner in which the applied voltage increases over time. Since a voltage sent to a servo valve controls hydraulic cylinder pressure, a negative factor is used to balance the ram’s forces caused by different hydraulic cylinder diameters so the punches do not move appreciably inside the die. When the press force reaches the “Desired Max Force”, a signal is sent to change the state to “Deforce”. The controller does tend to overshoot the desired max force and is related to the strain rate at the maximum force as well as the reaction time of the controller. The force overshoots by an average of 14.25 kN at 333.6 kN max force, 8.75 kN at 444.8 kN, and 4.25 kN at 556.0 kN. Pressing the abort button will also advance the state machine.
Ideally the “Coin” state would use automatic controls with force and position feedback in order to precisely control coining position as well as the applied force according to a predetermined strain rate profile. Due to the complexity and difficulties encountered programming the double error rejection feedback controller in LabVIEW required to perform these functions, this approach was not used.

![Figure 3-20: “Coin” state. Architecture (L), LabVIEW Block Diagram (R).](image)

The “Deforce” state relieves the forces applied to the coin in a controlled manner by moving the upper ram up and the lower ram down using a steady signal of -0.15 V and 0.15 V respectively. Similar to the “Position” state, when the press force falls before 500 lb, a signal is sent to advance the state machine.
The “Retract” state holds the lower punch and the coin inside the die while the upper punch moves upwards. Again, a PID controller holds the lower punch at the “Coining Position” set point while a small negative voltage (-0.5 V) is sent to the upper ram to move it up. The user can press the “Speed Up” button to increase the signal to -1.0 V to move the ram faster, and must press another button to advance to the “Eject” state. This phase of the coining process is dependent on the user ensuring the top punch has moved up high enough so contact will not be made between punches before moving on.
The final phase of the coining process is the “Eject” state, where the lower punch moves upward to push the finished coin out the top of the die. To finish the process, power to the press is shut off, the coin is removed manually to be measured later, and the data file is saved.

The LabVIEW front panel, as shown in Figure 3-23, is what the user sees and interacts with during the coining process. Several diagrams, charts, and numerical readouts are shown on the front panel but are only used for diagnostic purposes and are not required for press operation. When the coining program is started, a window prompts the user to enter the max force for the test in lb.

Figure 3-22: “Retract” state. Architecture (L), LabVIEW Block Diagram (R).
Figure 3-23 (Part 1): LabVIEW coin press controller front panel. Lower 2 graphs are shown on both parts for reference.
Figure 3-23 (Part 2): LabVIEW coin press controller front panel.
The items on the controller front panel, from left to right:

- “Coining Position” and “Eject Position” are the position set points for the PID controllers for the lower ram and are only adjusted if the tooling has been removed.
- “Requested Force” displays the user-entered maximum force for the test, the green light comes on indicating when the force is reached.
- Optional user buttons.
  - “Stop Rams” sends a zero voltage to both rams to stop movement in an emergency.
  - “Speed Up” increases the voltage to the upper ram in the “Position” and “Retract” states.
  - “Abort Coining” skips directly to the “Retract” state in the case of an emergency.
- “Top Position” and “Bottom Position” are fill-bars which show the position of each position sensor within their useable range as well as graphs which show the positions with an auto scaled y axis.
- “Current State” displays the name of which state the controller is currently in.
- State changing user buttons, these are the only front panel items which are required to press operation.
  - “Lower Blank” advances controller state from “Eject” to “Ready”.
  - “Position” advances controller state from “Ready” to “Position”.
  - “Eject” advances controller state from “Retract” to “Eject”.
- “Top Ram Applied V” and “Bottom Ram Applied V” each graph the controller output voltages to the upper and lower rams.
- “Press Force” graphs the total press force in lb₉.

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3.6 FEA Coining Model

An FEA model was developed using ANSYS in order to produce reliable computer simulations of the coining process. All modeling, solving, and post-processing of the FEA model was performed using ANSYS version 11 and utilized the journal file shown in Appendix C. Investigating the coining process using a FEA model alongside experimental results allows for the accuracy of the FEA model to be validated so the model can be easily modified to test several different geometries to explore the process further, without the need to manufacture expensive tooling.

The punch heads used for experimental testing were designed with an axisymmetric geometry to impress into the coin in order to avoid effects of geometry directionality. The FEA model is made drastically simpler by taking advantage of this axisymmetry, allowing a quicker solving 2-D model to be used. A cross section of the coin blank and tooling to be modeled is shown in Figure 3-24.
Figure 3-24: Cross section of coining setup to be modeled for FEA.

The coin blank and tooling are modeled as a 2-D plane in the first quadrant (positive x, positive y) with the element option of axisymmetry about the y axis. The body of deformable coin material is modeled as a rectangular area with a mapped mesh of 1:1 initial aspect ratio elements and the tooling was modeled as a series of straight lines surrounding the deformable coin blank.

The FEA model was slightly simplified from the real-world setup in order to deal with issues of excess element distortion and instability during solving. The lines which model with tooling boundary were connected together, eliminating the gap between the punch heads and the outer die. A small radius of 0.0254 mm (0.001”) was added to both ends of the angled wall of the punch head to avoid unrealistic stress concentrations. An overview of the geometry created in the FEA model is shown in Figure 3-25.
Boundary non-linearity due to changing contact status is accommodated for by creating contact pairs of elements on the edges of the deformable coin blank and the tooling boundary lines. The coin blank is first meshed with PLANE42 elements which are 2-D solid structural quadrilaterals with four nodes, each having translational degrees of freedom in the x and y directions, and have been programmed to account for plasticity, creep, swelling, strain hardening, large deflections, and large strains. Contact pairs are meshed using TARGE169 and CONTA171 elements to model surface-to-surface contact. CONTA171 are contact elements used to represent contact and sliding between 2-D “target” surfaces (TARGE169) and a deformable surface, which this element defines. TARGE169 are 2-D target elements which the contact elements are able to contact and interact with, and are set to function as perfectly rigid. The contact elements overlay the solid elements which describe the boundary of a deformable body and are potentially in contact with the target surface. The location and types of elements used are also shown in Figure 3-25.
Contact elements are meshed on the three outside edges of the coin blank, and target elements are meshed on the lines defining the tooling boundary. Two contact pairs are created; one pair consists of the bottom line of the coin blank and the bottom line of the tooling (which is held still), and the other pair consists of the top and right outside lines of the coin blank and the remaining tooling boundary lines which are assigned a pilot node to which the coining load is applied. This allows the bottom punch face to remain rigid and not move while the upper punch face moves rigidly downward into the coin blank according to the applied force. The line defining the outer die face changes length according to the position of the upper tooling, thus introducing minor extra sliding effects at the edge of the coin.

Plasticity effects are incorporated into the FEA model by defining a material true stress-strain curve based upon experimental results using the billet bulk upsetting test. The bulk upsetting test is performed as described in Chapter 4 and the true stress and true strain are found using equations 3-10 through 3-13.

\[
\sigma_E = \frac{F}{A_0} = \frac{4F}{\pi d_0^2}
\]

Engineering Stress in compression \hspace{1cm} (3-10)

\[
\varepsilon_E = \frac{l_0 - l}{l_0}
\]

Engineering strain in compression \hspace{1cm} (3-11)

\[
\sigma_T = \sigma_E (1 + \varepsilon_E)
\]

True stress in compression \hspace{1cm} (3-12)

\[
\varepsilon_T = \ln(1 + \varepsilon_E)
\]

True strain in compression \hspace{1cm} (3-13)
Where $F$ is the instantaneous applied force, $d_0$ and $A_0$ are the initial diameter and face area of the billet, $l_0$ is the initial billet thickness, and $l$ is the instantaneous thickness. Barreling of the cylindrical surface of the billet is not taken into account since only the initial contact area is considered.

The enter the experimental true stress-strain data into the FEA, a data table which defines non-linear material properties is activated and the data points shown in Figure 3-26 are input to define the true stress-strain curve using multilinear isotropic hardening for Von Mises plasticity. This model for true stress-strain is called multilinear because it uses a few data points connected by straight lines to define the curve, where the first line goes from 0, 0 to the yield point and the rest of the lines continue on to define the curve which increases in slope as strain increases due to strain hardening. This also defines the material to be isotropic and to use the Von Mises criteria for yielding. The original curve these data points correspond to is also presented in Figure 6-1.
Figure 3-26: Original true stress-strain curve and multilinear isotropic data used for FEA.

Multilinear true stress-strain data accurately represents the behavior of plastic deformation, but produces a more abrupt transition between elastic and plastic behavior of material which is near the yield stress.

Mesh convergence was attempted, however, it was found that larger elements got skewed excessively under load which impeded proper convergence of the FEA, and also could not properly represent the behavior of the coin material near the edge of the punch head design. On the other hand, smaller elements (including meshes with larger core elements and a refined mesh near the edges of the blank) relatively easily became inverted when the coining force was removed, preventing analysis convergence, and also had a tendency to be dragged outside of the
corners of the tooling boundaries where the outer die and punch faces meet. It is recognized that without a proper look into mesh convergence we can not necessarily think that the mesh used is ideal, but very few meshes were able to work with this initial FEA model.

A uniform mapped mesh of square PLANE42 elements with side length of 0.0508 mm (0.002 inches) was chosen because it was able to converge reliably with several different geometries and with a large range of applied loads. This resulted in 8472 elements for the 1.6002 mm (0.063 inches) thick blanks and a solution time typically 30 - 45 min, and 16191 elements for 3.175 mm (0.125 inches) thick blanks with a solution time of 60 – 90 min. An example of the geometry produced is shown in Figure 3-27, please note that the element sizes are enlarged for clarity.

![Figure 3-27: ANSYS coin FEA mesh using a 0.125" blank.](image)

It can be seen that the lower punch face and the outer part of the upper punch are initially in contact with the coin blank, the wall of the punch design is seen at the top center, and the gap between the initial blank and the outer die is seen at the right. The origin is at the bottom left corner of the model and the applied force is the arrow in the top left. Seen at the left side, a
restriction on the movement of coin blank nodes in the x direction is applied in order to prevent negative radius nodes from occurring.

Two load steps are required to investigate the coining process. The first load step presses the coin, it begins with no applied loads and slowly applies a downward force to the upper tooling target element’s pilot node until the requested maximum coining force is reached, then to study the spring back the second load step slowly removes the force until zero applied load is reached again. A number of substeps are used within each load step in order to incrementally change the applied load. Automatic time stepping was turned used, allowing ANSYS to change the size of the substeps taken based upon the behavior of the system. An initial substep of applying 0.005 of the maximum applied coining force was used, along with requiring a minimum number of 100 substeps and a maximum of 1000.
Chapter 4

The Bulk Upsetting, Ring, and Coining Tests

4.1 Experimental Samples

A major objective of this project is to develop a comprehensive Finite Element Analysis (FEA) model of the coining process which is able to accurately predict the required forming forces and energy use based solely upon the blank characteristics and geometry of the coin to be made. This model requires data for the true stress-strain curve of the materials under compression, as well as coefficients of friction for the materials contacting the tooling without lubricant. This data is found using open-die bulk upsetting of a billet, and the ring test.

The open-die bulk upsetting test involves compressing a solid cylindrical billet between two flat, parallel platens and recording data of the thickness of the billet as well as the applied force throughout the test. The platens were made to mimic the coin punch tooling exactly; they are made from M2 tool steel, heat treated to maximum hardness, and ground flat. The bulk upsetting tests are performed in the exact same manner as with the coins; the platens are ground flat to the same finish as the coin punch heads, the billets are of the same material and polished the same way as the coin blanks, the test is performed un-lubricated, and uses the same LabVIEW press controller as the coin tests in order to keep the strain rate the same. The billets used were turned on a lathe out of bars of copper 110 and brass 260 to the dimensions shown in Figure 4-1.
The ring test is performed exactly the same way as the bulk upsetting tests; the ring test uses the same tooling, press controller, materials, and polishing treatment of the samples. The only difference is that a solid cylindrical ring (rectangular toroid) is compressed to a certain thickness and the changes in dimensions are measured in order to find the coefficient of friction at the sample-tool interface. The ring test samples were made using the same methods and materials as the billet samples and were made to the dimensions shown in Figure 4-2.
An effective way to develop a model for the coining process is to break the problem down and control a single design variable in order to experimentally study the effects of a single isolated change at a time. This will allow several independent relationships to be developed, where each one relates forming forces and energy use to changes in a single aspect of the blank and coin geometry.

Consideration was given to study effects both on characteristics of the initial blanks, as well as the design geometry imposed upon their surfaces when pressed into a coin. It was decided to use two easily formable materials for coin blanks, copper 110 (99.9% pure) and brass alloy 260, in three different thicknesses. Copper was used to study all combinations of geometry along with 3 blank thicknesses, while the brass blanks were used for all geometry combinations with only one
blank thickness. Hardness was tested for a selection of blanks resulting and is summarized in Table 4-1.

Table 4-1: Measured blank material hardness of blanks.

<table>
<thead>
<tr>
<th>Blank material</th>
<th>Blank Thickness</th>
<th>Hardness (Rockwell B scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper 110</td>
<td>0.032”</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>0.062”</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>0.125”</td>
<td>34.3</td>
</tr>
<tr>
<td>Brass 260</td>
<td>0.062”</td>
<td>41.5</td>
</tr>
</tbody>
</table>

The hardness of the 0.125” thick copper blanks was found to be higher than the other thicknesses, possibly because of slight differences in the alloy or temper of the thickest material although material of the same alloy and temper were ordered. No material testing or heat-treatment of the blank material was performed in-house. The Rockwell test requires a minimum sample thickness to be valid (e.g minimum of 0.038” for a material of 28 Rockwell B) which the thinnest copper blanks are not. However, several stacked blanks were tested as well as individual ones and the same hardness values were obtained. Three samples are coined to different maximum forces for each geometry combination used. The geometry changes which were isolated and investigated consisted of design shape to investigate effects of design perimeter length, design depth, and wall angle. 26 punch heads were used, comprising all geometry combinations of design shape, depth, and angle. Each punch head design is tested using a flat ground punch on all versions of copper blanks. Punch heads of 0.010” and 0.020” depths were made in pairs to test the effect of single-sided coins and double-sided coins and were used only with 0.062” thick copper blanks. All punch heads were used in a single-sided configuration with 0.062” brass blanks. An outline for all
combinations of options to produce each unique coin sample is outlined below in Table 4-2 for copper coins, and Table 4-3 for brass coins.

Table 4-2: Design geometry and blank options for copper coins.

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Force</th>
<th>Blank Thickness</th>
<th>Design Shape</th>
<th>Design Depth</th>
<th>Wall Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper 110</td>
<td>75000 lbf, 100000 lbf, 125000 lbf</td>
<td>0.032&quot; 0.062&quot; 0.125&quot;</td>
<td>Ring Circle</td>
<td>0.005&quot; 0.010&quot; 0.015&quot; 0.020&quot;</td>
<td>0°, 15°, 30°, 45°</td>
</tr>
<tr>
<td></td>
<td>75000 lbf, 100000 lbf, 125000 lbf</td>
<td>0.062&quot;</td>
<td>2-Sided Ring 2-Sided Circle</td>
<td>0.010&quot; 0.020&quot;</td>
<td>0°, 15°, 30°, 45°</td>
</tr>
</tbody>
</table>

Table 4-3: Design geometry and blank options for brass coins.

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Force</th>
<th>Blank Thickness</th>
<th>Design Shape</th>
<th>Design Depth</th>
<th>Wall Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass 260</td>
<td>75000 lbf, 100000 lbf, 125000 lbf</td>
<td>0.062&quot;</td>
<td>Ring Circle</td>
<td>0.005&quot; 0.010&quot; 0.015&quot; 0.020&quot;</td>
<td>0°, 15°, 30°, 45°</td>
</tr>
</tbody>
</table>
All combinations of choices from Table 4-2 and Table 4-3 result in a total of 360 coins made, consisting of: 234 single-sided copper (78 of each thickness), 48 double-sided copper (0.062” thick blanks), and 78 brass (0.062” thick blanks),

All coin blanks were cut from rolled sheet metal on a water jet so that no effects from heating or strain hardening would occur in the blanks. A small tab was left on the edge of each blank which was then filed off by hand. All blanks are plain cylinders, cut to 0.990” diameter from sheets of thickness 0.032”, 0.062”, and 0.125”. The different possible dimensions of manufactured blanks are summarized in Figure 4-3.

Figure 4-3: Dimensions of coin blanks showing the thicknesses used.
All billet, ring, and coin samples were put in a rock tumbler and tumbled for 30 minutes with porcelain polishing media (2 mm diameter spheres) and a lubricant diluted with water in order to clean all surfaces of impurities and give all samples a uniform surface roughness. Surface roughness was measured across a length of 5 mm using a portable stylus-type tester provided by the McLaughlin Hall machine shop. The measured surface roughness is $R_a = 0.29 \, \mu m$ for the brass blanks, and $0.25 \, \mu m$ for the copper blanks. The Punches have a surface roughness of $R_a = 0.24 \, \mu m$.

Tooling was initially developed to produce blanks using the precision stamping process. While this tooling was capable of producing wonderful blanks with crisp edges, it ultimately was not used due to difficulties ensuring the extremely close-fitting tooling is aligned precisely and can be used repeatedly without interference between the two halves of the tooling. A detailed account of the design of the precision stamping tooling is given in Appendix D.

### 4.2 Degree of Coining Measurement Method

In order to compare the forming forces and energy used by coining with different geometries the degree of how well the coin is formed must be found. The degree of coining is expressed in terms of the volume of material which is permanently displaced beyond the punch face and into the punch cavity as a percentage of the total volume of the design geometry cut out of the punch, and is used for all coining measurements in this project. Comparisons will be made for the force and energy used to displace the blank material into the punch in terms of the actual volume displaced as well as the volume displaced as a percentage of the total volume of the punch design.
The degree of coining is determined assuming a constant volume forming process, the volume of material displaced into the punch design is determined by comparing the initial thickness of the blank to the thickness of the final coin. Measurements were taken with a high resolution digital micrometer (Mitutoyo No. 293-765-10, resolution = 0.00005 inches = 0.00127 mm). Initial thickness measurements were taken at the center of the blank. Anvil extensions were used, as shown in Figure 4-4, to allow the thickness measurements to be taken near the edge of the coin where the surface is not wide enough for the regular anvils. An example of the measurement locations is shown in Figure 4-5.

![Figure 4-4: Close-up of micrometer with thin anvil extensions for measuring coin thickness change.](image-url)
The volume of material displaced permanently is equal to the change in volume of the plain cylinder which lies below the formed surface. Therefore:

\[ V_D = V_{Total} - V_{Final\ Cylinder} = \frac{\pi}{4} \left( t_1 d_1^2 - t_2 d_2^2 \right) \]

The initial diameter \( (d_1) \) is known to be 25.146 mm (0.990 inches) and the final diameter \( (d_2) \) is 25.3492 mm (0.998 inches). The initial and final thicknesses \( (t_1 \) and \( t_2) \) are measured. Based upon their designs, the thickness change required for 100% coining to occur for each punch is calculated; the value is the same for all punches of equal depth. The thickness changes required for 100% coining are shown in Table 4-4.
Table 4-4: Thickness changes required for 100% coining.

<table>
<thead>
<tr>
<th>Design depth (inches)</th>
<th>Design depth (mm)</th>
<th>Δt for 100% coining (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.127</td>
<td>0.03188</td>
</tr>
<tr>
<td>0.010</td>
<td>0.254</td>
<td>0.06376</td>
</tr>
<tr>
<td>0.015</td>
<td>0.381</td>
<td>0.09563</td>
</tr>
<tr>
<td>0.020</td>
<td>0.508</td>
<td>0.12751</td>
</tr>
</tbody>
</table>

The thickness change that occurs solely from pressurizing the blank and increasing its density under pressure, without displacing material into a punch, is taken into account using a correction factor. This correction factor was found experimentally by compressing blanks of all types between two flat punches and takes into account the increase in diameter of the blank as well as any flash that is squeezed out between the punch head and die. Within the force range used for the coining experiments, this correction factor was found to increase (greater thickness decrease) with increasing force and increased more rapidly for the brass blanks. Lines of best fit were found for the thickness change to peak force relationship for each blank as shown in Figure 4-6.
Figure 4-6: Coin thickness changes using two flat punches.

The thickness change expected using flat punches for a sample is calculated from the curves above then subtracted from the measurements taken from all other samples.

Originally, the linear potentiometers mounted to the press were going to be used for measuring thickness change, but it was determined that their accuracy under dynamic coining is not quite good enough to obtain meaningful results. Still, the linear sensors were used for press control as well as giving us a good idea of thickness and force relationships during the coining process.

Coining test samples are given a unique code which concisely indicates which punch and blank combination was used so that the corresponding data can easily be organized and sorted through within spreadsheets. Each sample code follows the form of X###-X###deg### where each ‘X’ represents a letter variable and each set of ‘#’ represents a numerical variable. Descriptions of the variables and the possible values are summarized in Table 4-5.
Table 4-5: Breakdown of unique coin sample naming code.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Possible Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Blank material (brass, copper)</td>
<td>B, C</td>
</tr>
<tr>
<td>#</td>
<td>Number of punches used with a design</td>
<td>1, 2</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>###</td>
<td>Typical blank thickness in thousandths of an inch</td>
<td>032, 062, 125</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>X</td>
<td>Punch head design shape (circle, ring)</td>
<td>C, R</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>##</td>
<td>Punch design wall angle from vertical (degrees)</td>
<td>00, 15, 30, 45</td>
</tr>
<tr>
<td>deg</td>
<td>Indicates unit for wall angle</td>
<td>deg</td>
</tr>
<tr>
<td>###</td>
<td>Punch design depth in thousandths of an inch</td>
<td>005, 010, 015, 020</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>#</td>
<td>Setup sample number</td>
<td>1, 2, 3…</td>
</tr>
</tbody>
</table>

As an example, a coin with the code C1-062-R-00deg005-3 indicates that the blank is made of copper 110, a single punch head with design was used (with a flat punch head on the other side), the blank had a typical initial thickness of 0.062”, the punch design used was a ring shape with a 0° wall angle and a depth of 0.005”, and this is the third sample using this configuration.
Chapter 5

Viability of Lubricated Coining

An additional objective of this project is to investigate the viability of using lubrication in the coining process. By definition coining is a dry process, and although it can reduce the required force to produce a coin [3], lubrication is not used. The thought behind this is because any liquid lubrication will be incompressible it would introduce defects to the formed surface by filling in parts of the dies rather than allowing metal to flow to those areas.

Before conducting coining tests using lubrication, experiments were performed using the “Ring Test”. The ring test is a well-established experimental method which has been used extensively in determining the coefficient of friction at the part-tool interface in bulk forming. The ring test was originally published by Male & Cockcroft [7] and the graphs which were produced in their work have since been frequently used to find coefficients of friction. The Ring Test was also talked about extensively by Weinmann [8] which drew us towards using this test.

The Ring Compression test is best known as one used by Male and Cockcroft [6] who used it to study the frictional behavior of metals under conditions of bulk plastic deformation. The experiment samples consisted of metal rings with dimensions of 0.750” outside diameter ($D_o$), 0.375” inside diameter ($D_i$), and 0.250” thick ($h$). These dimensions have become the standard for performing ring compression tests and are of the ratio 6:3:2 ($D_o:D_i:h$). The test is valid in the range of 20 to 60 percent deformation and coefficients of friction between $\mu = 0.055$ to 0.57. The
The model used by Male and Cockcroft relates the change of internal diameter of a ring ($\Delta D$) to the amount deformation ($\% \text{Reduction}$) and the coefficient of friction ($\mu$), as presented in the original Equations 6-1 and 6-2.

$$\Delta D = m \left( \ln \left( \frac{\mu}{0.055} \right) \right)$$  \hspace{1cm} (5-1)

where:

$$\ln(m) = 0.044(\% \text{Reduction}) + 10.6$$  \hspace{1cm} (5-2)

However, searching the literature shows that these equations are almost universally unused. Instead, experimental data points are plotted on the original calibration curves, shown in Figure 5-1, and a value for coefficient of friction is obtained based upon which calibration curve the data points lie nearest. This is fortunate, because our work shows Equation 5-2 to be incorrect, in that it does not match the graphs or data for ring tests. In Figure 5-1, the decrease in I.D. is a percentage of the change in I.D. divided by the initial I.D., and the deformation is defined as the change in thickness divided by the initial thickness.
A recent project in our lab [9] took an in-depth look at the ring test and its calibration curves and determined that while the calibration curves appear to be correct as shown in Figure 5-1, the equations which supposedly represent the curves bear no resemblance to the graphs, possibly indicating why no one appears to ever use the original equations. By combining empirical information with our own experimental data, we found that the proper equations for the calibration curves were determined to be:

Figure 5-1: Constant coefficient of friction calibration curves [7].
\[
\Delta D = \left( 6.6338e^{(0.044 \times deformation\%)} \right) \log \left( \frac{\mu}{0.055} \right)
\] 

(5-3)

One of the major differences found was that the curves used \( \log \left( \frac{\mu}{0.055} \right) \) rather than \( \ln \left( \frac{\mu}{0.055} \right) \) as originally stated, and that the addition of 10.6 to Equation 5-2 prevented the curves from intersecting \((0, 0)\).

Different calibration curves can be obtained by setting \( \mu \) constant. Like the original Male & Cockcroft equations, Equation 5-3 is only representative of deformations between 20\% and 60\% and within the range \( \mu = 0.055-0.57 \). This equation now allows the coefficient of friction to be calculated directly from the changes in dimensions of the ring rather than plotting the measurements on a graph and estimating a value. Also found in this recent project was that all sample sets of ring tests exhibited a linearly increasing coefficient of friction as the percentage of deformation was increased, a phenomenon not apparent before when just plotting data onto Figure 5-1. Below is shown the difference between determining the coefficient of friction using the “traditional” method of plotting data points, and using the equation to calculate it, shown in Figure 5-2 and Figure 5-3, respectively. The codes for the different tests represent the test conditions used; the first ‘R’ indicates this is a ring test (as opposed to bulk upsetting), the second letter indicates the roughness of the platens (‘S’ for ground smooth and ‘R’ for left rough), and the third letter denotes the lubricant used (‘A’ for mineral oil, ‘B’ for used cooking oil, and ‘C’ for palm oil).
Figure 5-2: Ring test data plotted on the Male & Cockcroft calibration curves. Al 6061-T6 ring tests [9].

Figure 5-3: Coefficients of friction calculated using Equation 6-3. Al 6061-T6 ring tests [9].
This work led to performing our own experiments with lubricated coining. It is proposed that by decreasing the volume of lubricant used, by atomizing the liquid onto the blank’s surface, it may be possible to retain the fine detail and high quality surface finish typically obtained by normal coining, while making it possible to reduce forming forces and decrease wear on the punches. As well, four lubricants were tested to see if different characteristics of lubricants affected their ability to lubricate or maintain a fine finish. For the experiments, four different lubricants were tested against dry coining, using a combination of different punch heads.

Environmentally friendly lubricants based upon mineral oil, used cooking oil (vegetable), and palm oil (from here on labeled A, B, and C, respectively) were atomized using an electric paint spray gun which atomizes the lubricant by pressurizing the fluid then forcing it out a 0.5 mm nozzle. Another lubricant tested was PAM® cooking oil (labeled as PAM®) since it is an easily available commercial pressurized lubricant spray; it was sprayed onto the coin blanks using its provided nozzle. All lubricants were sprayed onto the blanks for a duration of 1 second per side, then immediately coined. The environmentally friendly lubricants which were used are experimental so their properties are not known exactly. Approximate properties of the lubricants used are listed in Table 5-1

<table>
<thead>
<tr>
<th>Lubricant ID</th>
<th>Oil Type</th>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Dynamic Viscosity (Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mineral</td>
<td>40</td>
<td>850</td>
<td>0.029325</td>
</tr>
<tr>
<td>B</td>
<td>Used cooking</td>
<td>25</td>
<td>920</td>
<td>0.046</td>
</tr>
<tr>
<td>C</td>
<td>Palm</td>
<td>37.8</td>
<td>920</td>
<td>0.043976</td>
</tr>
<tr>
<td>PAM®</td>
<td>Canola</td>
<td>25</td>
<td>920</td>
<td>0.05244</td>
</tr>
</tbody>
</table>

Table 5-1: Approximate properties of lubricants at given temperature [10][11][12].
Two punches which fit into one another were made specifically for experimenting with lubricated coining. One punch has a design which sticks out of the face of the punch (labeled as the “extrude” punch), while the other has the same shape of design cut into the face (labeled as the “cutout” punch). Drawings and dimensions of the punches are shown in Figure 5-4 and Figure 5-5.

**Figure 5-4: Dimensions of "extrude" punch for lubricated coining.**
Figure 5-5: Dimensions of "cutout" punch for lubricated coining.

The dimensions of the designs are not exactly the same between punches, but were designed to have a gap of approximately 0.508 mm (0.020 inches) between all non-flat surfaces when put together, shown in Figure 5-6. This was done in order to try and prevent any shearing effects caused by close fitting vertical surfaces. A plain, flat-ground punch was also used in experiments which only used one of the special punches.
Figure 5-6: Cross section of "cutout" and "extrude" punches showing the gap to prevent shearing effects.

All experiments with lubricated coining used 0.125” thick blanks made of copper 110 as outlined in Chapter 4. Dimensions of the design formed into the coin were measured with calipers to determine the volume of the blank material which was forced into the design, and therefore find the percentage coined.

5.1 Lubricated Coining Results

All samples were tested to a peak force of approximately 333.6 kN (75000 lb) in order to determine the performance of the different lubricants relative to each other as well as to the non-lubricated tests. 333.6 kN was chosen as the standard peak force because it was previously known (with similar materials and punches) that this will be enough force to almost fully form the coin without being too high as to form sharp flash around the edges which alters the results. The average percentage coined for each lubricant used and for each pair of punches is shown in Figure 5-7.
Figure 5-7: Percentage coined at 333.6 kN, regular and lubricated coining.

Experiments using the cutout punch show that some of the lubricants do in fact make it easier to coin. From 66.05% coined for the non-lubricated test, used cooking oil helped increase the amount of the design coined up to 78.78%, palm oil increase the amount even further to 85.67%, while the mineral oil and PAM® had essentially no effect.

We also find that the extrude punch typically forms the coin much more than the cutout punch because the extrude punch has a smaller face area that initially contacts the blank when coining, thus making the local stresses in the blank higher than with the cutout punch, forming it more easily. This may also explain why the extrude punch was relatively unaffected by the lubricants, since the punch pushes more into the blank with not much sliding at the blank-punch interface. A similar effect is seen with the tests which use both the “extrude” and the “cutout” punches. There
is a little more of a variation in the percentage coined among the tests, all which show the lubricated tests being coined a little more than the dry test.

The lubricated coining experiments were performed before the LabVIEW controller was fully functional and the different states needed to be advanced by a human, so there is a significant range of forces under which the experiments were performed. This wider range of test forces means that comparing lubricants only by looking at the percentage coined does not give us the full picture. To make up for variations in the actual peak applied force we can find the ratio of force applied to the percentage coined, which is shown in Figure 5-8.

![Figure 5-8: Effectiveness of lubricants at 333.6 kN, regular and lubricated coining.](image)

The force per percentage coined found for the experiments with the cutout punch reinforce the observations made about the effectiveness of the lubricant. Lubricant A has no effect, lubricant B
decreased the required force and lubricant C even more so, while \textsuperscript{PAM} \textsuperscript{®} slightly increased the force required to coin. Again we see that the tests using just the extrude punch are virtually unaffected by the lubricants and that the small variations found in Figure 5-7 were due only to variations in the peak applied force. Contrary to the observations from Figure 5-7 we now find that the lubricants did affect the cutout-extrude tests, with every lubricant decreasing the required force to coin from the dry tests.

We will also want to look at the force requirements for lubricated coining relative to the dry tests using the same punches; this is shown in Figure 5-9.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure5-9.png}
\caption{Effectiveness of lubricants relative to dry coining at 333.6 kN, regular and lubricated coining.}
\end{figure}
Using the cutout punch; lubricant A had no effect, lubricants B and C both decreased the required force, while PAM® actually increased it. The cutout punch is very similar to the other coin punches used to investigate the effects of design geometry (e.g. depth, wall angle, and shape), so we would expect to see similar results if lubrication were to also be used.

Again we find essentially no difference in the required coining force for the extrude punch, indicating that lubricants have no appreciable effect on punches which have a very small initial contact area with the blank, where it is likely that little amount of sliding occurs. When compared to dry coining, all lubricants decreased the forming forces required for the tests which used both the cutout and extrude punches, ranging from 71% to 81% of the force required.

Looking at the coins qualitatively, we see a general mottled look on the flat sides of the coins, while on the side shaped using the cutout punch this mottled effect only appears on some coins as shown in Figure 5-10.

Figure 5-10: Coins made using "cutout" punch (top row) and flat punch (bottom row). From left to right: Dry, A, B, C, PAM®.
On the flat side of the coins made with the cutout punch there is always a recessed ring, located opposite the ring in the cutout punch, where the blank material has actually lifted off of the flat punch. We have termed this phenomenon “ghost coining”, where the image from one punch shows up on the opposite coin face. This is discussed further in Chapter 6.

The same mottled surface finish generally shows up on both sides of the coins made using the extrude punch. Near the middle of the flat surface, located opposite of the ring sticking out of the extrude punch, there has appeared a shiny section which does not show up on the un-lubricated coin (the shiny section shows up black in Figure 5-11). Since the extrude punch has a smaller initial contact area with the blank, it is likely that the higher stresses this produces causes the lubricant to break down on the flat side, resulting in the blank material sliding against the flat punch.

Figure 5-11: Coins made using "extrude" punch (top row) and flat punch (bottom row).
From left to right: Dry, A, B, C, PAM®.
The mottled surface finish though fairly mild, is also seen on both sides of all coins made using both the cutout and extrude punches. These coins are shown in Figure 5-12.

![Image of coins](image.png)

**Figure 5-12: Coins made using both the "extrude" (top row) and “cutout” punch (bottom row). From left to right: Dry, A, B, C, PAM®.**

The level of detail of the punch design imparted upon the coin is also observed qualitatively. No appreciable difference in surface detail is seen between un-lubricated and lubricated coins with a surface made with the cutout punch head. However, on surfaces formed by the extrude punch head, we see that the edges of the 5.08 mm diameter circle are slightly more rounded on the lubricated coins when compared to dry ones which are sharper. This supports the theory that the incompressible lubricant fills in voids and prevents blank material from flowing there. While the difference in edge softness observed in these coins is relatively small it is certain that lubricants will have a more significant effect on smaller punch details.

It is observed that it is possible to use lubrication in the coining process to reduce the required forming forces, but requiring a sacrifice in surface quality. Required forming forces were reduced
to as much as 71.23% of the force required for dry coining (using PAM®, cutout-extrude). While a good level of detail was retained, a mottled surface finish appears on many lubricated coins which can be attributed to the incompressible lubricant forming a very thin film between the coin and the punch, preventing the exact surface quality and shape of the punch from being transferred to the finished coin. In some circumstances it may be beneficial to make coins in a two step process, first with lubricant to obtain the general shape while requiring lower forming forces, then a second time without lubricant in order to get the fine details. This is unlikely the usual case, as the small benefits of forming with lower forces will be outweighed by the extra energy required for two stage coining, as well as issues arising from using lubricant.
Chapter 6

Results of coining using different geometries

6.1 Billet and ring tests – data for FEA

Details of how the bulk upsetting, ring, and coining tests are performed as well as details of the experimental samples and the numbering system used and are detailed in Chapter 4. Open-die bulk upsetting of cylindrical billets was used to obtain the true stress-strain relationships for compression of copper alloy 110 and brass alloy 260. The data obtained from these tests is used in the FEA of the coining process later on. These tests were performed in-house in order to avoid slight differences and errors that would arise from using a standard model supplied with the ANSYS FEA package. This ensured that the proper material properties were used and under the same conditions (i.e. strain rate) as the coining process, since the LabVIEW coining process controller was used (with slight modifications) with the bulk upsetting tests. The true stress-strain data obtained from one of the three samples of each material are shown in Figure 6-1.
Figure 6-1: True stress-strain curves for Copper 110 and Brass 260 bulk upsetting tests in compression.

The first test conducted for each material shows a much different relationship in the elastic area of the curve: Copper Billet #1 in Figure 6-1, and Brass Billet #1 in Figure 6-1. It is likely that the hydraulic fluid in the press was still warming up during these first samples and thus caused the press to operate slightly differently (perhaps lower speeds or slower reaction times of the rams) and have an effect on the data. Therefore, the first sample data for each material is disregarded and data from the other tests used in the FEA. Other than these anomalies, the true stress-strain curves were always repeatable.
The ring test was also performed for samples of copper 110 and brass 260 in order to determine the coefficient of friction at the part-tool interface and, like coining, this was performed without lubrication. Even though this is an open die test it appears to be the only test available for estimating friction in coining and bulk forming at the part-tool interface.

As with the billet tests, this was tested in-house to make sure the exact materials and conditions used in coining are represented in the data to be used in FEA. Samples were tested with target deformations of 10% to 40%, in 10% increments and for both materials. The results for the dimensional changes of the rings are shown in Figure 6-2. The error bars are based upon the resolution of the measurement devices used.

![Figure 6-2: Dimensional changes for ring tests with no lubrication.](image)
Regression of least squares for the y-variable was used to fit curves to the data, the equations for the curves are:

Copper rings:

\[ \% \text{Decrease in ID} = 0.080(\% \text{Reduction})^{1.3825} \quad \text{with } R^2 = 0.9641 \]

Brass rings:

\[ \% \text{Decrease in ID} = 0.0296(\% \text{Reduction})^{1.6168} \quad \text{with } R^2 = 0.9613 \]

Diameter measurements of the rings had to take into account the barreling of the cylindrical faces for proper measurement. These measurements were corrected for using the method described in my paper which further investigates the ring test [9]. Superimposing the data for dimensional changes in the rings on top of the original calibrations curves published by Male & Cockcroft gives us Figure 6-3 from which coefficient of friction can be estimated to be about 0.12 for brass and 0.15 for copper since they follow those curves fairly closely.
However, rather than estimating using the graph and instead using Equation 5-3, we are now able to calculate the coefficients of friction experienced at the part-tool interface for different deformations which would be experienced in the coining process. The results of for the calculated coefficients of friction are outlined in Figure 6-4.
Figure 6-4: Interface friction change with deformation using no lubrication.

Again we can fit curves to this data to relate friction to the reduction in height.

Copper rings:

\[ \mu = 0.00002(\%\text{Reduction})^2 + 0.0001(\%\text{Reduction}) + 0.0906 \quad R^2 = 0.9941 \]

Brass rings:

\[ \mu = 0.000001(\%\text{Reduction})^2 + 0.0013(\%\text{Reduction}) + 0.0641 \quad R^2 = 0.7517 \]
We can also find the relationship between the coefficients of friction and the peak true stress experienced during testing, shown in Figure 6-5. The ring test is only valid starting at 10% reductions in height, corresponding to the lowest true stress for each set of data presented.

![Figure 6-5: Interface friction relationship to peak true stress (no lubrication)](image)

Figure 6-5: Interface friction relationship to peak true stress (no lubrication)

This data was intended to be the reference for a pressure-dependant coefficient of friction to be used in the FEA. However, the data for the brass rings is scattered quite a bit and only a loose fitted line can be found, and the data for the copper rings gives a close fitted, but extremely steep curve which gives negative coefficients of friction below approximately 150 MPa. The relationship between friction and true stress will need to be investigated much further if a stress-
dependant coefficient of friction is to be used in a FEA model. For now we will instead use the average coefficient of friction found for the material and use a constant value in the FEA. The average values found for the coefficient of friction are; for copper = 0.114, and for brass = 0.098. These estimates for friction are better than estimating visually from Figure 6-3, but much more is left to be understood about the interaction at the material-tool interface in order to develop better values.

6.2 Measurements during the coining process

During the coining process the thickness change of the coin is roughly proportional to the applied force as shown in Figure 6-6. During coining we find that when pressure is being applied to the coin, the thickness reduction is many times greater than the final permanent deformation. In Figure 6-6, the coin has a maximum thickness change of 1.3755 mm occurring at the maximum applied force at 52 seconds, while its permanent deformation is only 0.066675 mm when the force is removed. From 52 to 54 seconds we see the coin material thickness spring back as the force is reduced, only to leave a very small overall thickness change which is not visible in Figure 6-6.
The true stress-strain relationship for compression was found for coining and showed that it behaves purely plastically. The compressive true stress-strain found during coining is shown in Figure 6-7 along with the compressive true stress-strain curve found using the bulk upsetting test described in Section 6.1.
Figure 6-7: Loading and unloading true stress-strain curves for billet test and coin C1-062-R-00deg005-3.

The bulk upsetting true stress-strain curve exhibits a higher flow stress than for coining due to the high friction experienced at the material-tool interface caused by a much greater thickness reduction and diameter increase. This is not experienced in the coining process since the net plastic deformation is minimal, the blank’s diameter increase is limited by the outer die and the large deformations are limited to near the surface. Both tests show the same increases in true stress with increasing strain caused by strain hardening of the material.
Figure 6-7 also demonstrates very well that most of the energy which goes into the coining process is useless. In the bulk upsetting test the material springs back and the strain decreases slightly as the force is removed, leaving a heavily deformed sample. When removing the force in the coining test the overall strain decreases in the reverse manner as during loading, leaving a very small amount of overall strain in the finished part. Most of the energy put into the coining process goes toward pressurizing the blank material rather than forming it as is the case with the bulk upsetting test. Punch redesign or lubrication may be ways of reducing this wasted energy. The true stress-strain curves for coins formed at lower forces follow the same curve, but loop back earlier based upon the maximum strain reached. The true strain-rate as compared to press force is shown in Figure 6-8.

![Figure 6-8: Example of typical true strain-rate for coin C1-062-R-00deg005-3.](image-url)
Although unnoticeable in graphs showing thickness change, there is a small 60 Hz noise in the position sensor signal. When investigating position data this noise is insignificant, but when the position data is differentiated to find the strain rate, this noise becomes more of a problem and is evident in Figure 6-8. The true strain rate stays relatively constant during the compression and unloading phases of the coining process, going from an initial rate of about 0.3/s at zero force then down to 0/s at 550 kN, then constant at approximately -0.3/s during unloading. The strain rate for coins formed at lower peak forces follow the same curve, but turn negative earlier based upon the peak force reached.

The relationships presented for force and thickness change during the coining process, true stress-strain in compression, and strain rate in compression were found to be universal for all samples and is in part due to the large degree of automation of the LabVIEW controller.

### 6.3 Effects of design geometry

First, to determine the overall behavior of the coining process, experiments were conducted to a wide range of peak applied forces and the overall percentage coined and percentage of the diameter formed was measured. Results for this study are shown in Figure 6-9. Blanks of every material and thickness were compressed between 2 flat dies to determine a correction factor to apply to the coin thickness measurements which corrects for the diameter change of the blanks as well as for the small amount of flashing which is typically formed between the punch and outer die. Blanks were pressed at 333.3 kN, 444.8 kN, and 556.0 kN and the thickness change measured. A linear relationship was found to exist across this force range for each type of blank.
and was used as the correction factor. The percentage coined (based on the volume permanently deformed) was found for each test, then divided by the maximum applied force to find the forming requirement for a certain maximum force goal, expressed in terms of kN/1%. The forming requirement is instead expressed in terms of kN/mm for some relationships. The error for all results presented for percentage coined and forming requirements are dependent upon measurement error and the punch design depth, these errors are summarized in Table 6-1. Error bars are presented on graphs to which the values in Table 6-1 do not apply.

Table 6-1: Summary of errors for all coining results.

<table>
<thead>
<tr>
<th>Punch Design Depth</th>
<th>Error in Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005”</td>
<td>0.500%</td>
</tr>
<tr>
<td>0.010”</td>
<td>0.250%</td>
</tr>
<tr>
<td>0.015”</td>
<td>0.167%</td>
</tr>
<tr>
<td>0.020”</td>
<td>0.125%</td>
</tr>
</tbody>
</table>

Comparing forming requirements allows us to compare different experiments to one another while accounting for a range of forces which overshot the goal which may mask the relationships we seek.
Figure 6-9: Percentage of diameter and design formed for coin C2-062-R-00deg020

Figure 6-9 shows that the diameter increases very rapidly as soon as yielding occurs at an applied force of about 115 kN (based on 300.6 MPa yield stress and contact punch contact area) and occurs at the same time as the coin begins to form, rather than forming the diameter first followed by the punch design. It is also seen that the degree of coining increases rather linearly within the range tested.

The measurement changes of blanks compressed between flat punches was not measured for forces outside the 333.3 - 556.0 kN range so their behavior is unknown and cannot properly correct the measurements, especially around and below the force at which yielding occurs, as shown in Figure 6-10.
Effects of the wall angle on the required forming force was studied using punches with four different wall angles (0°, 15°, 30°, 45°) along with every combination of design depth, shape, blank thickness, and material. Figure 6-11 and Figure 6-12 show the forming force requirement per percentage coined for copper ring coins (Figure 6-11) and copper circle coins (Figure 6-12) for a peak forming force of 556 kN. All values involving the percentage coined from here on are corrected for diameter increase and flashing.
Figure 6-11: Effects of different wall angles. Coined to 556.0 kN using ring punch heads and copper blanks. Labels are in thousandths of an inch (punch depth, blank thickness).
Figure 6-12: Effects of different wall angles. Coined to 556.0 kN using circle punch head and copper blanks. Labels are in thousandths of an inch.

The same types of results are seen in the experiments using brass blanks, double-sided copper coins, and coins formed at lower forces. Almost no pattern or trend is discernible in the above graphs which indicate a specific effect that different wall angles of the design has on forming forces, except for a slight overall decrease in forming requirement when the wall angle is increased.
As seen in the graphs investigating the effects of wall angle, the depth of the punch design had the largest effect on the forming force required, showing that blanks which were 3.175 mm (0.125”) thick were very easily formed, 1.600 mm (0.063”) blanks were formed slightly easier, and 0.813 mm (0.032”) blanks required significantly more force.

In Figure 6-11 and Figure 6-12 it also appears that the depth of the punch design may have an effect on required forming forces but the relationship is not clear. Looking at a single coining configuration but changing the depth of the punch, we consistently find relationships as shown in Figure 6-13.

Figure 6-13: Force requirements for different design depths of C1-125-R-00deg### series coins.
So far there only appears to be a general trend of slightly increasing force requirement as the applied force increases. The effects of design depth on forming forces is still not clear because it has so far been expressed as force requirement based on a percentage of how much of the punch design has been filled. If we instead express as the force required for the actual thickness change in millimeters then we produce Figure 6-14.

![Figure 6-14: Force requirements for different design depths of C1-125-C-00deg### series coins.](image)

It is now clear that the force required to change the thickness of a coin is drastically reduced the deeper the design is. Moreover, especially looking at the data around 558 kN, the force requirement is reduced by the inverse of the ratio of the punch design depths. That is, if the depth of the punch design is doubled, the force required to form that coin is halved. This may indicate a
linear (or even inverse logarithm) relationship to the punch depth, as shown in Figure 6-15 and Figure 6-16 for all coining configurations tested.

![Figure 6-15: Relationship of forming requirement to punch depth using ring shaped punches coined to 558 kN.](image)

The relationship is such that if the depth of the design cutout increases, the force requirement will change to the inverse ratio; so if the design depth is doubled then the force requirement will be
cut in half. This allows forming requirements for a new punch to be calculated based upon the
knowledge of an existing punch of identical design but different design depth.

Figure 6-16: Relationship of forming requirement for different punch depths using circle
punches forming to 558 kN.

With the exception of the 0.813 mm (0.032”) copper circle coins, all combinations of coin
configurations tested produced the same style of curve.
The effects of stamping coins with a punch design on one side versus two sides were tested using copper blanks and several pairs of identical punches. The results for the highest maximum force tested are shown in Figure 6-17 and Figure 6-18.

Figure 6-17: Effect of 1-sided vs. 2-sided coins using a 0.010" deep punch(es) forming to 558 kN.
In all cases the force requirement for double sided coins was lower than the single sided coins, with an especially large difference on the 0.010” deep punches. Again, no significant trends are consistently seen across the samples for having to do with effects caused by changes in the design wall angle.

The effects of different perimeters of the punch designs were tested by experimenting with punches of all configurations, each in the shapes of circles and rings. The results of the average forming force requirements for each punch shape and for blanks of different thicknesses are shown in Figure 6-19.
Figure 6-19: Effects of two design perimeters with different blank thicknesses.

Each ring shaped punch has a mean perimeter 1.6 times the perimeter of the corresponding circle punch. Many ring-circle pairs of punches showed that the copper rings were 1.6 times easier to form than the circle coins, indicating an inverse-proportional relationship. However, looking at the overall results there is a trend that the perimeter of the design makes less and less difference to the forming requirements as the blank gets thicker and the process progresses further from sheet metal forming and towards bulk closed-die forming. The circle punch coins are only 1.6 times harder to form than the ring punches for coin blanks around 1mm thick.
6.4 Effects of using different types of blanks.

It has been shown several times earlier that as the blank thickness increases, the all measures of forming force requirements decrease. As the blank gets thicker the process progresses further away from sheet metal forming and more towards bulk closed-die forming. This relationship is also seen in Figure 6-11, Figure 6-12, Figure 6-15, Figure 6-16, and Figure 6-19. An overview of the forming requirements for a large selection of coins made from different thicknesses of blanks is shown in Figure 6-20.

Figure 6-20: Forming requirements for the three blank thicknesses, using one ring punch and copper blanks.
A relationship can be found for forming requirements related to blank thickness is found by dividing the forming requirements for corresponding coins with identical tooling geometry and blank material, but using a different thickness of blank. It was found that on average, the 0.813 mm (0.032”) blanks require 1.47 times the force to form as the 1.600 mm (0.062”) blanks; the 1.600 mm (0.062”) blanks require 1.33 times the force to form as the 3.175 mm (0.125”) blanks; and the 0.813 mm (0.032”) blanks require 1.96 times the force to form as 3.175 mm (0.125”) blanks. These numbers indicate a relationship where the force requirement increases proportional to the inverse of the square root of blank thickness ratio; meaning that if a second coin half as thick is used then the force requirement will be \( \frac{1}{\sqrt{1/2}} = \frac{1}{0.7071} = 1.414 \) times the force requirement of the first coin.

The effects of different blank materials was tested by stamping coins using 1.600 mm (0.062”) thick blanks made of copper 110 and brass 260, using every type of punch design. Based on the review of literature, it is expected that the force required to form these coins should be directly proportional to the yield stress of the material. Results for corresponding coin configurations made of copper and brass are shown in Figure 6-21.
Figure 6-21: Effects of different blank materials on forming requirements, using ring punches and 0.062” thick blanks.

Copper and brass were selected as the materials for the experiments because they would both be relatively easy to form and have different stress strain curves. Seen in Figure 6-1, the yield stresses of the two materials are nearly identical (300.65 MPa), however, the different blank materials do not behave the same at all when coined. Though their yield stresses and modulus of elasticity are effectively the same, the force requirement for brass coins continuously increases with more demanding punch configurations and forces. This indicates that the material’s yield stress is not the only factor affecting the flow of the material during coining, but that the entire
plastic section of the material’s stress strain curve plays a large role so that at higher forces there is a larger difference between copper and brass.

The electrical power used by the press was logged for every test run (voltage and current recorded for each of three phases). It was intended to determine the power required to run the hydraulic press electronics, the hydraulic pump, and the extra power used by the coining process, as well as compare the extra power used to make a coin from coin to coin as a backup to the primary measurements. The logging frequency of the power data loggers is only 1 Hz and was unable to provide much in the way of meaningful data. Figure 6-22 shows the power curve of the pump running with no movement, as well as the curves from other tests typical of data from all coins samples.
It was observed that with all switches off the press consumes a recorded 0.283 W, with the press turned on but without the pump running it drew a steady 101.58 W, and with the press and pump running with no ram movement the power usage was constant at 12.3 kW. As shown in Figure 6-22, once the hydraulic rams are moving and/or pressing a coin, the power curves are higher than without ram movement, but vary so much and without a fast enough logging frequency they are indistinguishable from each other and no differences between the coins can be made. Calculations were performed on several of these curves to determine how much extra energy is used in making coins. It was found that the extra energy used is fairly insignificant as it is much less than 1% of the energy used just to keep the pump running.
By far the largest factor observed relating the power used by the coining process is due directly to the time that the hydraulic press and pump are running. This leads us to conclude for now that using higher strain rates in the coining process is likely beneficial since any increase in power demand of the coining process from forming faster would still be a very small percentage of the overall power used, and would be more than outweighed by cutting down on the time the pump is on, reducing the massive overhead needed just to run the pump.

6.4.1 FEA Results

The increase in diameter and decrease in thickness of the coin blank after coining was measured and compared to experimental results using the same material and die configuration. This was measured by taking the x and y displacement values of nodes on the outside edge of the coin, one node in the middle of the right side of the coin, and one node in the middle of the area initially contacted by the upper punch, providing measurements of dimension change at the same locations as with the experimental tests.

Above 333.6 kN (75000 lb) all FEA simulations failed due to non-convergence caused by excess element distortion. An extremely fine mesh seemed like it might be capable of properly converging beyond this force, but was still regularly too unstable to be sure. Figure 6-23 shows the FEA results for the forming of the coin geometry and diameter.
Figure 6-23: FEA results for percentage of diameter and design formed for coin C1-062-C-15deg010 geometry.

For this geometry configuration, a force of 112.8 kN is calculated as the point where coin material would begin to yield and is shown in Figure 6-23 as a dashed line. This force is based on the applied force and the initial contact area of the upper punch and cannot account for local stress concentrations. Figure 6-24 shows a comparison of the FEA and experimental results for a copper coin made with the same geometry configuration.
Figure 6-24: Comparison of percentage of diameter formed for coin

C1-062-C-15deg010 geometry.

The results agree relatively well, initially yielding and fully forming at the same points. The diameter change in the FEA results is more dramatic because the multilinear isotropic hardening for Von Mises plasticity material model only supports a single straight line for the elastic zone and multiple connected lines to define plastic behavior, eliminating any transition area where the change between elastic and plastic behavior is of a yes or no nature rather than a smooth curve where the material begins to yield. If a much more complicated true stress-strain curve can be used for ANSYS material properties then the diameter change could be modeled more closely.

FEA and experimental results with the correction factor for the degree of coining are compared in Figure 6-25.
The FEA results for degree of coining agree quite well with the experimental data, clearly beginning to form at the calculated yielding force, a sharp increase, then beginning to level off when 50% formed. The FEA model broke down at forces greater than 333.6 kN, so modeling the coin to 100% formed and confirming the expected spike in force near 100% formed is not possible with this model. Above 200 kN the FEA data points start to become offset above the experimental data, most likely due to slight differences in the material used for coining and for the bulk upsetting tests.
Examples of graphical results using this ANSYS FEA model are shown below. Figure 6-26 a) – h) reveal to us the changes in contact status between the tooling and coin blank.

a) Contact status at $T = 0.005 \text{ s}$ for C1-125-C-45deg010 geometry
b) Contact status at $T = 0.13$ s for C1-125-C-45deg010 geometry

c) Contact status at $T = 0.5$ s for C1-125-C-45deg010 geometry
d) Contact status at $T = 0.6 \text{ s}$ for C1-125-C-45deg010 geometry

e) Contact status at $T = 1 \text{ s}$ for C1-125-C-45deg010 geometry
f) Contact status at $T = 1.5$ s for C1-125-C-45deg010 geometry

g) Contact status at $T = 1.8$ s for C1-125-C-45deg010 geometry
Figure 6-26: h) Contact status at T = 2 s for C1-125-C-45deg010 geometry

Shown in this series of figures is contact status over the course of the upper tooling incrementally applying force to the coin blank (max force occurs at 1.0 s) then releasing the force. This process is as follows:

a) A very small force is applied by the upper tooling, not enough to yield the material but enough to lift the center of the coin blank very slightly.

b) Some of the blank begins to yield, with some sliding towards the axis of symmetry, but most sliding outwards to fill the initial gap left between the blank and outer die.

c) Very little material remains still as the blank continues to expand in diameter.

d) Blank material contacts the outer die, causing most slipping against the punches to stop, while the center of the blank is squeezed up nearly into contact with the center of the punch.

e) Maximum applied force. Most of the blank is nearly in contact with the punches.

f) Force is partially removed and the center of the coin begins to spring back.
g) Most force is removed and small patches of sliding occur due to small amounts of spring back.

h) The force is fully removed, the formed center of the coin has sprung back further from the punch, and the finished coin is obtained.

Figure 6-27 shows the deformed shape and Von Mises stresses observed at the moment that a maximum force of 266.9 kN (60000 lb) is applied.

![Figure 6-27: Contours of Von Mises Stress (psi) at peak applied force for C1-125-C-45deg010 geometry](image)

The material used has a yield stress of 300.65 MPa (43600 psi), corresponding to the first four level of contours not yielding. This reveals that the only yielding which has occurred is located directly between the areas of the punches which initially contact, and at the corner of the design edge.
6.4.2 Ghost coining

Using FEA to observe the state of the coin material through the process helps us understand the phenomenon of ghost coining observed in this experimental work and why it occurs. Since the full volume of the material must exceed the yield stress in order to produce a 100% formed coin and will only begin to yield if compressed directly between the two punches. These experiments used a punch design with geometry much wider than it is deep and thus required the yielding outer material to push the inner coin material inwards and against the die, buckling it upwards rather than forming it properly, causing ghost coining.

In the experimental tests, ghost coining was observed to occur in two modes, the first mode appears to be caused by a single occurrence of buckling, while the second mode is caused by two occurrences of buckling where the material has moved up as well as down. A diagram of these modes is shown in Figure 6-28.

![Diagram of ghost coining modes](image)

Figure 6-28: The two observed modes of coin buckling or ghost coining.
The second mode of ghost coining appeared to be the more severe of the two cases, only being produced at higher forces and with certain punch geometry. It was observed in the experimental tests that ghost coining became much more pronounced with higher forces, thinner blanks, and deeper punch designs. Ghost coining was very minor on all 3.175 mm (0.125”) blanks, typically of the first mode on 1.600 mm (0.063”) blanks, and very often of the second mode on 0.813 mm (0.032”). Examples of ghost coining are shown in Figure 6-29.

![Figure 6-29: Examples of ghost coining for three thicknesses of copper blanks.](image)

L-R 0.813mm, 1.600 mm, 3.175 mm

The thinnest coin shows a large ghost coined circle of the second mode, the middle coin shows a large circle ghost coined of the first mode, and a very small impression can be seen on the back of the thickest coin.

Ghost coining is not seen on typical coins used for money since this appears to be caused by the very large aspect ratio (width to depth) of the punch designs. This large gap not being pressed on by the punches allows for buckling of the material and actually brings this phenomenon more into the realm of sheet metal forming rather than bulk closed-die forming, especially for thinner coins.
Chapter 7
Conclusions and Summary

A number of aspects of the coining process have been investigated, both through experimentation using several types of tooling and materials, and by developing and using a FEA model. Several relationships have been found which describe the effects of changing the type of coin blank or the geometry of the coining tooling has on how much volume of the coin is formed at different forces.

Coins tested were made of copper 110 and brass 260. The open-die bulk upsetting test was used to find the true stress and strain curves of both materials, and the ring test was used to determine the coefficient of friction between copper and the tooling to be an average of 0.114, and between brass and the tooling to be an average of 0.098. The results from these experiments were used as inputs into the FEA model of the coining process.

Experimental tests allowed us to find many relationships while some tests proved inconclusive. Coins were formed to 333.3 kN, 444.8 kN, and 556.0 kN in order to compare different geometries. By testing the process over a wide range of forces we found a general force-% coined curve shape which is expected of all coins. Just after the yield stress of the blank material is reached, the diameter quickly increases until it contacts the outer die and the diameter is formed at about twice the force as at yielding. While the diameter begins to increase, the thickness of the
coin reduces and material is pushed into the punch cavity, filling the design’s volume up rather linearly. The force limit of our press was reached before any coins could be 100% formed.

Tests on the effects of changes in the wall angle were inconclusive. As the punch design depth increased the force requirement went down in a manner roughly inverse of the ratio of the increase in depth. Graphs of this showed that either a linear or an inverse logarithmic relationship is possible. Effects of coining with a punch on one side versus two sides was tested and found that the single sided coins universally required more force for the same degree of coining. Effects of the perimeter of the punch design were surprising. It was expected that a longer perimeter increased friction and would require more force to form. However, it was found that a longer perimeter actually reduced the forces required for thinner coins, a difference that got smaller as the coin blanks got thicker. The FEA model revealed that this is because the ring punches had a more spread out initial contact area and thus was able to yield the blank material more effectively than the circle punches.

Different thicknesses of blanks were tested, 0.032”, 0.063”, and 0.125” thick. Thinner blanks required 1.4 times the force to form than a coin half its thickness. Different materials were tested and, based on the literature, a direct correlation of forming force to the yield stress of the material would be found was expected. We found however that even though the yield stress and modulus of elasticity of both materials were nearly identical, they did not behave the same. It rather seemed to be related to the full true stress-strain curves of the material, as the force requirement for brass coins increased for more demanding punch designs and for higher forces.
Power used by the hydraulic press was measured for each experimental sample but was relatively inconclusive since the logging frequency of the power meters was only 1 Hz and the extra power used to deform the blank into a coin was so much smaller than the auxiliary power.

The FEA model was able to match experimental results relatively closely, but only up to about 333.3 kN, the lowest force used for the bulk of the experimental samples. Under high loads the mesh would become excessively distorted and elements could become inverted, preventing proper solution convergence. Until this force though, the FEA model provided us a good look into what happens to the coin while it is under load and the mysteries of ghost coining were unveiled.

All results, both experimental and from the FEA model, have given us great insight into what really happens during the coining process, what factors affect the forming forces required, and steps which would be useful to take in order to perform further research. Performing this work and developing the FEA model of the coining process allows us to understand the coining process more completely and will allow designers to determine required forces, energy consumption, and greenhouse gas emissions in order to make the process more economical and environmentally friendly.
Chapter 8

Recommendations

Originally it was planned to program the press controller to use a double disturbance rejection negative feedback controller to control the force and position of both hydraulic rams. This was not eventually used due to increased programming complexity and limitations of the sensors. In addition to being able to have better control over position during coining, this type of controller would allow the user to easily control the strain rate during the coining process and could actually follow a predefined strain rate curve.

While interesting to study, the phenomenon of ghost coining does not show up on typical coins used for money and were very apparent in these experiments due to the very large width to depth aspect ratio of the punch designs. The FEA model showed us that this large aspect ratio caused the blank material to be pushed inwards and buckle, causing the design to show through the coin, rather than pressing and forming the material. It is advised that further studies on coining investigate the effects of this width-to-depth aspect ratio of the punch design, or at least keep it closer to 1 in order to better study the effects of coining instead of sheet metal buckling. It would also be advantageous to narrow the field of study on coining on a per-project basis in order to increase the quality of the results. Since this project is very much an introductory study of the coining process, a more overall approach was taken to study many different aspect of the process.
The FEA model developed is also very introductory with respect to the coining process. A better model should be able to be developed which can model the process all the way to forming a coin 100% without running into solution convergence issues. It may require a finer mesh, some type of refined mesh, a total makeover in terms of the settings and physics used, or may just require more computational resources.
References


A.1 Feedback Controllers

Control theory is a branch of mathematics which deals with controlling a continuous dynamic system by manipulating inputs to the system in order to obtain the desired behavior. An open loop controller receives no feedback on the actual outputs of the system; rather it relies on a known relationship to control the output such as controlling the speed of an electric motor under a constant load by varying the voltage input alone. However, a feedback controller uses measurements of the system’s output fed back into the controller in order to actively alter the inputs to the system to control the output. Typically, the objective of feedback controls is to calculate the necessary input to the system required to correct for error measured between the system output and the desired set point.

Closed loop controllers have several advantages over open loop controllers. They are able to compensate for unforeseen disturbances such as increasing the force on a hydraulic cylinder which is having its position controlled, it is guaranteed to perform even with small uncertainties in the system model since the feedback gives information about what is happening, and it can stabilize unstable systems.

The transfer function of a controller is a mathematical representation of the relationship between the input and output of a system, in terms of spatial or temporal frequency. A system’s transfer
function is found by taking the Laplace transform of the (typically) differential equations which relate the inputs and outputs. Block diagrams are extensively used to graphically display and organize the relationships concerning the controller. An example of a generic block diagram for a closed loop, single input and single output (SISO), negative feedback control system is shown in Figure A-1.

![Generic negative feedback block diagram.](image)

Figure A-1: Generic negative feedback block diagram.

To find the transfer function of this system we can represent the relationships between the inputs and outputs of each part of the controller by functions as shown in Figure A-2.

![Block diagram labeled with functions for finding the transfer function.](image)

Figure A-2: Block diagram labeled with functions for finding the transfer function.

Assuming the controller, system, and sensor all have linear relationships which do not change with time, then using this new block diagram we can find the signal at each point as a product of
the preceding function and its input, each as a function of $s$. The Laplace transform is taken at the end to change the overall relationship from a function of $s$ to a function of time, $t$. Therefore:

**System Output**

\[ Y(s) = P(s)U(s) \]

**System Input**

\[ U(s) = C(s)E(s) \]

**Error**

\[ E(s) = R(s) - F(s)Y(s) \]

Therefore, the system output in terms of the controller inputs becomes:

\[
Y(s) = \left( \frac{P(s)C(s)}{1 + F(s)P(s)C(s)} \right) R(s)
\]

The overall system output transfer function is then written as:

\[ Y(s) = H(s)R(s) \]

Where $H(s)$ is termed the “closed loop transfer function” of the system and is a product of the desired set point. Now, to become useful to a programmer, the Laplace transform of this function must be taken, but will not be discussed here.

A PID (Proportional-Integral-Derivative) controller is an extremely widely used and simple to implement feedback controller. It consists of the sum of three terms, each a function of the error
between the measured system output and the desired set point. As the name of the controller suggests, one term is purely proportional to the error, one term integrates the error and multiplies by a factor, and the final term differentiates the error and multiplies by a factor. The three factors \((K_P, K_I, \text{ and } K_D)\) are “tuned” to the system based upon certain recommendations and do not require any specific knowledge of the relationships within the system to produce an effective and stable controller. The PID controller can be written as the following.

\[
u(t) = K_P e(t) + K_I \int e(t) dt + K_D \frac{d}{dt} e(t)\]

Where the error is defined as:

\[
e(t) = r(t) - y(t)\]

Given that \(r(t)\) is the desired set point and \(y(t)\) is the measured system output. An example of how a PID was incorporated into the “eject” case of the coin press LabVIEW controller is shown in Figure A-3.
Figure A-3: PID controller implemented in the coin press controller block diagram.

All inputs and “K” factors originate from outside of the case loop, to the left. Moving from the left to the right of the case, the different terms can be identified. First, the subtraction of the measured position from the set point position is seen near the left, in the middle is the integral and derivative functions, followed by multiplying the results with the “K” factors, then finally the three terms are added together and output to the right side of the case loop.

A.2 LabVIEW

Made by National Instruments, LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a software package used as a system design platform and development environment which uses a graphical programming language (named “G”). LabVIEW is widely used for virtual instrumentation, data acquisition, data storage, and analysis for a wide range of
applications. It is ideal for testing and measurement, automation, instrument control, data acquisition (DAQ), and data analysis.

A LabVIEW program is called a virtual instrument (VI) and consists of the front panel and the block diagram. The front panel is used to display controls and indicators to the user during operation of the VI while the block diagram contains the graphical code. Block diagrams are easily created by dragging and dropping the desired elements of the system into place and connecting them together with wires. Controls and indicators on the front panel are linked to elements on the block diagram. The wires do not represent electrical flow as is the case with other wiring diagrams, but instead dictate the flow of data from the output of one element to the input of another. LabVIEW VI’s are compiled into executable code which LabVIEW processes during the runtime rather than compiling stand-alone code like many other programming languages such as C.

LabVIEW applications execute based upon the data flow rather than a fixed order like when programming in C. VI’s are broken up into nodes and wires where each element (node) in the block diagram has inputs and outputs which are connected together by wires which define the data flow. An element can only be executed when all the necessary inputs are available. For example, when adding two numbers together they are only added when both are available, so if one number must first be output from another element, the execution of this element is suspended until it receives the input data from the earlier element. Loops and circuits wired in parallel are also executed in parallel which helps LabVIEW in being very well suited for multi-tasking.
Elements that can be placed on the front panel consist of controls and indicators: Boolean buttons, knobs, numerical or string inputs, and graphs. Elements used in block diagrams cover a huge range of operations such as: simple math (addition, multiplication…), Boolean operations, integration, differentiation, and other data analysis. Structures are also a fundamental part of the block diagram and consist of: sequence structure, case structure, for loop, and while loop.

Structures influence how and when different elements executed in the block diagram. A while loop is commonly used to keep the VI running until the user manually tells it to stop, or part of the VI indicates it is finished and stops the while loop automatically. A case structure acts the same as a while loop but has several different cases, each which contains different elements and wiring and executes different programs according to which case is selected. A special variant of the case structure, called a state machine, uses an output from the current case to instruct the case structure to switch to another case, allowing easy programming of distinct operations with a certain logical order. A state machine structure within a while loop forms the core of the coining press control system.

Figure A-4 shows an example of a LabVIEW block diagram which simulates the level of water in a tank. The thick black box is a while loop which keeps the elements inside it running until the stop button is pressed, everything outside of the black box are different parameters which are set just as the while loop executes the first time and dictate how the simulation will run..
Figure A-4: Example of a LabVIEW block diagram [13].

The front panel that corresponds to the block diagram shown in Figure A-4 is shown below in Figure A-5. Each element on the front panel has a label which matches labels found on the corresponding elements on the block diagram.
Several types of controls and indicators can be seen in Figure A-5. There are several numerical controls (e.g. “Time_step”, h_max[m]”) are scattered around, indicating the current value of the data as well as providing up and down arrows to easily change the value. Another style of control is seen in the top left (“Pump control, u [A]”), a slider bar which limits the range of the data and provides a visual indicator of the data value. The large blue fill bar indicates the current level of the tank being simulated, and the graph to the right shows the tanks level over time.
Appendix B
Basic theory of non-linear FEA

In this paper we will only be addressing methods applied when using FEA for stress analysis of solid mechanical structures. Other similar methods, conditions, or notation may be used when dealing with other FEA problems such as fluid dynamics and thermodynamics.

The process of FEA is based on the two conditions that: a finite number of parameters determine behavior of a finite number of elements that make up continuum domain, and that the solution of the complete system is equivalent to the assembly of the individual elements.

The following is a simplified procedure one would take in order to use FEA to find a solution to a problem. First, the user required knowledge of the real physical structure. Typically, real-world problems involve very complex shapes, whether man-made or natural, thus it is necessary for the user to first simplify the problem geometry. After this, boundary conditions, applied loads, and material properties can be identified. With real world observations inevitably come experimental errors of all sorts (instrumental etc.).

Once the problem has been simplified and all of its characteristics found, the user should use mathematical models and analytical methods to find an approximate solution to the problem. This step is not necessarily required to perform a FEA, but it is of the utmost importance that the user understands the problem at hand and the physics of the problem. FEA is, by nature, a ‘garbage in, garbage out’ (GIGO) process, meaning that if a user is not fully aware of what they are doing
then nonsensical input data will be processed into nonsensical output data. While the analysis may appear to work and produce a solution, no confidence should be put into this solution since its analysis performed by someone who did not understand the problem in the first place. Understanding and calculating rough mathematical or theoretical solutions allows a user to set up a FE analysis properly, and gives them something to compare to the FE solution. Therefore, performing rough calculations beforehand, in order to fully understand the problem at hand, is the only way to instill confidence in a solution produced by a FEA. The solution for this step has modeling (idealization) error in it now.

Now a FEA can finally be conducted. An assumption about the field quantity is made, such as assuming it is a polynomial over each discretized element (Gaussian quadrature). The FEA solution is a numerical solution, since only numbers are put out rather than functions, and includes discretization error and calculation error (round-off, truncation).

Verification of a computational numerical model is to determine if it is an accurate discrete analog of the mathematical model. Validation is the process of determining how well the mathematical model (and hence the verified computational numerical model) represents the physical reality of the system. All commercial FEA packages have been verified and validated for the methods used on basic, well-understood problems. This relationship of verification and validation between the four different types of solutions is shown in Figure B-1.
Figure B-1: Relationship between verification and validation of different solutions

The computational cost of FEA, a measure of the computing effort needed to solve a problem, is an important concept to understand in order to utilize the technology to its full potential. Solutions requiring a high computational cost take a longer time to run (or require more expensive computing equipment) when compared to solutions requiring less computational cost. However, solutions of low computational cost run the risk of greater inaccuracies, errors, or instability. Complex problems can take many weeks or months to solve, so methods of reducing computational cost or actual solution time are highly desirable.

For a problem of a certain cost, the actual solution time can easily be reduced by using higher capacity computing equipment (such as distributed computing, using computers with faster processors, or multiple processors within a computer) but comes at the expense of much higher monetary costs. Reducing computational cost is an effective way of lowering solution times while maintaining the same level of computing capacity, but requires greater user effort and knowledge.
in order to maintain reliable results. It is the responsibility of the user to reduce computational costs by ensuring the FEA problem is not unnecessarily complex and by performing a mesh convergence check. Performing a FEA of a static problem using transient analysis, or running a non-linear analysis of a linear problem are two examples of a FEA which is unnecessarily complex. Problems with geometric symmetry (including axisymmetry) only require half of the geometry to be modeled and will essentially cut the solution time in half as well. A mesh convergence analysis is a relatively user-time consuming process but can yield impressive time savings in the long run, especially in situations where a large number of simulations need to be performed under slightly varying conditions. For a mesh convergence, the user runs several FE simulations, increasing the mesh density for each successive run, and compares the results between successive iterations, as shown in Figure B-2.

![Displacement Magnitude](image)

Figure B-2: A plot of maximum displacement versus n shows the changes in displacement results for the different mesh densities [14]

For a stable and properly solvable FEA problem, as the mesh density is increased, the solution will eventually tend towards a single value, which we could consider to be the “true” solution that
the FEA will produce. However, getting the most accurate solution possible using a very fine mesh comes at the cost of massive computational effort, so it is wise to choose a coarser mesh while still retaining an accurate enough output value. Typically, a mesh is considered suitably converged when two consecutive values do not differ appreciably, usually within 1% difference. Advanced users can also perform local mesh refinement to reduce computational cost while maintaining accuracy. Local mesh refinement creates a higher mesh density in areas of high interest, and lower density in less interesting areas, as shown by example in Figure B-3.

![Figure B-3: Example of local mesh refinement](image)

(a) A locally refined mesh  
(b) A body-fitted mesh

When a FEA is solving, many iterations (consisting of calculating the governing equations simultaneously) are performed until it arrives at an acceptably close solution. This is similar to what was seen with mesh convergence, where the higher and higher mesh density got closer and closer to the mathematical answer. While solving, this comparison of answers is performed on the sum of the absolute value of the residuals (errors caused by calculation errors) of the governing equations. While a small overall residual is not necessarily indicative (but still very reliable) of a properly converged FEA, a large residual value is a definite indicator that something is wrong.
A FEA solution is considered to be converged when the residuals reach a certain value, ANSYS uses 1% as the default convergence criteria for force, moment, and volume convergence.

**B.1 Linear FEA**

In FEA, the general discretization of a continuum problem is posed by mathematically defined statements in the form. For static solid mechanics problems, the structure must be in equilibrium. For 2-D, that is:

\[ \sum F_x = 0, \sum F_y = 0, \sum M = 0 \]  
Equations for equilibrium \hspace{1cm} (B-1)

This equilibrium does not account for inertial, acceleration, or thermal effects. To understand the workings of FEA we will first examine an infinitesimally small unit cell of a solid in 2-D. We will take a unit cell which is square and of dimensions \( \Delta x \) and \( \Delta y \) as shown by the solid square block in Figure B-4.
Normal strain ($\varepsilon$) in either direction is the ratio of change in length of a deformed shape to the length of the original, undeformed shape. The horizontal strain for Figure B-4 (a) can be expressed as:

$$\varepsilon_x = \frac{\Delta u}{\Delta x} \rightarrow \varepsilon_x = \frac{\partial u}{\partial x}$$  \hspace{1cm} (B-2)

And vertical strain for Figure B-4 (b) as:

$$\varepsilon_y = \frac{\Delta v}{\Delta y} \rightarrow \varepsilon_y = \frac{\partial v}{\partial y}$$  \hspace{1cm} (B-3)

The shear strain ($\gamma$) is the amount of change in a right angle of the deformed unit when compared to the undeformed one. Since we are only dealing with linear FEA for now, it must be assumed that only small deformations take place. The shear strain for Figure B-4 (c) is:
When $\theta_1, \theta_2 \ll 1$, 

\[ \gamma_{xy} = \theta_1 + \theta_2 \approx \tan \theta_1 + \tan \theta_2 \implies \gamma_{xy} = \frac{\Delta v}{\Delta x} + \frac{\Delta u}{\Delta y} \quad \text{(B-4)} \]

\[ \varepsilon_{xy} = \frac{1}{2} \gamma_{xy} = \frac{1}{2} \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \quad \text{(B-5)} \]

Where $\varepsilon_{xy}$ is known as the (average) shear strain, and $\gamma_{xy}$ is called the engineering shear strain.

We can now easily expand this example into a 3 dimensional form by adding the original depth ($\Delta z$) and change in depth ($\Delta w$) and expressing it in matrix form following the previous equations.

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy} \\
\gamma_{yx} \\
\gamma_{yz} \\
\gamma_{zy}
\end{bmatrix} = \begin{bmatrix}
\frac{\partial}{\partial x} & 0 & 0 \\
0 & \frac{\partial}{\partial y} & 0 \\
0 & 0 & \frac{\partial}{\partial z} \\
\frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z}
\end{bmatrix} \begin{bmatrix}
u \\
y \\
w
\end{bmatrix}
\]

\text{Strain-Displacement Relationship (B-6)}

This form does not change for different materials since it only involves changes in dimension. This is a linear operation and is fine for very small strains (because we assumed $\theta_1, \theta_2 \ll 1$) and a different relationship must be used for nonlinear problems.
\[
\varepsilon_x = \frac{1}{E} \left[ \sigma_x - \nu (\sigma_y + \sigma_z) \right]
\]
\[
\varepsilon_y = \frac{1}{E} \left[ \sigma_y - \nu (\sigma_z + \sigma_x) \right]
\]
\[
\varepsilon_z = \frac{1}{E} \left[ \sigma_z - \nu (\sigma_x + \sigma_y) \right]
\]
\[
\gamma_{xy} = \frac{\tau_{xy}}{G}
\]
\[
\gamma_{yx} = \frac{\tau_{xy}}{G}
\]
\[
\gamma_{xy} = \frac{\tau_{xy}}{G}
\]

where:

\[
G = \frac{E}{2(1+\nu)}
\]

Shear Modulus \hspace{1cm} (B-8)

Where E is the Elastic modulus and \(\nu\) is the Poisson’s ratio of the material. If the material is isotropic, then one value each of E and \(\nu\) is necessary since these materials properties will be the same in all directions. If the material is non-homogeneous then E and \(\nu\) will be different for different unit cells, and also have different directional values if it is anisotropic non-homogeneous. The six Equations in B-7 can be expressed in matrix form as:

\[
\{\varepsilon\} = [C]\{\sigma\}
\]

(B-9)

In which [C] is known as matrix of material compliance. Or alternatively it can be expressed as:
\( \{ \sigma \} = [E]\{\varepsilon\} \)  

(B-10)

Where \( [E] = [C]^{-1} \) and \([E]\) is known as the matrix of material stiffness (stiffness matrix). We now have the governing equations required for FEA; the requirements for equilibrium, the strain-displacement relationship, and the stress-strain constitutive equations. We can now generalize the form of linear FEA as:

\[
[K]\{\dd \} = \{\dd \} \quad \text{General linear FEA form} \quad (B-11)
\]

Similar in appearance to Equation B-10, the general form of FEA consists of:

- \( [K] \) - the general stiffness matrix (Property)
- \( \{\dd \} \) - a vector of unknowns such as resultant strains (Behavior)
- \( \{\dd \} \) - a loading vector such as the applied forces (Action)

Examples of properties, behaviors, and actions across different disciplines are shown in Table B-1

<table>
<thead>
<tr>
<th>Property</th>
<th>Behavior</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>Stiffness</td>
<td>Displacement</td>
</tr>
<tr>
<td>Thermal</td>
<td>Conductivity</td>
<td>Temperature</td>
</tr>
<tr>
<td>Fluid</td>
<td>Viscosity</td>
<td>Velocity</td>
</tr>
</tbody>
</table>

Table B-1: Properties, behaviors, and actions for different disciplines
The preceding has been a look into what is required to perform a structural analysis of a single unit cell, or element. By connecting several elements together by their edges (or faces in 3D) we can construct a much larger and more complicated geometry of a real-world problem. This only requires that the same equations need to be solved for each element, but they must be performed simultaneously.

**B.2 Non-linear Analysis**

Difference between linearity and non-linearity, if for any two vectors \((x\text{ and } y)\) in the same vector space, and a scalar \((a)\), a function \((f(x) = y)\) is said to be a linear map if the conditions of homogeneity and additivity are met, shown below.

\[
f(ax) = af(x) \quad \text{Homogeneity} \quad (B-12)
\]

\[
f(x_1 + x_2) = f(x_1) + f(x_2) \quad \text{Additivity} \quad (B-13)
\]

This indicates as well that linear solutions due to various loads are also able to be scaled (multiplied by a scalar) and superimposed (results from individual loads added together). Using Equations 3-11 and 3-12, we also find that any linear mapping of a zero vector must result in a zero vector as well, that is:
\[ f(0) = 0 \]  
Linearity of a zero vector  \hspace{1cm} \text{(B-14)}

All problems that do not satisfy the conditions of homogeneity and additivity are non-linear. We can now create a form for the general solution of both linear and non-linear problems.

\[ [K]\{\bar{u}\} = \{\bar{F}\} \]  
General linear FEA form  \hspace{1cm} \text{(B-15)}

\[ [K(\bar{u})]\{\bar{u}\} = \{\bar{F}\} \]  
General non-linear FEA form  \hspace{1cm} \text{(B-16)}

Where \( K \) is the stiffness matrix, \( \bar{u} \) is the input vector, and \( \bar{f} \) is the output vector. Note that for the non-linear general solution, the stiffness matrix is a function of the input vector, therefore to solve the problem we must know the input as well as a function of the input, requiring more time.

Nearly all problems in the real world are non-linear in some way or another and over a full range of inputs, but using careful assumptions of the smallness of certain quantities, many problems can be reduced into a much simpler to solve linear problem. In mechanical engineering, a very common use of the assumption of linearity occurs when studying small deformations of metals. If we are able to assume that all strains within the problem will be small (typically strain < 0.002 (0.2%)), then we are able to state that the problem stays within the elastic zone of the materials stress-strain curve, and thus is linear, as seen by:

\[ \sigma = E\varepsilon \]  
Hooke's Law  \hspace{1cm} \text{(B-17)}
If great care is taken when making assumptions of linearity, such as with elastic deformation of metals, very reasonable solutions of the behavior of the problem can be made. However, many problems are in fact not linear and foolish assumptions of linearity will lead to unrealistic solutions, such as using Hooke’s Law to solve for a problem in which a metal will yield.

Linear FEA problems are solved by performing calculations of a set of many equations which are solved simultaneously. Iterations of these calculations are performed until the solution tends towards a single value and a good approximation of the answer to the real-world problem is found. However, the solution to a non-linear FEA problem cannot be solved so simply. The FEA solver must progress gradually from the initial conditions of the system to the final conditions. This uses an extra lever of iterations (load steps), in which it solves over the course of small increments or time steps, using the results from the previous iteration as the initial starting point for the current one. Time is not necessarily treated as actual time, but merely as a counter during the solution. Load steps are user selected points which describe the load history, whereas substeps are incremental solutions within a load step to enhance stability and accuracy. Using substeps which are too small will result in unnecessarily long solution times, and too big will cause errors or divergence.

This gradual progression towards the final conditions can use ramped loading, where the applied loads are linearly interpolated for each substep from the values of the previous load step to the values of this load step, or can use stepped loading, where the load is changed at the first substep of the current load step and is kept the same for all substeps. Stepped loading is useful for transient load steps and rate-dependant behavior such as creep and viscoplasticity. When applying
loads progressively the first step should not cause yielding, and many small steps should be used at an abrupt transition. “Mildly” nonlinear problems are able to take larger steps and typically the FEA solver can automatically adjust the stepping process based upon the progression of the solution. This requires a little more computational time but will usually result in a closer result than if the user spends more human time trying to control the stepping process manually.

Based on the types and severity of nonlinearities in the model, an FEA program may also set several solution options in order to increase success in solving. In ANSYS, the “solution controls” can consist of: load increments, automatic adjustment of load increments during the solution, convergence tolerances, convergence enhancement tools, reasonable limit on equilibrium equations, activates prediction on contact changes and onset of yielding.

There are three main sources of non-linearity which concern us when using FEA for stress analysis of solid mechanics: geometric, material, and boundary conditions.

**B.3 Geometric non-linearity**

Geometric non-linearity accounts for changes in stiffness that are not from material properties, but are due to complications such as large deflections, large rotation, large strain, and stress stiffening. Geometric nonlinearities are a concern in structural FEA especially when a structure may experience large deflections. Large deflections can cause a change in the structures geometric configuration and will cause the structure to respond nonlinearly. An example of geometric non-linearity due to changing geometric configuration is shown in Figure B-5.
A beam is pinned to a fixed support on one end about which a torsion spring is attached. This spring will resist upwards forces applied to the end of the beam. Ignoring gravity in this problem, we start with the condition of equilibrium from which we can find the balance of the moments about the pinned joint on the beam.

\[
\sum M = 0 \rightarrow FL \cos \theta - k_T \theta = 0
\]

Rearranging this gives:

\[
\frac{k_T}{L \cos \theta} \theta = F
\]

which is in the general form of a non-linear problem.

\[
[K(\bar{u})][\bar{u}] = \{\bar{F}\}
\]
If we are able to assume that the angle of this beam will only undergo very small changes then we can simplify the problem to one of the linear type.

\[
\text{If } \theta \ll \frac{\pi}{2} \text{ then } \cos \theta \approx 1
\]

Starting with equilibrium of moments:

\[
\sum M = 0 \rightarrow FL \cos \theta - k_T \theta = 0 \rightarrow FL - k_T \theta = 0
\]

can be rearranged into:

\[
\frac{k_T}{L} \theta = F
\]

which is in the general form of a linear problem.

\[
[K]\{\ddot{u}\} = \{\ddot{F}\}
\]

If we plot the linear and non-linear solutions to this torsion spring and beam problem, we can easily see why care must be taken when assuming linearity of a problem.
For rotations under 0.3 the two curves remain fairly close to each other, differing by just 0.013 (5%) at a rotation of 0.3 rad. After this point though, the curves start to depart more and more until the non-linear solution becomes undefined at $\pi/2$. This is a non-linearity of the hardening type, since changes in the system's geometric configuration cause the artificially increase the stiffness.

**B.4 Material non-linearity**

Material non-linearity is caused by factors which are built directly into the material itself, as opposed to being caused by changing geometric configuration which artificially changes the
stiffness of the system. Seen in all non-brittle metals, the non-linear relationship between stress and strain beyond yielding (plastic deformation) is a main cause of material non-linearity.

Material data of the stress-strain relationship requires definition of a hardening rule if unloading or reversed loading occurs in the problem, that is, isotropic hardening (no Bauschinger effect), or kinematic hardening (with Bauschinger effect). A yield criterion is used to determine the state of yielding for an element. Examples of yield criterion are: Tresca (ductile materials), von Mises (ductile materials), Mohr-Coulomb (brittle materials), and Drucker-Prager (pressure-dependent materials such as soil and foam). Using true stress-strain or engineering stress-stain curves in the correct situations is important. Additionally, temperature and strain rate can also affect the material data.

Looking back to the torsion spring and beam problem of section 0, if we find that the spring constant changes with the angle of the beam to the horizontal, then this adds in a factor of material non-linearity. Let the spring constant be expressed as:

\[ k_T = k_0 - k_1 \theta \rightarrow \]

Adding this new torsion spring relationship into the non-linear solution found in section 0, we find:
\[
\frac{k_0 - k_1 \theta}{L \cos \theta} \theta = F
\]

This solution now involves both geometric and material non-linearity and again shows the general form of a non-linear solution. Adding the new torsion spring relationship into the linear solution in section 0 we find:

\[
\frac{k_0 - k_1 \theta}{L} \theta = F
\]

This also gives us a non-linear solution fitting the general form and considers only material non-linearity. Again the assumption is made that \( \theta \ll \pi/2 \). Plotting these new solutions along with the ones from Section B.3, we produce Figure B-7.
Figure B-7 shows just how much variation there can be between a linear solution and different types of non-linear solutions, even for such a simplistic problem like a torsion spring attached to a pinned beam. This shows very clearly that it is critical that the problem is fully understood and that the proper analysis is used.

**B.5 Boundary non-linearity**

Boundary condition non-linearity occurs in problems with features in which the stiffness of a structure changes based upon its status, such as whether a tension-only cable is slack or taut or if a roller support is in contact with another structure or not. Status changes may relate directly to
the load as in the case with the cable, or indirectly as with a bending beam contacting another beam, or determined by some other external cause. Figure B-8 shows an example of a changing status non-linearity problem in which we want to investigate the displacement of point B as a result of the tension load, \( P \). However, this tension force will eventually cause point C of the bar to come into contact with the other wall, changing the boundary conditions of the problem.

![Figure B-8: Example of a boundary non-linear problem](image)

We will only consider horizontal displacements in this problem, that is, along the axis ‘\( u \)’. The first boundary condition of this problem is that the horizontal position of point A cannot move.

\[
\begin{align*}
    u_A &= u(0) = 0
\end{align*}
\]

This boundary condition must be satisfied regardless of status. The governing equation for this problem is the mathematical model of an axially loaded bar.

\[
P = EA \frac{du}{dx} \quad \rightarrow \quad u(x) = \frac{px}{EA}
\]
When the bar is not contacting the second wall, the displacements of points B and C are the same and are both less than the unstressed distance between the bar and the second wall. That is \( u_B = u_C < u_0 \). There is a non-contact status and we obtain the free-body diagram shown in Figure B-9.

\[
\begin{align*}
L & \quad \text{Left half} & \quad P \quad \text{Right half}
\end{align*}
\]

\textbf{Figure B-9: FBD with non-contact status}

Where the displacement of a point located at \( x \) is:

\[
u(x) = \begin{cases} 
\frac{Px}{EA}, & 0 \leq x \leq L \\
\frac{PL}{EA}, & L \leq x \leq 2L
\end{cases}
\]

When the applied force causes the bar to contact the second wall, that is \( u_B \geq u_0 \), the contact status is changed and we obtain the free-body diagram shown in Figure B-10.

\[
\begin{align*}
P/2 & \quad \text{Left half} & \quad P/2 \\
\text{Right half}
\end{align*}
\]

\textbf{Figure B-10: FBD with contact status}
where:

\[
u(x) = \begin{cases} 
\frac{Px}{2EA}, & 0 \leq x \leq L \\
\frac{P(2L - x)}{2EA}, & L \leq x \leq 2L 
\end{cases}
\]

Figure B-11 shows the relationship that is obtained when the above solutions are put together and solved for the displacement of the bar at point B when subjected to different loads.

While the solution can be found using a linear analysis for small loads which do not cause a change in status, the non-linear nature of the full solution shown in Figure B-11 is very clear and boundary non-linearity must be taken into account.

While any problem may be solved using a non-linear FEA, it is unnecessary to do so in certain situations where linearity of the system can be assumed. Non-linearity of a solid, structural
system must be taken into consideration when there are changes in geometric configuration, material properties, and boundary conditions. Non-linear behavior will occur in systems which experience: large displacements or deformations, material yielding/plasticity, and changing status of contact or interference. When using FEA to study the coining process, we must consider all three types of non-linearity since the process involves large strains, yielding of the material, and changes in contact between the coin and the dies.
Appendix C
ANSYS FEA Journal File

!Circle Punch Coin Model

!BIN consistent units: in, s, lbf, psi

!Clear any previous work and enter preprocessor menu
finish
/clear
/prep7

!Define element type #1 as PLANE42 with axisymmetry
et,1,42
keyopt,1,3,1

!create material data table - multilinear isotropic hardening for Von Mises plasticity
tb,miso,1,1,8
  tbtemp,0
  tbpt,defi,0.0169,43605.59
  tbpt,defi,0.0586,50111.98
  tbpt,defi,0.1354,62171.86
  tbpt,defi,0.2259,86214.76
  tbpt,defi,0.2989,120146.33
  tbpt,defi,0.3453,152695.69
  tbpt,defi,0.3835,194650.75
  mp,ex,1,2580212.43
  mp,prxy,1,0.343

!parameters for adjustable geometry

!thickness of blank
blank_t = 0.125

!depth of punch design
punch_d = 0.010

!radius to inner corner of punch design wall
R1 = 0.246455

!radius to outer corner of punch design wall
R2 = 0.253526068
!define coin blank geometry
k,1,0,0
k,2,0.495,0
k,3,0.495,blank_t
k,4,0,blank_t
l,1,2
l,2,3
l,3,4
l,4,1
al,1,2,3,4

!define tooling boundary geometry
k,98,0,0
k,99,0.499,0
k,100,0,blank_t+punch_d
k,101,R1,blank_t+punch_d
k,102,R2,blank_t
k,103,0.499,blank_t
lstr,99,98
lstr,100,101
lstr,101,102
lstr,102,103
lstr,103,99
lfillt,6,7,0.001
lfillt,7,8,0.001

!mesh coin blank
esize,0.002
type,1
mat,1
amesh,all
allsel

!define contact and target element types friction
et,2,169
et,3,171
keyopt,3,10,2
mp,mu,2,0.12
allsel

!create contact pair 3
r,3

!mesh bottom with TARGE169
type,2
real,3
mat,2
lesize,5,,,1
lmesh,5
allsel

!mesh bottom of blank with CONTA171
lsel,s,line,,1
nsll,s,1
type,3
esurf
allsel

!create contact pair 2
r,2

!mesh remaining tooling with TARGE169
type,2
real,2
mat,2
lesize,6,,,1
lesize,7,,,1
lesize,8,,,1
lesize,9,,,1
lesize,10,,,1
lesize,11,,,1
lmesh,6,11
allsel

!create upper tooling pilot node
tshap,pilo
kmesh,100
allsel

!mesh top and right edges of blank with CONTA171
lsel,s,line,,2,3
nsll,s,1
type,3
esurf
allsel

!restrain nodes on axis of symmetry in x direction
nsel,s,loc,x,0
d,all,ux,0
allsel,all

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!enter solution menu
finish
/solu

!apply full circle maximum force to pilot node
kse1,s,kp,,100
nslk
f,all, fy,-70000

!set up and create load step #1, time is 0s - 1s
nlgeom,on
time,1
nsubst,200,1000,100
outres,all,all
nropt, unsym
lswrite
allsel

!remove force on pilot node
kse1,s,kp,,100
nslk
f,all, fy,0
allsel

!set up and create load step #2, time is 1s - 2s
nlgeom,on
time
nsubst,200,1000,100
outres,all,all
nropt, unsym
lswrite
allsel

!solve load step 1 and 2
lssolve,1,2
Appendix D

Precision Blanking Shear Punch

Tooling was designed and manufactured for the precision shearing of coin blanks. This tooling was made to fit on the same hydraulic press used for coining in order to quickly produce high quality, precisely sized blanks from sheet metal. The design for the precision shear punch was based off of typical punches which require a triple-action press, but instead uses springs to supply the impingement ring and ejection forces. Equations used for the design were from both Kalpakjian & Schmid [1] as well as Tschaetsch [2].

The design is made specifically for producing blanks from Copper 110 sheet metal, 1.6 mm (0.0625 inches) thick, and 25.15 mm (0.990 inches) in diameter. Although the punch design is specific for one type of blank, it was made sure that it was also suitable enough for making 0.8 mm (0.032 inches) and 3.2 mm (0.125 inches”) blanks out of copper 110 sheet, as well as 1.6 mm blanks made of brass and nickel, all of the same diameter. All calculations shown are specific to making the 1.6 mm copper blanks. The shear force required is:

\[
F_s = 0.7TL\sigma_{UTS}
\]

Where \(T\) is the sheet thickness at 1.5875 mm, \(L\) is the perimeter of the part being punched at 78.998 mm, and \(\sigma_{UTS}\) is the ultimate tensile strength of copper 110 at 220.63 MPa. Therefore:

\[
F_s = 0.7(1.5875 \text{ mm})(78.998 \text{ mm})(220.63 \text{ MPa})
\]
\[ F_s = 19368.3 \text{ N} \]

The break clearance required for precision shearing is the distance between the edge of the punch and the edge of the die. Using Table 19.1 in Tschaetsch we find the specification for break clearance. The parts being made have a punch diameter to sheet thickness ratio \((q)\) of 15.84, but the highest in table is 1.2, which we use instead. Assuming a sheet thickness of 1.6mm, this gives a break clearance of between 0.005 mm and 0.01 mm. A conservative value was used and made to a conveniently close size (0.01 mm = .393 thousandths of an inch, went conservative with 0.5 thou). This conservative value was eventually rounded up again to make machining easier, giving a punch O.D. of 25.0952 mm, and the die an I.D. of 25.146mm (0.988” and 0.990”).

An impingement ring is used to hold the material around the area being sheared in order to stop it from being drawn into the die in order to get as clean of a shear line as possible. The impingement ring sticks out of the upper die, presses into the metal, and presses the metal against the lower die. It has a triangular cross section with a 90° point, as shown in Figure D-1.

![Figure D-1: Cross section of the impingement ring][1]

[1]: https://example.com/figure_d1.png
$F_R$ is the force that the impingement ring needs to press into the sheet metal with and is given by:

$$F_R = 4lhR_m$$

Where $l$ is the length of the impingement ring (based on its diameter at the point), $h$ is the height of the ring based upon sheet thickness and given in Table 19.2 in Tschaetsch, and $R_m$ is the ultimate tensile strength of the material. Table 19.2 in Tschaetsch gives a ring height of 0.3 mm for a sheet thickness of between 1 mm and 2 mm. A 99.75 mm (1.25”) diameter impingement ring was used since it was the smallest size that could be conveniently designed into the punch tooling. This gives an impingement ring force of:

$$F_R = 4(99.75 \text{ mm})(0.3 \text{ mm})220.63 \text{ MPa}$$

$$F_R = 26409.4 \text{ N}$$

Normally, the impingement ring force is supplied by a dedicated hydraulic ram or similar. Since our only press is just dual-action, this force was instead supplied by a die spring which, at full compression, exerted 5900 N (1200 lbf). While not as much force as was calculated, this proved to work very well in practice.

The ejection force is the force required to push the blanked part out of the die after it has been punched. It is in relation to the required shearing force and is given by:
\[ F_E = 0.12F_s \]

\[ F_E = 2324.2 \text{ N} \]

Like the impingement ring force, the ejection force was supplied by a spring. However, the most forceful spring found which could easily fit within the lower die was not quite forceful enough and was just barely unable to push the blanks out. Since the spring provided almost enough force, a separate base was made to fit under the lower die which uses a cam to put on the blank from below.

Figure D-2 shows an assembly of the precision shear punch tooling as it is installed on the press Rams along with a cross section of the tooling to show the internals.
Figure D-3 shows the stages of the shearing process in the case of this tooling.

a) The upper punch moves down causing the impingement ring to come into contact with the sheet metal (colored black), and the sheet metal to contact the opposing punch.

b) The upper punch continues to move down until the sheet contacts the lower die, at which point the impingement ring begins to press into the sheet.
c) As the die spring continues to be compressed and further pushes the impingement ring into the sheet metal and the sheet against the lower die, the upper punch moves down and comes into contact with the sheet.

d) The upper punch emerges from the piece of tooling which has the impingement ring, pushes the sheet metal into the lower die and shears it into the designed shape. The upper tooling is retracted and the opposing spring (should) push the blank out of the die for retrieval.

Figure D-3: Stages of the precision shearing process.
In practice, this precision blanking tooling was able to produce extremely fine coin blanks with sharp edges. However, since the clearance between the punch and die is so small, and the edges are as close to 90° as possible, reliable alignment of the tooling on this particular hydraulic press which did not result in interference was very difficult to achieve. The best solution to this problem is to use alignment pins between the upper and lower parts in order to guide the punch into the die reliably and without interference, but this will require an expensive redesign of some of the parts. In the end, only a few blanks were produced with this tooling, and the samples for the experimental work were made to the same dimensions with a water jet cutter.