Springback Calibration of Sheet Metal Components Using Impulse Forming Methods

THESIS

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Abstract

Impulse forming techniques are used to produce high strain rates to improve the formability of sheet metal. While these techniques are not commonly used in industry at the present time, research and testing has demonstrated enormous potential for new manufacturing processes incorporating these methods. The objective of this paper is to discuss the feasibility of the use of disposable actuators to eliminate springback in sheet metal components. Two impulse forming methods were investigated, electromagnetic forming and forming using an electrically driven expanding plasma, while three parts of increasing complexity were tested: a simple curved aluminum part, an aluminum aerospace part with a convex flange, and a high-strength steel structural u-channel part. The parts were pre-formed to a rough shape using traditional forming methods and then calibrated to the final desired shape using the impulse forming techniques. These processes work by transferring a large current through a thin aluminum actuator, generating a large controlled electromagnetic impulse in the case of electromagnetic forming or a high-pressure shockwave due to foil vaporization in the case of forming using electrically driven expanding plasma (fugitive foil forming). The test setup was optimized according to parameters such as actuator design, tool material, part stand-off distance, and capacitor discharge energy. In each case, the use of impulse forming methods resulted in significant springback reduction so that the parts were at or very near
the desired specifications, demonstrating that these techniques can be used to improve current sheet metal production processes.
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Chapter 1: Introduction

Many metal parts produced today are quite complex, with an ever-increasing number of complicated, high strength parts being used in product assemblies. This makes these structural components extremely difficult to produce since “conventional” forming methods are reaching their limits. “Conventional” forming here refers to any method using large static forces to accomplish the forming. This includes, but is not limited to deep drawing, stretch forming, hydroforming, and stamping.

For parts where the production volume is small, one-sided dies are typically used and it is not uncommon for a component to undergo several sub-processes during manufacture. One example of a manufacturing process used in production is flexible-die forming, where a flexible tool half (such as a rubber pad or flexible diaphragm) applies pressure to form a blank around a solid tool half. Hatipoğlu et al. (2007) gave some examples of common aluminum sheet metal parts in the aviation industry that were manufactured using flexible-die forming.

This process, however, has some inherent problems that must be overcome to form the parts to specification. These problems can include wrinkling, crowning, and springback, and these cannot often be corrected within the flexible-die or other conventional forming processes. As a result, complex processes such as hot forming or annealing/re-hardening are required to manufacture current sheet metal components.
The purpose of this study is to demonstrate the feasibility of using impulse forming with disposable, or throwaway, actuators in low-volume production processes. The forming process for three unique parts, an aluminum “flanged” component, an aluminum “curved” component, and a high-strength steel u-channel component, will be investigated using a combination of conventional and impulse forming techniques. Each part, shown in Figure 1, has characteristics inherent to a specific class of common sheet metal components. The results throughout the investigation will be compared to the results obtained using conventional forming techniques.

Figure 1: Curved Component, Flanged Component, and U-Channel Component
Chapter 2: Background

In current production processes of complex sheet metal parts, a time-consuming annealing step must be performed prior to forming, which decreases the mechanical strength of the part but increases formability. If the desired shape can then be achieved, a second heat treatment step is necessary to re-strengthen the material. For parts that are especially difficult to form, a combination of multiple heat treatment steps and forming operations must be used to fabricate the required shapes. A costly manual calibration step is often required after the re-hardening due to the distortion of the part geometry as a result of the heating and subsequent cooling during the heat treatment process. Figure 2 shows an example of this process chain. It is desired that the use of electromagnetic forming in the process will remove the need for the “external vendor” steps.
In order to achieve the goal of eliminating these heat treatment and manual calibration steps from component production, a redesign of the entire forming process is required. It is expected that the redesign will lead to considerably lower costs and shorter lead times. The lead time especially will be reduced due to the elimination of shipping in the middle of the manufacturing process and the time needed at the heat treatment company. Without the dependence on the heat treatment company the part manufacturer will be able to react with more flexibility regarding customer orders of parts manufactured with this process and apply the low-waste or lean protocols of single-part flow.

A possible approach for the process redesign is the combination of conventional quasi-static forming and impulse forming techniques. The difference between impulse forming methods, such as electromagnetic forming or forming using electrically driven...
expanding plasma (referred to in this document as fugitive foil forming), and other forming methods are the high local pressures that can often cause high deformations rates to occur during the process. Daehn and Balanethiram (1994) showed that this can result in higher formability for some materials when compared to conventional forming methods. In this work, novel electromagnetic actuators are used to apply large local forces to the workpiece, permitting it to remain in the T6 temper condition throughout the entire forming process. Promising results of this combination of quasi-static and impulse forming have already been demonstrated by Vohnout (1998) and Psyk et al. (2007). In both research works electromagnetic forming (EMF) was used to further form and calibrate aluminum sheet metal parts that were pre-formed by conventional deep drawing. A single deep draw to final specification would have been too aggressive and ruptured the part.

In this paper two methods to calibrate structural sheet metal parts using impulse forming will be introduced: electromagnetic forming and fugitive foil forming. In contrast to past work, which used “traditional” actuators with durability for multiple discharges, within this work a concept of “disposable” actuators was used. These actuators are designed to only be able to withstand one capacitor bank discharge, but are inexpensively produced.
Impulse For
ming Methods

Electromagnetic Forming

The process of electromagnetic forming (EMF) is the method used to form the curved and flanged components to their respective final shapes. This section will introduce the principles of the process as they pertain to these two components.

Fundamentals

Electromagnetic forming is typically practiced as a high velocity forming method, meaning that the deformation rate is significantly higher than typical quasi-static (conventional) forming techniques. Weimar (1963) showed that strain rates between $10^3/s$ and $10^4/s$ can be achieved. In high velocity forming, stored electrical energy is rapidly transformed to kinetic energy in the workpiece, which is accelerated to velocities up to several hundred meters per second. In the three cases investigated, the change in shape of the parts occurs due to the transformation of the kinetic energy into plastic work when the parts strike a die.

Electromagnetic forming uses the principles of magnetism and electromagnetic induction. A typical electromagnetic forming system consists of a discharge circuit and the components which are necessary for the operation of the system. Figure 3 shows a block diagram of the principal setup of such systems. A capacitor bank discharges a current (with a maximum, or peak, current on the order of 100,000 amps, depending on the parameters of the system) through an actuator using a high-speed triggering mechanism. This results in a large damped sinusoidal current flowing through the actuator, which creates a powerful magnetic field around the actuator. This magnetic field
induces eddy currents in the blank which cause a magnetic repulsion between the actuator and blank. Since the actuator is fixed before the experiment begins, the blank is forced away from the actuator. The electrical energy (current) put into the actuator is large, thus the resulting repulsion translates to a large mechanical energy (high velocity/momentum) in the blank. By increasing the charging energy, the current and magnetic pressure will be increased which results in a greater forming force. The principal limiting factor for this process is that the blanks must be made from a highly electrically conductive material such as copper or aluminum.

Figure 3: Winkler's (1973) Schematic Block Diagram and Equivalent Circuit of an Electromagnetic Forming System

The use of electromagnetic forming to reduce springback in a complex-shape part has been discussed in past research works. Within these studies two different basic
methods for the springback reduction were introduced. The reduction of springback in the first method is based on high-speed impact of a workpiece into a die. This method was analyzed in the work of Baron and Henn (1964) and Yamada et al. (1981). Both studies used impulse forming to form plates into spherical dies. Baron used explosives to generate the high impact velocities of the workpieces while Yamada impinged a high-speed plastic projectile on water, which transmitted a shock wave onto the sheet metal. Baron found that an increase of the deployed explosive charge leads to a decrease in springback. Yamada found an optimal collision speed at which the springback is very close to zero. Impact speeds below the optimum resulted in a part radius bigger than the die radius, while higher collision speeds generated a smaller workpiece radius than the radius of the die. Golovashchenko (1999) also investigated the use of pulsed high-speed forming technologies to decrease residual springback by using high-speed impact, and suggested that springback reduction increases with part impact velocity.

The second basic method for springback reduction is to clamp a conventionally formed workpiece to a die that has the target geometry and apply a pressure pulse to the workpiece to relieve the internal stresses. This method was investigated by Golovashchenko (2005) and Iriondo et al. (2006). Both works show a significant reduction of springback. According to Golovashchenko’s work, *Springback Calibration Using Pulsed Electromagnetic Field*, springback is reduced or eliminated because the applied electromagnetic force on a fixed part results in elastic waves running back and forth through the thickness of the part multiple times, thus relieving the internal residual
stress in the part. In his work he showed that 90% or more of the internal stresses causing springback were eliminated by the EMF treatment.

The proposed method of using electromagnetic forming for springback calibration in this paper is to be achieved by securing the part in its final position before using the electromagnetic forming process to reduce the internal residual stresses.

Advantages

Electromagnetic forming has some significant advantages compared to conventional quasi-static forming operations. One such advantage is the increased formability of the workpiece. It was shown by Vohnout (1998) and Bruno (1968) that the formability can be increased by 100% or more compared to that which is obtained in quasi-static forming.

Large impact pressures are created during electromagnetic sheet metal forming against a die. Due to these impact pressures the workpiece very closely assumes the shape of the die. This makes it possible to form fine details and features which cannot economically be formed using quasi-static techniques. Kamal (2005) theorized that due to a plastic wave front running through the workpiece after striking the rigid tool, residual strains in the part will be reduced, and that this in turn reduces springback and distortion in the part. Since the primary force is applied without any physical contact, a good surface finish without tool marks can be achieved on both the driven and impact sides of the blank.

Electromagnetic forming, especially with the use of disposable actuators, is an agile process, meaning that it is simple and inexpensive to make low volumes of many
different parts, each of which require different tooling. As demonstrated in this work for the curved and flanged component, a single-sided tool can be used for many applications, especially when used in conjunction with a forming process such as rubber-pad forming. Additionally, the only significant capital cost is a capacitor bank, and EMF can be used for a wide variety of applications including flanging, drawing, shearing, and embossing.

*Disposable Actuators*

To withstand the large and complicated impulse load cases experienced during EMF, traditional actuator concepts include large reinforcements which represent a large portion of the overall tooling costs. To reduce these costs, the concept of “disposable” actuators was developed, wherein each actuator is only used to calibrate one workpiece. The basic idea of this concept is that the EMF actuator is manufactured out of thin sheet metal and placed on one side of the part. On the other side of the part is the solid tool which contains the desired shape of the workpiece. Due to the magnetic pressure generated by the EMF actuator, the part is formed around the tool to acquire its final geometry. The tool, part and actuator are pressed together into a rubber pad. This is necessary to counteract the electromagnetic forces which try to repel the actuator from the part. It also allows the actuator to follow the workpiece contour very closely. This results in a small gap between the actuator and part, which increases process efficiency, as shown by Beerwald (2004). Expensive reinforcements are not necessary for this type of actuator since it must only be durable enough to provide one electromagnetic impulse. Figure 4(a) and Figure 4(b) show an example of a traditional EMF tool which was embedded in a deep drawing punch. Psyk et al. (2007) used this tool to investigate the
feasibility and potential of a process combination of quasi-static pre-forming with a subsequent electromagnetic calibration step. In Figure 4(c) a disposable EMF actuator used within the current study is shown.

Figure 4: (a) Cutaway of a Traditional EMF Actuator Embedded in a Deep Drawing Punch. (b) Traditional EMF Actuator Embedded in a Deep Drawing Punch. (c) Disposable Coil Used in this Work to Calibrate the Flanged Component.

Although the dimensions of the parts manufactured with these two coils were different, they are suitable to compare the general design since both tools were used for the calibration of complicated sheet metal parts after a quasi-static pre-forming step. The images in Figure 4 clearly show that the expenditure necessary for the design, construction and fabrication of the traditional coil is much greater than for the disposable coil.
In the following experiments AA-6061 aluminum is used as the actuator material due to its good electrical conductivity as well as its ability to be laser-cut, making actuator production a simple and cost-effective process. After production, the actuators were covered with high-dielectric strength Kapton® polyimide tape to provide the required electrical insulation between the actuator and other metallic components in the experiment setup.

In this paper the general feasibility of this calibration concept will be demonstrated for two possible applications: the flanged and curved components.

*Fugitive Foil Forming*

Fugitive foil forming is the method used to further improve the curved component and form the u-channel component to its final shape. This section will introduce the principles of the process.

*Fundamentals*

Fugitive foil forming, or forming using electrically driven expanding plasma, uses the same basic principles as electromagnetic forming, described by the capacitor bank diagram shown in Figure 3. In this case, the actuator is the thin foil that is vaporized to generate the shockwave, resulting in the forming pressure. This is referred to as a “fugitive” foil because it is consumed during the forming application.

The method in which fugitive foil forming releases a high-pressure shockwave is that the foil exceeds its cohesive energy by a large amount before destabilizing, releasing an expanding plasma. Therefore, a large electrical power is desired as it minimizes destabilization. Power increases as current increases and the time in which the current is
applied decreases. This large power in a short time allows more current, and therefore energy, to be put into the foil prior to sublimation and yields a larger impulse, or force over time. This results in more mechanical energy, and thus a greater forming pressure.

In this work the foil is 1145 aluminum with a thickness between 0.002 inch (0.05 mm) and 0.006 inch (0.15 mm). Chau et al. (1980) showed that the foil thickness has a significant role in the effectiveness of the fugitive foil method. If the foil is too thin it will vaporize while the current is too low to generate the required shockwave, resulting in pressures that are too low to effectively form the part. If the foil is too thick it will not vaporize quickly enough and the principle forming mechanism will be due to electromagnetic impulse, resulting in a loss of planarity in the flyer and ultimately in a part that is not dimensionally correct. As a result, an optimal coil thickness can be found that is a balance of the vaporization and magnetic impulse effects.

For a fugitive foil there should be an optimal theoretical charging energy. If the charging energy is too low, the foil will break before vaporization, which severely limits the shockwave magnitude, and thus the forming pressure. If the charging energy is too high, the foil vaporizes very quickly, and most of the current passed through the foil is wasted due to the increased resistivity of the plasma generated from the foil vaporization. An optimal energy exists between these two extremes.

Fugitive foil forming will be used to calibrate the u-channel component. Iriondo et al. (2009) devised a method to calibrate thin-walled steel U-channels using EMF. The part is placed in a match-metal die with the exact final desired shape and a durable electromagnetic actuator that is close to the final desired shape, such that there is a small
gap between the part and the die and actuator assembly. The u-channel component in this study is very comparable, but it is believed that the disposable fugitive foils will be a more efficient forming tool than the durable actuator, especially for parts with limited production quantities.

Advantages

The advantages of fugitive foil forming are comparable to those of electromagnetic forming. The increased formability and large impact pressures apply to an even greater degree with fugitive foils. Chau et al. (1980) showed that local pressures in the hundreds of megapascals can be applied to the workpiece. Additionally, fugitive foils translate very well to agile forming for high-value, difficult to form parts at low volumes. While the cycle time for fugitive foil forming in production may be slower than other processes, the larger forming pressures can eliminate production steps for complex parts, and thus reduce total production time.
Chapter 3: Methodology

Equipment

The capacitor bank used for all experiments is produced by Maxwell Magneform and has a maximum working voltage of 8.66 kV and a maximum energy storage of 16 kJ. The forming machine has an internal system inductance $L_i$ of 100 nH, a resistance $R_i$ of 0.0025 Ω and a capacitance $C$ of 426 μF. The discharge energy is controlled by adjusting the charging voltage. The capacitor bank is shown in Figure 5.

![Capacitor Bank](image.jpg)

Figure 5: Capacitor Bank

The press used for the curved and flange component experiments is a single-acting hydraulic press with a maximum force of 12000 pound (53,400 N). The hydraulic press is shown in Figure 6.
The first component to be formed is made from AA-6061 (T6) aluminum with a thickness of 0.025 inch (0.64 mm). The only feature is a circular curve with a radius of 2.75 inch (69.85 mm) across the entire length of the part in one direction. The part is shown in Figure 8(c). This component is representative of a class of parts, namely those with gradual one-dimensional curves where springback is the primary concern. A simple un-optimized disposable actuator is used.

The goal of this experiment is to form the blank to the shape of the AA-6061 aluminum tool with no springback or bounce-back effects. Three variables were changed
during the experiment to investigate the optimal test setup: the capacitor charging energy, the type of forming process, and the actuator design.

Two forming methods were used: flat blank electromagnetic forming and hybrid forming. For flat blank electromagnetic forming, the part was accelerated from the flat, unformed condition into the tool. This method allowed for stronger coil designs because the coil was left in the flat condition and did not require a change in shape prior to the impulse. The disadvantage to this method was that the part could be accelerated so rapidly that it would “bounce back” off of the tool, resulting in a part that would not meet dimensional specifications. For hybrid forming, the blank and coil were placed under the tool and the whole setup was pressed into rubber. Thus, the blank was in the shape of the tool prior to the electromagnetic impulse. Electromagnetic forming was then used to convert the elastic energy in the part to plastic energy so that permanent plastic deformation would occur in the sample. The setup for flat blank electromagnetic forming is shown in Figure 7, while the hybrid forming setup is shown in Figure 8.

Figure 7: Setup for Flat Blank Electromagnetic Forming
The rubber pad was made from three one-inch thick pieces of natural rubber, with a shore hardness of 60A and a tensile strength of 3.77 ksi (26 MPa). To set up the experiments, the flat blank and actuator were placed under the tool and the entire assembly was pressed into the rubber pad. Thus, the blank was pressed firmly against the tool prior to electromagnetic forming, as shown in Figure 8(b). Electromagnetic forming was then used to convert the elastic energy stored in the part into plastic energy, so that permanent plastic deformation would occur. The experiment setup is shown in Figure 8(a).

Figure 8: (a) Experiment Setup for the Curved Component; (b) Die and Part Setup in the Press; (c) Actuator and Part against Die Surface
For this component, the actuator design is a single turn actuator that follows the edge of the blank. This design was chosen to allow an effective comparison between the actuators with a minimum of complicating variables. Each actuator was 0.025 inch (0.64 mm) thick, which meant that they required little material and could be pressed easily into the rubber pad to assume the exact shape of the tool. One actuator had a width, a, of 0.5 inch (12.7 mm) wide, while the other actuator was 1 inch (25.4 mm) wide, allowing the effect of actuator width to be investigated. The 1 inch (25.4 mm) wide actuator design is shown in Figure 8(c). The electrical resistances of the 0.5 inch (12.7 mm) and 1 inch (25.4 mm) actuator were $6.97 \times 10^{-3}$ Ω and $4.78 \times 10^{-3}$ Ω, respectively. To approximate the inductance, $L_a$, of the EMF coils an RLC-analysis was performed. Due to the deformation of the workpiece and the coil itself during the forming process, the inductance changes with time $t$. Therefore, the inductance calculated by the RLC-analysis can be approximated as a function of time:

$$L_a(t) = 1.2 \times 10^{-7} \times t + 0.2 \times 10^{-2}$$

**Flanged Component**

The second example part investigated within this research work is a convex structural bracket with a changing radius at a few points along the flange, and two joggles along the radius (see Figure 1). The component is made from AA-6061 aluminum with a thickness of 0.063 inch (1.6 mm).
Figure 9: (a) Top View of a Pre-Formed Part; (b) Side View of a Pre-Formed Part with the Bending Angle $\phi$; (c) Deviation Analysis of a Pre-Formed Workpiece, by Percentage of Measured Points

It is not possible to form this part in the T6 temper condition within the required tolerances by using quasi-static methods. Figure 9 shows the defects resulting from the hydroforming step. The wrinkling of the part is clearly shown in Figure 9(a). It is also obvious that the convex area of the workpiece has not assumed the desired shape. Figure 9(b) shows the bending angle, which is larger than the desired 90° angle due to springback.

The picture of a deviation analysis between the digitalized pre-formed part and the CAD model shows the pre-calibration forming defects quantitatively (Figure 9(c)). At the convex surface of the workpiece, the plot gets darker from the bending radius toward
the edge of the part. This results from an increasing distance between scanned points on the workpiece and the model, due to springback. The wrinkles are represented by the darkest areas of the deviation plot. The slightly darker tips of the part are the result of a crown which is produced during the pre-forming operation. The deviation analysis will be discussed in greater detail later in the chapter.

As the experiments are run three parameters will be measured. If rubber-pad forming is being used, a load cell will be used with the press to determine the setup pressure. A Photon Doppler Velocimetry (PDV) analysis tool will be used as the experiment is run. As with the curved component, a Rogowski coil will be used to analyze the current trace. The Rogowski and PDV analysis results can be put onto a single graph to obtain the current and velocity measurements for the part. Additionally, the same press and capacitor bank were also used for these experiments. The basic form of the actuator used for this application is a U-shape. The exact actuator shape is illustrated in Figure 10(c). It was expected that the wrinkle removal along the convex area of the part would require the highest magnetic pressure, while the area with the crown would require less pressure (see Figure 9(c)).
To achieve the desired pressure distribution with respect to these forming tasks, the actuator had locally varied widths. Reducing the width of the actuator, and thus the actuator cross-sectional area, has a significant effect in increasing magnetic pressure, and therefore in localizing magnetic force. A wider section of 0.6 inch (15 mm) was chosen to cover the workpiece area which has small crowns, on the flat face of the tool. For the section of the part with the wrinkles and joggles, a narrower branch of 0.5 inch (12.7 mm) was chosen.

Figure 10: (a) Experiment Setup for the Flanged Component; (b) Die and Part Setup in Press; (c) Actuator and Part on Die Surface
mm) was implemented. The actuator thickness was 0.012 inch (0.3 mm). The electrical resistance of the coil was approximately $1.249 \times 10^{-2} \, \Omega$.

For the forming operation the actuator was bent around the die as shown in Figure 10(c). On the flat side of the part, a steel blank holder pressed the actuator against the part and inhibited its movement during the process. The curved part of the workpiece and the actuator are pushed into a rubber pad by a hydraulic press. Thus the actuator is pressed securely against the part, resulting in an efficient forming process when the capacitor bank is discharged. The complete setup as used during the experiments is shown in Figure 10(a), while a detailed cross-sectional view of the setup is shown in Figure 11.

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Figure 11: Cross-Sectional View of the Experiment Setup for the Flanged Component
The influence of three parameters was investigated during the experiments: press force, charging energy, and tool material. The goal was to find the optimal conditions for each parameter to form the part to specification. Additionally, a deviation analysis was performed to determine the accuracy of the final formed part shape. This was completed by digitizing the part shape using a laser scanner and comparing it to the CAD model of the part, as shown in Figure 9c. This will be explained in more detail later in this chapter.

**U-Channel Component**

**Experiment Setup**

The part investigated in this work is a steel u-channel made from high-strength DP600 steel. The steel has a yield strength of 43.5-68.2 ksi (300-470 MPa) and a tensile strength of 84.1-97.2 ksi (580-670 MPa). An image of the part prior to calibration is shown in Figure 12 below.

![Figure 12: Un-calibrated U-Channel Part](image-url)
The walls of the part are required to be 90° relative to the bottom of the part. Using current production processes, significant springback exists in the part after forming, as shown in Figure 12 above. A novel new forming technique is required to eliminate this springback so that the part can be formed to specification. The purpose of this work is to find a low energy calibration approach to form the u-channel parts to specification using fugitive foils as the forming medium. The most sensitive areas for optimization of the calibration process will be determined.

To run the experiments, the un-calibrated u-channel parts are placed inside a match-metal steel die. This forces the part into a shape close to the final desired shape prior to impulse calibration. The die set, with the part inserted, is shown in Figure 13 below.

Figure 13: U-Channel Part in Match-Metal Die
The fugitive foils are made of 1145 aluminum with varying widths and thicknesses. The investigated thicknesses are 0.002 inch (0.05 mm) and 0.003 inch (0.08 mm). The investigated widths are 0.5 inch (12.7 mm) and 1 inch (25.4 mm). The increased thickness allows more current to pass through the foil before vaporization, increasing impulse energy, but requires more energy, reducing the efficiency of the process. The wider foils distribute the forming pressure over a larger area, which decreases efficiency but reduces local deformation. The foils widen at the edges to ensure that the vaporization occurs towards the middle, where the shockwave will contact the part. The thin and wide foil designs are shown in Figure 14 below.

![Figure 14: 0.5 inch (12.7 mm) and 1 inch (25.4 mm) Wide Fugitive Foils](image)

The fugitive foils, along with the part and die are covered with Kapton® dielectric tape to prevent arcing between the fugitive foil and the die or part. Once the part, fugitive foil, and tape are in place a steel block is bolted to the top of die in order to hold the setup in the correct position. The entire experiment assembly is shown in Figure 15 below.
Once the experiment assembly is complete it is placed into a steel box, where the experiment will take place. The fugitive foil ends are connected to electrical contacts of the capacitor bank. A ventilated steel box contains the experiment to ensure safety before and after foil vaporization. The experiment setup is shown in Figure 16 below.
Figure 16: U-Channel Experiment Setup

To complete the experiment, the capacitor bank is discharged at the desired charging energy, vaporizing the foil and thus reducing springback in the u-channel part. The current and voltage traces are taken in real time during the experiment.

Upon completion of the experiments, the parts were analyzed. Three main factors were investigated in this analysis: the current and voltage trace characteristics, the relevant calibrated wall angles, and the presence of local deformation. This resulted in five key measurable factors per experiment: the presence of local deformation, the springback angle at the top and bottom of the part wall (relative to the bottom of the part), foil burst current and time to burst, peak current.
Experiment Plan

Single-Foil Experiments

The single-foil experiments investigated a variety of factors: foil width, foil thickness, foil location, optimal charging energy, and repeatability. It was determined that the 0.5 inch (12.7 mm) foils were most effective at the bottom of the part, where local deformation was limited and the distribution of the forming pressure over a smaller area was more effective. The wider 1 inch (25.4 mm) foils were more effective towards the top of the part wall, as they resulted in less local deformation. At each location, for each foil width, 0.002 inch (0.05 mm) and 0.003 inch (0.08 mm) foils were tested. The thinner foils require less material and less energy for vaporization, keeping costs lower, but provide less forming pressure than the thicker foils. CAD models of the two foil locations and widths versus the u-channel part are shown in Figure 17 below.

Figure 17: 0.5 inch (12.7 mm) Wide Foil at the Lower Wall Location (Left); 1 inch (25.4 mm) Wide Foil in the Middle of the Upper Wall Location
Additionally, an optimal charging energy was determined for each foil. In this investigation, the optimal charging energy was determined by testing a given foil setup at various charging energies. Here, a higher charging energy generally resulted in a better calibration angle up to some maximum charging energy at the onset of local deformation. Since local deformation is unacceptable for the part specification, the maximum allowable charging energy was just below the level at which local deformation was observed.

After the optimal charging energy was determined, three experiments were run for each test setup with a specific location, foil thickness/width, and charging energy. The data from each experiment were analyzed to determine if the fugitive foil process could produce repeatable results. The overview of the testing project plan is shown in Figure 18 below. Note that “test location 2” corresponds to the image on the right and “test location 4” corresponds to the image on the left in Figure 17.

1. Experiment Matrix

Investigations:
- **Test location** (1, 2, 3, 4)
  - 0.5” wide foil at 1 and 2
  - 1” wide foil at 3 and 4
- **Foil thickness** (0.002” and 0.003”)
  - Determine optimum charging energy for each foil width and thickness
- **Run each individual test setup 3 times**
  - 24 total tests
  - Run 2 tests for each setup initially
    - time constraint

Figure 18: Overview of Single-Foil Test Plan for U-Channel Part
As Figure 18 shows, in addition to testing whether the result was more effective with the foil located higher or lower along the part wall, effectiveness was tested depending on if the foil was located on the outside or inside of the part wall. This resulted in two foil thicknesses being tested at four different locations (two on the outside and two on the inside). Each experiment setup was run three times, resulting in 24 total tests.

Two-Foil Experiments

Following the single-foil experiments, the next investigation was to determine if better results could be achieved using two fugitive foils concurrently for the impulse forming process. The two foils were connected in parallel so that both would explode simultaneously. The foils chosen were those with the best calibration result between locations 1 and 2 and with the best calibration result between locations 3 and 4 were used (These locations are shown in Figure 18). The idea behind these experiments was that the use of two foils would result in a more uniform calibration result. A CAD drawing showing the two-foil setup is shown in Figure 19 below.
Data Measurement and Analysis

*Electromagnetic Forming*

For all experiments, a Rogowski coil was used to measure the output current from the capacitor bank. This coil is run in a loop around the output lead of the bank. When the capacitor bank discharges, it induces a current in the Rogowski coil, and thus changes the voltage in the Rogowski coil. This change in voltage is measured by a voltage divider, and is then converted into the capacitor output current and recorded. A typical current trace for an electromagnetic forming application will be in the form of a damped sinusoidal wave, and is shown in Figure 20 below.
For select flanged component experiments, a Photon Doppler Velocimetry (PDV) analysis tool was used to record position and velocity of the part in real time. The PDV system uses a laser to measure the position of the blank with a maximum sample rate of 5 GHz. The laser reflections are captured and the change in frequency of the waves is analyzed using a computer to yield position and velocity measurements at any given time as the experiment is run. This can be recorded at the same time current is measured.

Sample PDV data is shown in Figure 21 below. Figure 21(a) shows the raw PDV data, which is a series of repeating waves. The frequency of the waves is measured, resulting in the position of the part, and ultimately the part velocity, which is shown in Figure 21(a).
Figure 21: Sample PDV Data for an EMF Application
For select flanged component experiments, a Konica Minolta Vivid 910 laser scanner was used to digitalize the calibrated shapes. The laser scans the workpiece and the beams are captured to create a collection of points that, when put together, create a digitized 3-D model of the part surface. For this work the surfaces of the workpieces facing the die were scanned. To analyze the shapes produced, a deviation analysis was performed using the CAD software CATIA V5 R17. This compared the point clouds from the laser scans to the inside surface of the CAD model, which resulted in a deviation plot showing the distance between matching points on the CAD model and the laser scans. An example of a deviation analysis for the flanged component before EMF is shown in Figure 9(c).

**Fugitive Foil Forming**

In fugitive foil forming, as used in the u-channel component, the high local pressures can result in local deformation in the part. The presence of local deformation is first determined by a simple visual inspection of the part. The part cannot be formed to specification if undesirable local deformation is present.

For select u-channel components where more detail of the part surface was required, a Mitutoyo S-3000 Surface Measuring Instrument was used to create a two-dimensional profile of the parts. This machine moves a needle across the face of a part to measure the surface contour. The displacement of the needle up and down is recorded, along with the length it has traveled across the surface. This measures the flatness across a part wall, which is an important factor to determine the effectiveness of the part calibration.
For the u-channel components, the springback angle was measured in two locations: at the bottom and top of the part wall. This is measured by tracing the edge of the part onto paper and using a protractor to find the angle. It must be noted, therefore, that this angle is an approximation only, but allows the result to be quantitatively measured quickly and easily. This technique is accurate to approximately one half of a degree.

Figure 22: Springback Angle Measurements at the Bottom (α) and Top (β) of the U-Channel Part Wall

The springback angle measurement for an un-calibrated part is shown above in Figure 22. Angle α refers to the angle at the bottom of the wall and angle β refers to the
angle at the top of the wall. In this case, $\alpha=96^\circ$ and $\beta=104^\circ$. In the parts which were formed using a fugitive foil, a smaller angle means that more springback was eliminated.

The last three parameters to be measured are the foil burst current, time to foil burst, and peak current. These are determined using the current and voltage traces, which are collected for each capacitor bank discharge. As with the curved and flanged components, the current trace is measured using a Rogowski coil. Additionally, voltage is measured using a high voltage divider. Since it takes some amount of time for the capacitor bank to discharge, the current and voltage traces are waveform plots taken over the entire discharge time. The y-axis is the current (or voltage) magnitude and the x-axis is time. A typical current and voltage trace from this study is shown, with the three relevant measurements labeled, in Figure 23 below. Note that the peak current and foil burst current are each individual points along the current trace.

![Current-Voltage Trace with Relevant Data Labeled](image)

**Figure 23:** Current-Voltage Trace with Relevant Data Labeled
As Figure 23 shows, the peak current is simply the maximum current achieved during the experiment. This is important because it is related to the impulse in the experiment, where impulse is force integrated over time (and force is proportional to current). The foil burst current is the point where vaporization initiates. This is typically highlighted by a local voltage maximum, significant noise seen in the current trace, or both. Figure 23 shows that both of these criteria are true. The foil burst current is important because it shows the current at the time of foil vaporization. A greater burst current for a given test setup should result in a more powerful shockwave. The time to burst is important because dE/dt, or power, is maximized with a shorter time to burst and greater burst current.
Chapter 3: Curved Component

Influence of Electromagnetic Forming on Microstructure

It is critical that structural components remain in the T6 hardness condition for optimal mechanical properties. The electromagnetic coupling which occurs during EMF could develop enough heat or strain in the blank to change the microstructure. There was no in, so the effects were investigated in this experiment by comparing optical micrographs of an electromagnetically formed part to the as-received blank material. The two micrographs were compared visually for any noticeable changes. The two micrographs is shown in Figure 24 below.

Figure 24: Micrographs from the As-Received Aluminum (Left); Electromagnetically Formed Part (Right)
In addition to visually comparing the micrographs, hardness testing on the Vickers B scale was completed on the unformed material and the formed blank, and compared to the expected value for 6061-T6 aluminum from literature. The as-received material had a hardness of 59.88, the formed part had a hardness of 57.18, and the expected hardness from literature was 60. The lower value of the formed part can be attributed to slight curvature of the sample, which slightly lowered the hardness value. A more accurate measurement could be obtained in the future using Rockwell micro-hardness testing. The micrographs and hardness tests clearly show that there is no change in mechanical properties after electromagnetic forming.

Flat Blank Electromagnetic Forming Results

For flat blank electromagnetic forming, the effect of actuator width on the final shape of the part was the primary consideration. During electromagnetic forming, the highest impulse loads would occur in the areas of the part that were closest to the actuator. This can result in severe impulse load gradients during the forming process, the effects of which are shown in Figure 25. This figure shows a part formed using a 0.5 inch (12.7 mm) actuator width. The final part shape has severe local deformation at the areas of the blank that were initially nearest to the actuator. The images on the right side of Figure 25 and Figure 26 show the electromagnetically formed part compared to a blank pressed into a rubber pad with a force of 12000 pounds (53,400 N).
An actuator width of 1 inch (25.4 mm) results in a much more uniform forming pressure across the part, as shown in Figure 26. However, due to end effects at the corners of the actuator, a uniform magnetic field is not created at the corners of the coil. This results in very little impulse load at the corners of the blank, and thus they were not accelerated away from the actuator at the same rate as the rest of the blank. As a result, the corners get folded under the part as the rest of the part accelerates away from the actuator. This effect also appears in the parts formed with the 0.5 inch (12.7 mm) wide actuators, although not to the same magnitude.
Figure 26: Effect of 1 inch (25.4 mm) Actuator Width on Formed Shape after Flat Blank Electromagnetic Forming

The presence of such significant local deformation, along with the end effects at the actuator corners, made the flat blank electromagnetic forming process unsuitable to form the part to specification. The hybrid forming process resulted in a far more uniform final part shape, and will be discussed in detail in the following section

Experiment Radii vs. Target Radii after Hybrid Forming

Since the desired shape is a one dimensional curve, the effectiveness of an experiment could be gauged by simply determining the part radius and comparing this to the target part radius of the tool. Since hybrid forming resulted in uniform curvature of the part, this process was chosen for comparison. The radius was measured using the chord length, \( l_c \), and chord height, \( h_c \), of the formed part. These values are shown schematically in Figure 27(d). Once the radii of all formed parts were determined, they were compared to the target radius of the tool as well as the radius of a part formed only by rubber pad forming, shown in Figure 27.
Figure 27(a) shows that, while the target radius was not achieved, electromagnetic forming significantly improved the part radius. This is also shown for each actuator width in Figure 27(b) and Figure 27(c). The use of electromagnetic forming resulted in an average decrease in the part radius of 7.75 inch (196.7mm), while the difference between the target radius and the average part radius was 1.7 inch (43.3 mm), resulting in a springback decrease of almost 82%. The maximum decrease in part radius, obtained using a 0.5 inch actuator and a charging energy of 5.6 kJ, was 8.23 inch (209.1 mm). This was 1.22 inch (30.9 mm) greater than the target forming radius, meaning that over 87% of the springback was eliminated using EMF calibration. The key parameters for an optimal formed radius were thinner actuators and higher charging energies.

Figure 27: (a) Effect of Discharge Current on Part Radius; (b) Effect of 0.5 inch (12.7 mm) Actuator Width on Part Shape; (c) Effect of 1 inch (25.4 mm) Actuator Width on Part Shape; (d) Target Part Shape
Influence of Disposable Actuators

For disposable actuators it is necessary to consider if the actuator will fail when the capacitor bank is discharged during forming. In the case of the flanged component, it was typical for the actuator to fail during the forming process. The usual area of this failure was at the turn of the actuator. Due to the change in direction of the actuator, the current flow was concentrated close to the inside actuator edge. The higher current density at the inside edge led to increased Joule heating and higher temperatures in this region. As a result, the material strength of the actuator decreased and the magnetic forces caused the material to fail at this weak point. Evidence of the higher temperatures at the actuator turn were the partly melted edges of the inside radius. In most cases the Kapton® tape which covered the actuator withstood the heat and stayed intact.

Influence of Press Force on Achieved Part Geometry

As described in the State of the Art, the distance between actuator and workpiece is expected to have a significant effect on the forming force and process efficiency. To achieve a very small gap distance, the part and tool were pressed against the actuator using a hydraulic press and rubber pad. The force applied by the press can affect the distance between the workpiece and part, as it could pre-form the part and thereby reduce the gap. Other than the charging energy, the gap distance is a primary factor which
influences the impact velocity of the part at the die (for the same actuator geometry), since it is within this distance that the part gets accelerated.

For process design it is important to know how a variation of this effective standoff distance will affect the forming result. Three different pre-loads were used: 2000 pounds (8900 N), which is the minimum load at which the workpiece assembly was completely pressed into the rubber pad, 6000 pounds (26700 N), and 12000 pounds (53400 N), which is the load limit of the press. However, it was determined that in this case there was no significant relation between the press force and the final formed shape of the part. This can be explained by the fact that the part was already in contact with the die in most areas at 2000 pounds. Therefore, higher press forces did not change the contact between workpiece and die significantly and as a result no influence of the press force was detected.

Influence of Charging Energy on the Forming Result

In the background section it was described that for the same actuator geometry an increase of the charging energy leads to a higher magnetic pressure. For the electromagnetic calibration it is essential to know the optimal energy to form the desired shape and to eliminate the wrinkles which are produced in the pre-forming step. The correlation of input energy with springback is also important. Since overbending is the commonly used approach to compensate for springback this information is needed for the die design. Three charging energies were investigated: 4.0 kJ, 4.8 kJ, and 5.6 kJ. For these charging energies, the current through the coil varied between approximately 120
kA and 145 kA, with a rise time of about 12 μs. For these experiments the steel tool was used, with a press force of 2000 pounds (8900 N).

Figure 28: Percentage of Points of the Scanned Parts with a Deviation from the CAD Model Between -0.02 inch and +0.02 inch (-0.5 and +0.5 mm) versus Charging Energy

The relationship between achieved shape and applied charging energy is shown in Figure 28. The quality of the shape is expressed by the percentage of scanned points from the CATIA analysis which are located within a maximum distance of ±0.5mm from the target geometry. This is defined as the “deviation”. The dashed line in the diagram is the average value of the parts which were only pre-formed. Figure 28 shows that an increase in charging energy, and thus an increase in magnetic pressure, will improve the part
quality. The larger magnetic pressure was equivalent to a larger forming force, and resulted in a greater reduction in the wrinkles and better formation of the joggles.

The increase in forming pressure as charging energy increased also had an effect on the velocity of the workpiece. Although a hydraulic press and rubber pad was used to press the actuator and part against the tool, there is still a small gap remaining. As a result, the forming pressure due to the electromagnetic impulse should accelerate the part into the die at some velocity. This was measured using a Photon Doppler Velocimeter (PDV) system, which measures the part velocity in real-time. This can be compared to the magnetic pressure, which is approximately proportional to the current measured by a Rogowski coil. The current and velocity data versus time are shown in Figure 29.

Figure 29: Example Current and Velocity Trace for Flanged Component
The part velocity was measured at two locations: at the joggle and at the part center. As the plot shows, the part is accelerated from rest to its peak velocity in approximately 10 μs. This process occurs rapidly due to the part’s close proximity to the tool, and the rapid increase in current (magnetic pressure). The velocity decreases to 0 almost instantaneously as the part strikes the die. The forming pressure and peak velocity will increase as charging energy increases. As Figure 28 shows, this results in more accurate formed components.

Influence of Tool Material on the Forming Result

Different tool materials could affect the part’s achievable quality of small geometric features and the springback values due to their material properties, such as Young’s modulus, hardness, and damping characteristics. Therefore, knowledge about the influence of the tool material is also important for the tool design. Three different tool materials were investigated: alloy 4140 steel, which has high stiffness and low electrical conductivity, AA-6061 (T6) aluminum, which has high conductivity and still relatively high stiffness, and Garolite® G-10/FR4, which is a glass cloth laminate with an epoxy binder; this material has no electrical conductivity and is by far the softest and best damping material of the group. 4.0 kJ was chosen as the charging energy and 2000 pounds (8900 N) was again selected as the press force.

Psyk et al. (2007) showed that, for electromagnetic forming, the charging energy stored in the capacitor bank is transformed first into a pressure pulse and then into kinetic and deformation energy. At the moment the workpiece hits the die the remaining kinetic
energy is transferred from the workpiece into the die. If this energy cannot be completely
dissipated or absorbed by the die material it is transferred back into the workpiece. This is
a possible cause of the “rebound effect” in the part. In the work of Risch et al. (2004), the
influence of the damping characteristics and the part stiffness on the rebound effect was
investigated using finite element analysis. In that work, it was discovered that an increase
of the damping coefficient, which means an increase in the damping characteristics of the
tool, seemed to reduce the rebound effect up to some optimal value. Beyond this optimal
value an increased damping coefficient leads to a decrease in the geometric accuracy.

Figure 30 shows the results of the realized part quality for each tool material. The
best results were achieved with the Garolite® G-10 die. Since the Garolite® G-10 tool
was relatively soft and its damping characteristics were desirable, it was able to dissipate
the kinetic energy of the part quite well, and it is possible that this led to the better
springback and rebound behavior as well as the improved shape accuracy which was
observed compared to the metal tools. The poorer results of the aluminum tool and steel
tool were very similar.

Due to the desirable characteristics of the Garolite® G-10 tool, additional
experiments were performed at a 2000 pound (8900 N) pre-load and an increased
charging energy of 4.8 kJ. The quality of the parts formed with the Garolite® G-10 tool
and steel tool at 4.0 kJ and 4.8 kJ are shown in Figure 28 above, and provide further
validation that the Garolite® G-10 tool resulted in a higher part quality, even at varied
charging energies.
Figure 30: Percentage of Points of the Scanned Parts with a Deviation from the CAD Model between -0.02 inch and +0.02 inch (-0.5 mm and +0.5 mm) versus Tool Material

A deviation analysis of a part formed with this new parameter setup is shown in Figure 31. This analysis shows that the wrinkling was eliminated. However, the deviation analysis also shows that crowns were formed in the area of the bending radius at the part edges. These defects are illustrated by the darker areas in the plot.
Figure 31: Percentage of Points of the Scanned Parts with a Deviation from the CAD Model between -0.04 inch and +0.04 inch (-1 mm and +1 mm) versus Part Shape

The improvements due to the electromagnetic calibration are shown in Figure 32(a). In this figure a workpiece that was only pre-formed is compared to a part which was calibrated with the new parameter setup of 4.8 kJ charging energy and the Garolite® G-10 die. This image shows the elimination of the wrinkles and the formation of the joggles along the part flange. Compared to the two metal tools, the springback values of the parts calibrated with the Garolite® G-10 die were also lower. Springback was reduced significantly, as shown in Figure 32(b) for angles measured at three positions along the flange.
Figure 32: (a) Comparison of Part that is only Pre-Formed with Part that is EMF-Calibrated; (b) Comparison of Measured Flange Angles in Part before and after EMF Calibration

This is equivalent to an average reduction of the bending angle from 95.3° to 90.3°, while the target bending angle was 90°. These results demonstrate that it is possible to manufacture the part with a combination of flexible-die forming and EMF
calibration using a disposable actuator. However, to remove all of the defects from the pre-forming process, some further optimization of the pressure distribution will be necessary.

Fugitive Foil Forming

Following the investigation of the flanged component a new process, fugitive foil forming, was developed that showed significant improvements over the EMF process with disposable actuators. In the fugitive foil forming process for the flanged part, a thin aluminum foil is connected to a thicker copper actuator. When the capacitor bank discharges the current into the actuator, the resulting high current densities in the aluminum cause the foil to vaporize. This results in both a brief electromagnetic impulse as well as the release of a high-pressure shockwave, which serves as the primary forming mechanism.

The setup for the fugitive foil process is shown in Figure 33. An aluminum flyer with a thickness of 0.032 inch (0.813 mm) was used to transfer the forming pressure from the fugitive foil to the part. Preliminary experiments indicate that the optimal coil thickness is 0.006 inch (0.152 mm), while higher charging energies appear to increase shape quality of the part. The foil and flyer are placed in a Garolite® G-10 channel which directs the shockwave and thus the flyer toward the part, increasing forming efficiency. The part and Garolite® G-10 tool are then pressed down on top of the actuator, foil, and flyer assembly.
Figure 33: Experiment Setup for Fugitive Foil Forming (Full and Sectioned Views)

The result of fugitive foil calibration compared to a part that was only hydroformed is shown in Figure 34. In addition to the improvements over the pre-forming method, the use of the fugitive foil process resulted in a significant improvement of the flanged component shape over calibration from electromagnetic forming. The part formed using the fugitive foil technique was completely within dimensional tolerances, with all defects from the pre-forming (hydroforming) process removed, and produced comparable or better results to those achieved with the current production method used in industry.
Figure 34: Comparison of a Part that is only Pre-Formed to a Part Formed using Fugitive Foil Forming
Chapter 5: U-Channel Component

Single-Foil Experiments

The three experiments for each test setup described in Figure 18 were placed into a table showing relevant data. This experiment data is shown in Table 1 below.
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<th>Test #</th>
<th>Thickness (in)</th>
<th>Width (in)</th>
<th>Position on Part</th>
<th>Charging Energy (kJ)</th>
<th>Local Deformation?</th>
<th>Burst Current (kA)</th>
<th>Time to Burst (μs)</th>
<th>Peak Current (kA)</th>
<th>Springback Angle</th>
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<td>slight</td>
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<td>57.77</td>
<td>9.15</td>
<td>58.49</td>
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</tr>
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<td>0.5</td>
<td>bottom inside</td>
<td>8</td>
<td>-----</td>
<td>87.5</td>
<td>11.05</td>
<td>124.2</td>
<td>94.5</td>
</tr>
<tr>
<td>21</td>
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<td>0.5</td>
<td>bottom inside</td>
<td>8</td>
<td>-----</td>
<td>86.86</td>
<td>14.41</td>
<td>122.2</td>
<td>92</td>
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<tr>
<td>24</td>
<td>0.003</td>
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<td>middle inside</td>
<td>9.6</td>
<td>-----</td>
<td>89.76</td>
<td>17.96</td>
<td>178.4</td>
<td>95</td>
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<td>bottom outside</td>
<td>6.4</td>
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<td>62.86</td>
<td>8.11</td>
<td>87.34</td>
<td>99</td>
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<td>26</td>
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<td>0.5</td>
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<td>-----</td>
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<td>97</td>
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Table 1: Single-Foil Experiment Data
The components for each experiment setup were compared to an un-calibrated part. The un-calibrated parts had average part angles of 104° at the top of the part wall, and 96° at the bottom. The images showing a representative part for each test setup and an un-calibrated part are shown in Figure 35 below.

![Representative and un-calibrated parts](image)

<table>
<thead>
<tr>
<th>Actuator Thickness</th>
<th>Test #</th>
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<td>0.002 inch (0.05 mm)</td>
<td>3</td>
</tr>
<tr>
<td>0.002 inch (0.05 mm)</td>
<td>14</td>
</tr>
<tr>
<td>0.002 inch (0.05 mm)</td>
<td>25</td>
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Figure 35: Selected Results from Single-Foil Experiments
The goal was to run three tests for all experiment setups outlined in Figure 18. As Table 1 shows, this was not the case for all setups. The 0.003 inch (0.08 mm) thick, 1 inch (25.4 mm) wide foils at the inner foil location required a very large amount of energy to vaporize and get a reasonable forming force. As Table 1 shows, the test was run at 9.6 kJ. This generated an unreasonably high pressure in the steel containment box used in the experiment, and therefore no further experiments were run with the 0.003 inch (0.08 mm) foils at the middle location. Even at 9.6 kJ, the forming results using these foils were not as effective as those of lower energy experiments with the 0.002 inch (0.05 mm) thick foils with the same setup.
Three tests were also not completed for every test setup with an outside foil location. As Table 1 shows, only 3 out of the 12 experiments were completed for the experiments with the foil outside the part. This was because, in each of the 3 experiments with an outside foil location, there was almost no forming effect on the component walls. In order to fit the foils on the outside of the part, the channel must be widened to accommodate the foil and Kapton® tape. When this happens, the u-channel is not forced into its exact final shape and thus the shockwave from the foil must form the part into its final shape and then calibrate springback, making the forming process far less efficient.

Generally, the springback angle was smaller at the bottom of the part wall than at the top. This is because the un-calibrated part had wall angles that were smaller at the bottom than at the top. The repeatability of the bottom springback angle was very good, with the angle varying by only 0.5-1 degree in each 3-experiment set. The upper springback angle, however, does vary quite a bit. Foil vaporization characteristics are dependent on strength of the connection between capacitor bank and foil, along with the normal variations in the bank discharge, and foil cross-sectional area. The area is not completely uniform due to the fact that foils are cut by hand. This is evidence that the two-foil method is needed for better calibrated and truly uniform results.

The optimal forming setups were clear at both the top and bottom of the part. At the top, the 0.002 inch (0.05 mm) thick, 1 inch (25.4 mm) wide foils on the inside of the part yielded the best results, as shown by test #3 in Figure 35. At the bottom, the 0.003 inch, 0.5 inch foils on the inside of the part were best, as shown by test #19 in Figure 35.
The best overall result, test #19 in Figure 35, had a top and bottom springback angle of 91°. By visual observation, the part appeared to be flat across the extrusion length. If this was the case, it would mean that the foil vaporized along its entire length evenly. A 2D profilometer was used to quantitatively measure the flatness. It was compared to an un-calibrated part, to determine how flat the parts were in the extruded direction when they were received. The flatness plot is shown in Figure 36 below.

Figure 36: Flatness Measurement for Single-Foil Experiment (Test #19, Blue) and Un-Calibrated Part (Red)
As Figure 36 shows, the two parts had a very similar contour across the extruded length. The entire range of depths measured was less than 0.3 mm. The curves are not smooth due to very fine scratches found on the as-received parts. Figure 36 suggests that the parts stay flat during calibration.

Two-Foil Experiments

In the two-foil experiments, both foils are connected to the capacitor bank in parallel and are completely vaporized after capacitor discharge. It appears that the results are the sum of combined effects of the vaporization of the two foils. The results suggest an improvement over the use of a single foil, as the parts are more uniform. This is due to a significant improvement in the consistency of the top springback angle. A representative two-foil forming result is shown in Figure 37 below.

Figure 37: Two-Foil Experiment (Test #29 Shown)
The two-foil experiment results were placed into a table showing relevant data. This experiment data is shown in Table 2 below.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Foil Thickness (in)</th>
<th>Foil Width (in)</th>
<th>Position on Part</th>
<th>Charging Energy (kJ)</th>
<th>Local Deformation?</th>
<th>Burst Current (kA)</th>
<th>Time to Burst (μs)</th>
<th>Peak Current (kA)</th>
<th>Springback Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.003</td>
<td>0.5</td>
<td>bottom inside</td>
<td>9.6</td>
<td>yes</td>
<td>121.4</td>
<td>17.47</td>
<td>200.5</td>
<td>86.5 91</td>
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<tr>
<td></td>
<td>0.002</td>
<td>1</td>
<td>middle inside</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.003</td>
<td>0.5</td>
<td>bottom inside</td>
<td>8</td>
<td>yes</td>
<td>147.2</td>
<td>16.61</td>
<td>190.1</td>
<td>88.5 91.5</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>1</td>
<td>middle inside</td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td>8</td>
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<td>186</td>
<td>95 94</td>
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<td>15.43</td>
<td>197.5</td>
<td>93 91</td>
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<tr>
<td>33</td>
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<td>0.5</td>
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<td>9.6</td>
<td>no</td>
<td>187.9</td>
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<td>208</td>
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<td>0.002</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Two-Foil Experiment Data
A 2D profilometer was again used to measure the surface contours of the two-foil experiments. In this case, the flatness was measured up the part wall from bottom to top. This shows how evenly the forming pressure was distributed along the part wall. Test #19, a single-foil experiment, was compared to Test #31, a two-foil experiment that had some visible local deformation along the wall length. The results of the flatness test is shown in Figure 38 below.

Figure 38: Flatness Measurement for Single-Foil Experiment (Test #19, Blue) and Two-Foil Experiment (Test #31, Red)
As Figure 38 shows, the single-foil part was very uniform along the length of the wall, with a variation of about 0.1 mm. However, the two-foil experiments were not as uniform. It was clear from visual inspection that this part had local deformation along the length of the wall. This was corroborated in the flatness tests. Even with this data, the total range of deformation was less than 0.7 mm. This demonstrates that, with further work to optimize the charging energy and experiment setup, local deformation in the parts can be controlled.

One reason the proper angle was not achieved is that the foil was located either at the middle or the bottom of the part in every experiment. As Figure 19 shows, even the “upper” foil location was at the middle of the part. A two-foil setup with one foil at the bottom and one foil near the top of the part should be more effective. This is further validated by the two-foil experiment results so far. As Figure 37 shows, forming was good at the bottom and middle of the part, but the angle was actually less than 90 degrees at the top. This occurs because the middle of the part that is covered by the foil is accelerated so rapidly that the top of the part is essentially left behind as the middle of the part is deformed. This is a similar mechanism to that which affected the curved component, shown in Figure 26.

To combat this issue, the foil was moved closer to the top of the part. Experiments were run at charging energies of 8 kJ and 9.6 kJ. The 9.6 kJ experiment showed improvement, as the data in Table 2 shows, but the bottom and top springback angles were only reduced to 91° and 93°, respectively. Additionally, local deformation was still prevalent using this setup. The next experiment, test #33, attempted to eliminate the issue.
of local deformation by using a wider, 1.5 inch foil at the top of the part. This experiment was run at 9.6 kJ, and while it did succeed in limiting the local deformation, it also resulted in significantly poorer forming results, with bottom and top springback angles of 94.5° and 96°, respectively.

While the desired angle of 90° at the part wall was not achieved, the two-foil experiments show many improvements over the single-foil experiments and especially over the un-calibrated parts.
Chapter 6: Conclusions

Curved Component

While the target radius was not achieved in the curved component, a significant improvement in the formed radius was achieved using the hybrid technique of rubber-pad forming followed by an electromagnetic impulse. Increasing the discharge current increased the forming result regardless of the actuator design or test type. While the simple electromagnetic forming technique resulted in a greater degree of forming (smaller resulting radius), especially with the narrow actuators, the 1 inch (25.4 mm) wide actuators led to more consistent results, and the rubber pad technique resulted in the most consistent forming pressure across the entire part, and thus the most consistent results. A maximum of 87% of the springback was eliminated from the part, while an average springback decrease of nearly 82% was achieved.

In the future, results could be improved by developing more robust actuators capable of higher forming energies, as well as designing new actuators that applied forming force to the middle of the part as well as the edges. It could also be possible to use a two-step process, where the majority of the necessary forming was accomplished in the first step, while the dimensions were calibrated to the final specifications in the second step. Also, the ability of the process to create a consistent curve across the whole part means that there is a possibility of using a die with a smaller radius than that which is
desired for the part, and being able to form the part to specification after springback, much like over-bending using conventional forming techniques. Unlike conventional techniques, the careful control of discharge energy can provide an additional level of control on the springback reduction.

Flanged Component

The wrinkling of the flanged workpiece resulting from the performing step was eliminated. It was also possible to form the contour of the curved branch, including the joggles, within the required tolerances. The springback of the flanged part was significantly reduced, but complete removal of springback was not possible using the hybrid forming technique. Due to an actuator shape that was not completely optimized, there were some bulges at the ends of the best parts produced in this study. These dimensional defects were located at the bending radius. To apply the technique to industrial production some further analyses, experimentation, and improvements are required. For example, a further investigation of the springback behavior is necessary to produce parts within the required tolerances and specification. In this study, the best forming results were obtained by forming over a relatively soft Garolite® G-10 tool.

The fugitive foil forming process was able to form this part completely to specification. It improved on the hybrid forming process by further reducing the springback angle to the desired 90° and eliminating the bulges at the ends of the parts. However, further work must be completed regarding this method to improve reliability and reproducibility of the results, as well as further optimization of the foil and flyer thickness and material.

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U-Channel Component

The fugitive foil forming approach shows clear advantages over traditional forming methods for the u-channel components. The results are repeatable, but further improvement is needed to calibrate the parts to specification. The most promising experiments appear to be the two-foil methods, as they balance the reduction in springback with low local deformation. It is clear that the fugitive foil technique is more efficient than the traditional electromagnetic forming technique for this application, and that the fugitive foil technique can be used to eliminate large amounts of springback in high-strength steel. However, upon the completion of many variations of the two-foil experiments, including varying the foil location, foil width, and charging energy to achieve optimal results, it is unclear if this technique can be used to eliminate all springback from the parts and form the u-channel completely to specification.

Springback Control

This work has shown that electromagnetic calibration with a disposable actuator approach is feasible and that current production processes of curved and flanged aluminum sheet metal parts can be improved. It was shown that good forming results were achieved with the EM actuators designed for the curved and flanged components. A simple disposable actuator with only one turn and a varied width to optimize the applied magnetic pressure appears to be an effective solution.

The fugitive foil process can be used to form a dimensionally correct aluminum part in the T6 condition and can even improve on EMF processes currently being developed, as demonstrated with the flanged part. While the u-channel component was
not formed completely within specification, the study still demonstrated that fugitive foil forming is a viable process for springback control of high-strength steel parts.

Additionally, components formed using EMF or fugitive foil forming techniques can be equivalent to or improve upon those produced using current production methods.
References


Appendix A: Additional Experiment Data for U-Channel Component
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<th>Test #</th>
<th>Foil Thickness (in)</th>
<th>Foil Width (in)</th>
<th>Position on Part</th>
<th>Charging Local Burst Time to Peak Springback Angle</th>
</tr>
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<tbody>
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<td>-----</td>
<td>-----</td>
<td>-----</td>
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Table 3: Experiment Data for all U-Channel Component

Continued
### Table 3 continued

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<th>Position on Part</th>
<th>Charging Energy (kJ)</th>
<th>Local Deformation?</th>
<th>Burst Peak Current (kA)</th>
<th>Time to Peak Burst (μs)</th>
<th>Peak Current (kA)</th>
<th>Springback Angle on Part</th>
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#### Two-Foil Tests

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<th>Position on Part</th>
<th>Charging Energy (kJ)</th>
<th>Local Deformation?</th>
<th>Burst Peak Current (kA)</th>
<th>Time to Peak Burst (μs)</th>
<th>Peak Current (kA)</th>
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<td>200.5</td>
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<td>208</td>
<td>96</td>
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Appendix B: Current/Voltage Trace Data for U-Channel Component
Figure 39: Current/Voltage versus Time Plot for Test 1
Figure 40: Current/Voltage versus Time Plot for Test 2
Figure 41: Current/Voltage versus Time Plot for Test 3
Figure 42: Current/Voltage versus Time Plot for Test 4
Figure 43: Current/Voltage versus Time Plot for Test 5
Figure 44: Current/Voltage versus Time Plot for Test 6
Figure 45: Current/Voltage versus Time Plot for Test 7
Figure 46: Current/Voltage versus Time Plot for Test 8
Figure 47: Current/Voltage versus Time Plot for Test 9
Figure 48: Current/Voltage versus Time Plot for Test 13
Figure 49: Current/Voltage versus Time Plot for Test 14
Figure 50: Current/Voltage versus Time Plot for Test 15
Figure 51: Current/Voltage versus Time Plot for Test 16
Figure 52: Current/Voltage versus Time Plot for Test 18
Figure 53: Current/Voltage versus Time Plot for Test 19
Figure 54: Current/Voltage versus Time Plot for Test 20
Figure 55: Current/Voltage versus Time Plot for Test 21
Figure 56: Current/Voltage versus Time Plot for Test 22
Figure 57: Current/Voltage versus Time Plot for Test 23
Figure 58: Current/Voltage versus Time Plot for Test 24
Figure 59: Current/Voltage versus Time Plot for Test 25
Figure 60: Current/Voltage versus Time Plot for Test 28
Figure 61: Current/Voltage versus Time Plot for Test 29
Figure 62: Current/Voltage versus Time Plot for Test 31
Figure 63: Current/Voltage versus Time Plot for Test 32