Agile Production of Sheet Metal Aviation Components Using Disposable Electromagnetic Actuators*

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Abstract

Electromagnetic forming is a process used to produce high strain rates that improve the formability of sheet metal. The objective of this paper is to discuss the feasibility of the use of disposable actuators during electromagnetic forming of two aluminum components: an industry part whose main feature is a convex flange with two joggles, and a simple part with a one-dimensional curve throughout. The main forming complications after the parts were formed using conventional methods were the presence of wrinkles and excessive springback. The goal of this work is to use large, controlled electromagnetic impulses to minimize the springback of these components from a rough-formed shape, with the end result being a dimensionally correct part. The optimum test protocols for electromagnetic calibration of the components were determined by optimizing parameters such as design of the actuator, tool material, and capacitor discharge energy. The use of disposable actuators for electromagnetic calibration of the parts showed significant reductions in springback compared to the parts which were only preformed using conventional techniques (hydroforming and rubber-pad forming). Springback was decreased in the curved component by up to 87%. For the flanged component, the wrinkles were eliminated, the joggles were formed properly, and the average bending angle of the part was improved from 95.3° to 90.3°, very near the target bending angle of 90°. This study demonstrates that these forming techniques can be used to improve current sheet metal production processes.

* *The authors would like to thank Cutting Dynamics, Inc. for providing financial support, materials, and tooling for this study. Thanks to Geoffrey Taber for his support for the experiments. Thanks to the Martin-Schmeiβer Foundation for providing financial support for this study.*

Keywords

Forming, Aluminum, Agile

1 Introduction

Aircraft structures are quite complex, with an ever-increasing number of complicated, high strength aluminum sheet metal parts being used for their assembly. This makes these structural components extremely difficult to produce since conventional forming methods are reaching their limits. “Conventional forming” refers to any method using large static forces to accomplish the forming. Also, because production volumes are usually quite small for any given component, one-sided dies are typically used and it is not uncommon for a component to undergo several sub-processes during manufacturing. One example of a manufacturing process used in aircraft 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. This forming method is commonly used in the aviation industry to manufacture aluminum sheet metal parts [1].

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 forming process. As a result, an 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. It is desired that a high-impulse electromagnetic forming (EMF) process will make these heat treatment steps unnecessary, allowing parts to be formed to specification in the T6, or full-hard, condition.

It is expected that the use of electromagnetic forming will lead to lower part costs and shorter lead times. Without the time-consuming heat treatment steps the part manufacturer will be able to react with more flexibility regarding customer orders of parts manufactured with this process. This will contribute to an “agile” production process, meaning that it is simple and inexpensive to make low volumes of many different parts, each of which require different tooling.

In this paper two new methods to calibrate structural aluminum aviation parts using electromagnetic forming will be introduced. In contrast to past work, instead of using “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 discharge, but are inexpensively produced.

The purpose of this study is to demonstrate the feasibility of using electromagnetic forming with this kind of actuator in a production process. The forming process for two unique parts, a “flanged” component and a “curved” component, will be investigated using a combination of conventional and impulse forming techniques. This combination of quasi-static and impulse forming has been investigated for a deep drawing process in the work of Vohnout and of Psyk [2], [3]. Each part, shown in Figure 1, has characteristics inherent to a specific class of aviation sheet metal parts. The results of the investigation will then be compared to the results obtained using conventional forming techniques.

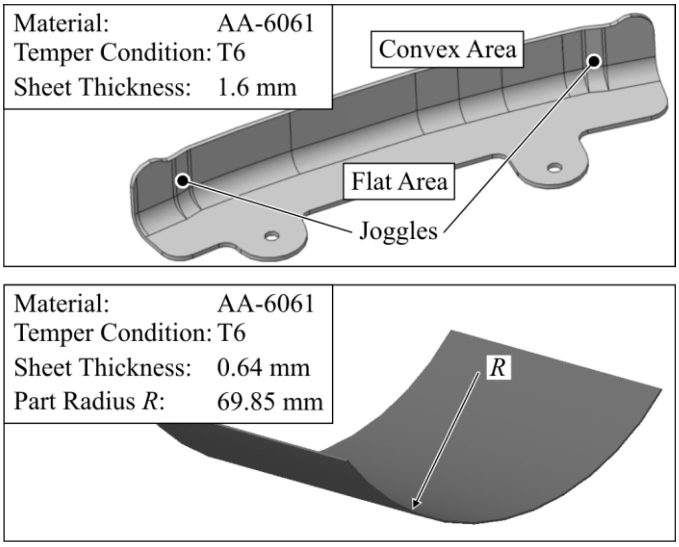


Figure 1: *Curved component and flanged component*

2 Electromagnetic Forming

2.1 Fundamentals

Electromagnetic forming uses the principles of magnetism and electromagnetic induction. A typical electromagnetic forming system consists of a discharge circuit and the components that are necessary for the operation of the system. A capacitor bank discharges a large current (with a peak on the order of 10^4-10^5 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. This results in large mechanical energy (high velocity/momentum) acting on the blank, which forces the blank away from the actuator. This forming energy can be adjusted by changing the energy to which the capacitor bank is charged. A larger charging energy will result in a larger magnetic pressure on the blank, and thus greater forming energy. Strain rates between 10^3/sec and 10^4/sec can be achieved with this process [4]. The principal limiting factor for this process is that the actuator and blanks must be made from a highly electrically conductive material such as copper or aluminum.

2.2 Disposable Actuators

To withstand the large and complicated impulse load cases experienced during EMF, traditional actuator concepts include large reinforcements that represent a large portion of the overall tooling costs. Since aviation parts are often low-volume, the tooling costs have a significant influence on the total cost per part. Thus the concept of “disposable” actuators was developed, wherein each actuator is only used to calibrate one workpiece and recycled afterwards. The basic idea of this concept is that the EMF actuator is manufactured out of thin, inexpensive 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. The tool, workpiece, and actuator are pressed together into a rubber pad, which counteracts the electromagnetic forces that would otherwise repel the actuator away from the workpiece. The rubber pad 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 [5]. In the following experiments AA-6061 aluminum is used as the actuator material due to its relatively good electrical conductivity as well as its ability to be laser-cut, making production a simple and cost-effective process. After production, the actuators are covered with high voltage Kapton® insulation tape to provide the required electrical insulation between the actuator and the workpiece.

3 Curved Component

3.1 Experimental Setup

The first component to be investigated has only one feature: a circular curve across the entire length of the part, as shown in *Figure 1*. This component is representative of a class of parts, namely those with gradual one-dimensional curves where springback is the primary concern. A very simple un-optimized disposable actuator is used. Two variables were investigated in this work: the actuator design and the capacitor charging energy.

To set up the experiments, the flat blank and actuator were placed under the tool and the entire assembly was pressed into rubber using a hydraulic press. Thus, the blank was pressed firmly against the tool prior to electromagnetic forming, as shown in *Figure 2*B. Electromagnetic forming was then used to convert the elastic deformation of the part into plastic deformation, reducing residual strain and thus springback [6]. The capacitor bank is produced by Maxwell Magneform and has a maximum working voltage of 8.66 kV and a maximum energy storage of 16 kJ. The experimental setup can be seen in *Figure 2*A.

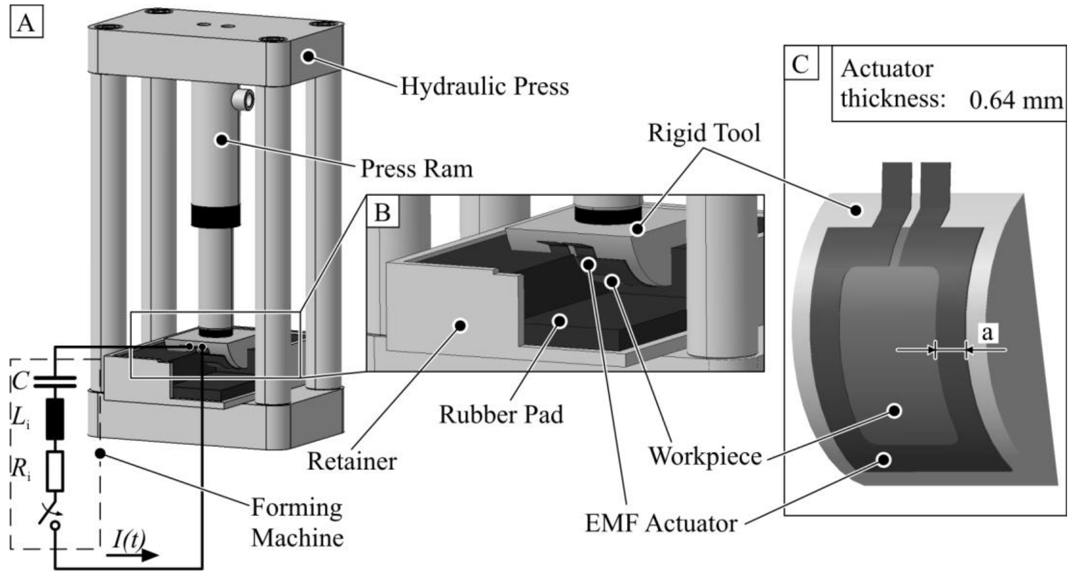


Figure 2: *A) Experimental setup for the curved component. B) Die and part setup in press. C) Actuator and part on die surface*

For this component, the actuator design is a thin single turn actuator that follows the edge of the blank. This design was chosen to allow an effective comparison between the actuator widths with a minimum of complicating variables. Two actuator widths (*a*) were investigated: 0.5 inch (12.7 mm) and 1 inch (25.4 mm). The actuator design can be seen in *Figure 2*C, where the 1 inch actuator is shown.

3.2 Effect of Actuator Width and Charging Energy

Experiments were completed at charging energies between 0.8 kJ and 5.6 kJ at intervals of 0.8 kJ. Output currents ranged from 75 kA to 160 kA for the 0.5 inch coils and from

95 kA to 210 kA for the 1 inch coils. *Figure 3*B and C show the parts formed with the two different actuator widths. These formed parts were compared to a part pressed into the rubber pad with a force of 12000 lbs with no electromagnetic forming, which is the bottom part shown in both figures. *Figure 3*D shows the target part shape with the correct radius.

To quantitatively compare the effects of changing the charging energy and actuator width, the radius of each part was determined. Since the radius decreases as the amount of plastic deformation in the part increases, a smaller radius is more desirable. The calculated radius was then compared to the applied charging energy for each actuator width. The resulting plot can be seen in *Figure 3*A.

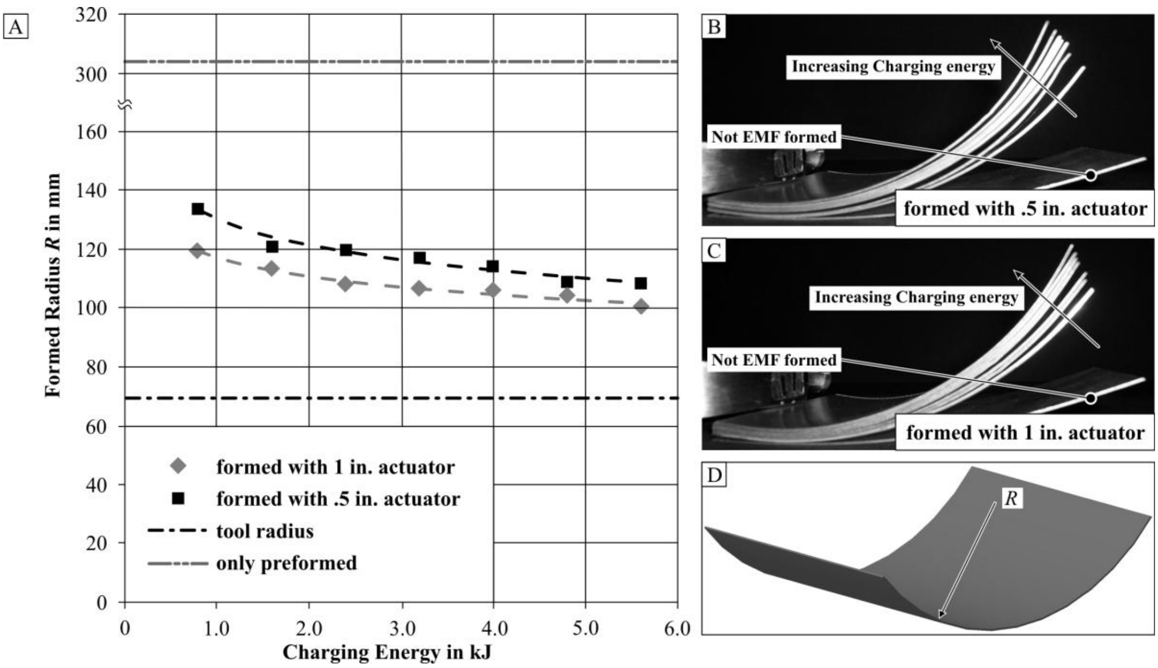


Figure 3: *A) Effect of charging energy on part radius B) Effect of 0.5 inch wide actuators on part shape C) Effect of 1 inch actuators on part shape D) Target part shape*

An increase in the charging energy as well as a decrease in actuator width will lead to an increase in the applied magnetic pressure. In the case of a greater charging energy the magnitude of the applied pressure is greater, while in the case of a smaller actuator width the magnetic pressure is concentrated on a smaller area. The plot shows that it is an increase in the magnitude of the magnetic pressure which primarily affects the formed radius. The average difference in radius between the parts formed with the 0.5 inch actuators and the 1 inch actuators was 9.4 mm. The decrease in the formed radius by increasing the charging energy from 0.8 kJ to 5.6 kJ was 18.9 mm for the 0.5 inch actuators and 25.3 mm for the 1 inch actuators.

3.3 Experimental Radii vs. Target Radii

Once the radii of all formed parts were determined, they were plotted against the target radius of the tool as well as the radius of a part formed only by rubber-pad forming. *Figure 3*A shows that, while the target radius was not achieved, electromagnetic forming significantly improved the formed radius. The use of electromagnetic forming resulted in an average decrease in the part radius of 196.7 mm, while the difference between the target radius and the average part radius was 43.3 mm, resulting in a springback decrease of nearly 82%. The maximum decrease in part radius, obtained using a 0.5 inch actuator and a charging energy of 5.6 kJ, was 209.1 mm. This was 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 improvement in the formed radius were thinner actuators and higher charging energies. In future developments of this procedure, it would be beneficial to increase the number of turns in the actuator to increase the blank area exposed to magnetic pressure.

4 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 (see Figure 1). It also contains two joggles along the radius, as shown in the figure. It is not possible to form this part in the T6 temper condition within the required tolerances by using quasi-static methods. *Figure 4* shows the defects resulting from the hydroforming step: wrinkles (*Figure 4*A and C), springback (*Figure 4*B), and crowning (*Figure 4*C).

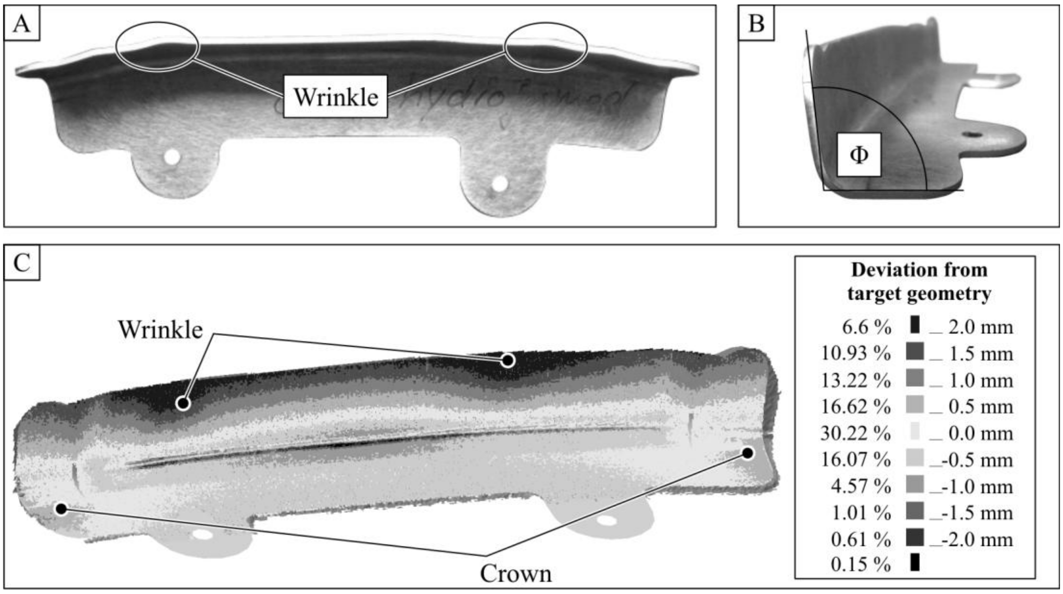


Figure 4: *A) Top view of a preformed part B) Side view of a preformed part with the bending angle Φ C) Deviation analysis of a preformed workpiece, by percentage of measured points*

4.1 Experimental Setup

The basic form of the actuator used for this application is a U-shape. The exact actuator shape is illustrated in *Figure 5*C. It was expected that the wrinkle and springback removal along the convex area of the part would require the highest magnetic pressure, while the removal of the crown along the flat area would require less pressure (see *Figure 4*C). To achieve the desired pressure distribution with respect to these forming tasks, the actuator had locally varied widths. A wider section of 0.6 inch (15 mm) was chosen to cover the workpiece area that 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 implemented.

The same hydraulic press and capacitor bank were used for this component as for the curved component. For the forming operation the actuator was bent around the die as shown in *Figure 5*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 were pushed into a rubber pad by the press. Thus the actuator was pressed securely against the part, resulting in an efficient forming process when the capacitor bank was discharged [5]. *Figure 5*A shows the complete setup as used during the experiments.

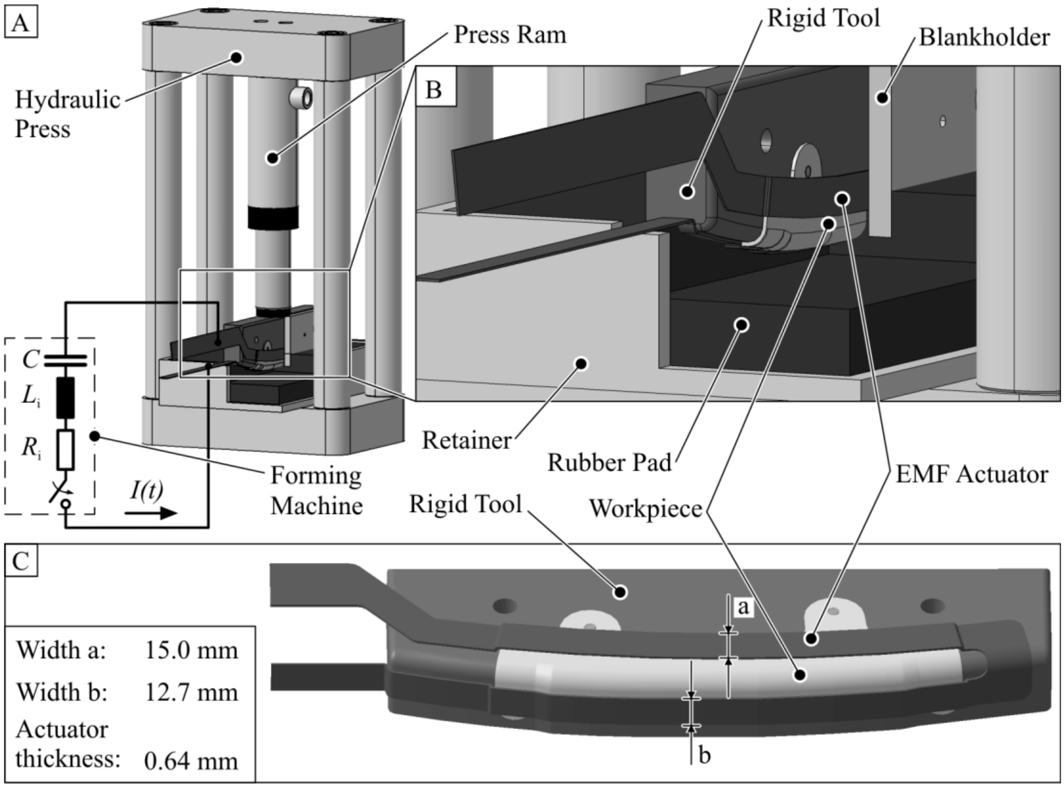


Figure 5: *A) Experimental setup for the flanged component B) Die and part setup in press C) Actuator and part on die surface*

The influence of two parameters was investigated during the experiments: charging energy and tool material. The goal was to find the optimal conditions for each parameter to form the part to specification. After the forming was completed, a laser scanner was used to digitalize the part shape. Distance analysis was then performed to obtain deviation plots showing the distance between matching points on the CAD model and the laser scans, as shown in *Figure 4*C.

4.2 Effect 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. This actuator failure did not affect the finished quality of the formed part.

4.3 Effect of Charging Energy and Tool Material

In Section 2.1 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 optimum energy to form the desired shape and eliminate the wrinkles that are produced in the preforming step. The correlation of input energy with springback is also important. Since over-bending 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 frequency of 20 kHz. For these initial experiments the steel tool was used.

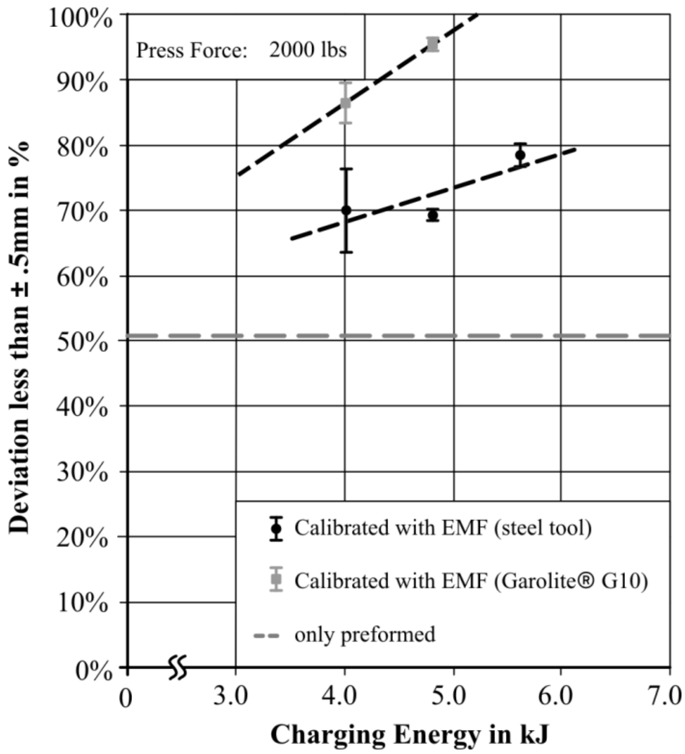


Figure 6: *Percentage of points of the scanned parts with a deviation from the CAD-model between -0.5 mm and 0.5 mm versus charging energy*

Figure 6 shows the relationship between achieved shape and applied charging energy. The quality of the shape is expressed by the percentage of scanned points from the distance analysis that are located within a maximum distance of ±0.5 mm from the target geometry. This is defined as the “deviation”. The dashed line in the diagram is the average value of the parts that were only preformed. The figure 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.

Different tool materials could affect the 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 die 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 initial charging energy for these experiments.

Figure 6 shows the results of the realized part quality for the steel and Garolite® G-10 dies. The best results were achieved with the Garolite® G-10 die. Since this 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.

A deviation analysis of a part formed against the Garolite® G-10 die with an increased charging energy of 4.8 kJ is shown in *Figure 7*. This analysis shows that the wrinkling was eliminated, but also shows that humps were formed in the area of the bending radius at the extreme part edges or ends; these defects appear as darker areas in the figure.

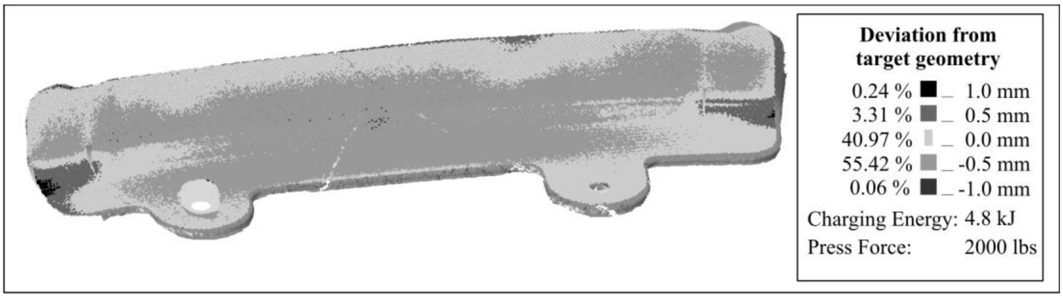
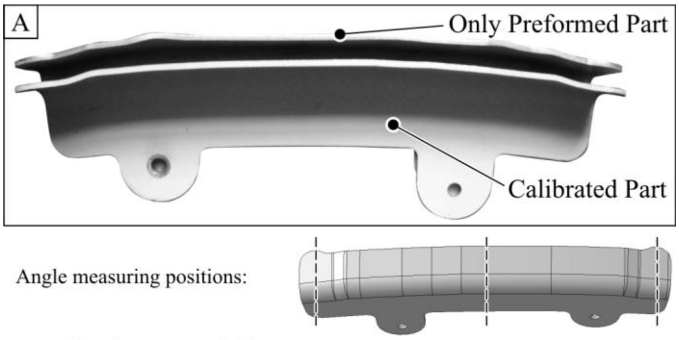


Figure 7: *Percentage of points of the scanned parts with a deviation from the CAD-model between -0.5 mm and 0.5 mm versus part shape*

*Figure 8*A shows the improvements due to the electromagnetic calibration. In this picture a workpiece that was only preformed 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 flange.



B

Charging Energy: 4.8 kJ
Press Force: 2000 lbs

	Left side of the Part	Part center	Right side of the Part
Measured angle before EMF calibration in ° (average)	94	97	95
Measured angle after EMF calibration in ° (average)	90	92	89

Figure 8: *A) Comparison of a part that is only preformed with a part that is EMF calibrated B) Comparison of measured flange angles before and after EMF calibration*

Compared to the two metal tools the springback values of the parts calibrated with the Garolite® G-10 die were reduced significantly. *Figure 8*B shows springback angles measured at three positions along the flange, with an average reduction of the bending angle from 95.3° to 90.3°. The target bending angle was 90°.

4.4 Future Outlook – Exploding Foil Forming

A new method that is currently being explored to form the curved component is exploding foil forming. In this process a thin aluminum foil is connected to a thick 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.

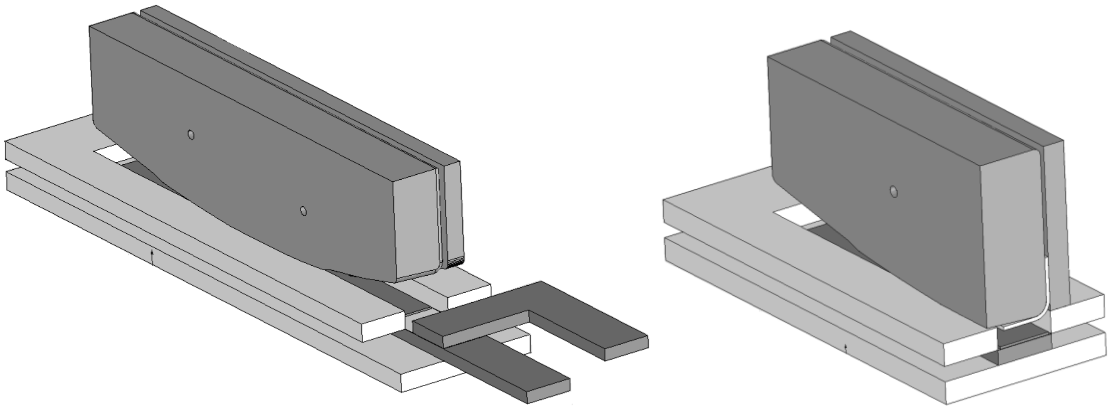


Figure 9: *Experimental setup for exploding foil forming (full and sectioned view)*

The setup for the exploding foil process can be seen in ***Figure 9***. A 0.032 inch (0.813 mm) thick aluminum flyer was used to transfer the pressure from the exploding foil to the part. It must be noted that the foil thickness has a significant role in the effectiveness of the exploding 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 [7]. As a result, an optimal coil thickness can be found that is a balance of the vaporization and magnetic impulse effects. Preliminary experiments indicate that the optimum 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.

The result of exploding foil calibration compared to a part that was only hydroformed can be seen in *Figure 10*. In addition to improvements over the preforming method, the use of the exploding foil process resulted in improvement of the flanged component shape over calibration from electromagnetic forming. The part formed using the exploding foil technique was completely within dimensional tolerances with all defects from the preforming (hydroforming) process removed, and produced comparable results to those achieved with the current production method. This process must be further investigated to determine optimal testing parameters, such as the optimal foil and flyer thickness and material, along with the optimal charging energy. The reliability and repeatability of this method must also be examined.

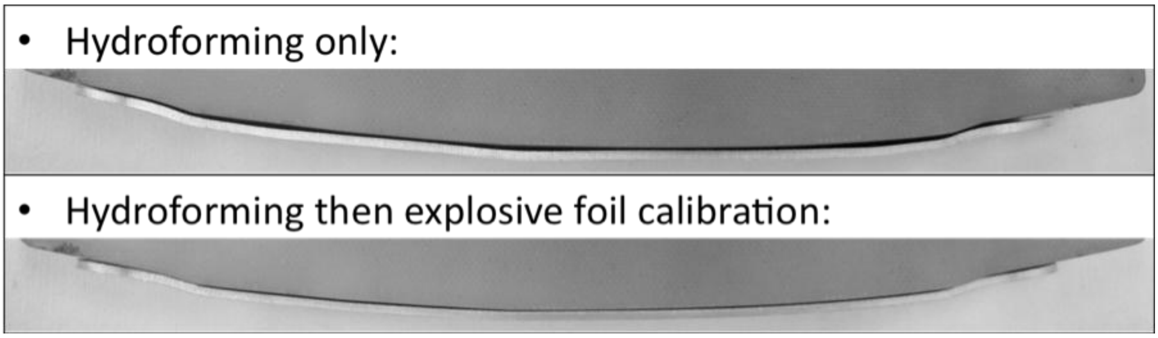


Figure 10: *Comparison of a part that is only preformed with a part that is explosive foil calibrated*

5 Conclusions

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

While the target radius of the curved component was not achieved, a significant improvement in the formed radius was achieved using electromagnetic forming along with the rubber-pad forming process. Increasing the discharge current or decreasing the actuator width decreased the formed radius of the parts regardless of the actuator design, but reducing actuator width had a limited effect because it only reduces the area affected by magnetic pressure. 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 that could achieve higher forming energies and, to a larger extent, by designing new actuators that applied forming force to the central region of the part as well as the edges. 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.

The wrinkling of the flanged workpiece resulting from the preforming 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 as well. The complete removal of springback was not possible. 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. In this study, the best forming results were obtained by forming over a relatively soft Garolite® G-10 tool. The use of this tool material with exploding foil forming was demonstrated to be an improvement over this process. However, further work must be completed regarding this method to improve reliability and reproducibility of the results, as well as further optimization of the process parameters. Even with these challenges, the exploding foil process has shown that a dimensionally correct part can be formed fully in the T6 condition, and that parts formed using EMF or exploding foil techniques can be equivalent to or improve upon those produced using current production methods.

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