D. Electromagnetic Forming of Aluminum Sheet

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Objective

- The purpose of this project is to develop electromagnetic forming (EMF) technology that will enable the economic manufacture of automotive parts made from aluminum sheet. EMF is a desirable process because the dynamic nature of the deformation results in benefits including increased forming limits and reduced springback. These benefits would result in increased use of aluminum and therefore more fuel-efficient vehicles due to mass reduction.

Approach

- Address analysis methods for forming system design.
- Address development of durable actuators (coils).
- Address industrial embodiment of the EMF process.

Accomplishments

- Completed a literature search for information on EMF, coil materials and coil design/durability.
- Completed design and assembly of a 150 kJ pulsed power unit at LANL.
- Ford Motor Company designed an integrated forming coil system for high-volume automotive stamping.
- LANL completed a literature review of patents, relevant coil materials, and the design of EMF coils.
- Installed the 150 kJ pulsed power supply at PNNL, demonstrated operation, and installed automated computer control system capable of automated cyclic testing and sheet metal forming.
- Completed fabrication of an experimental apparatus to evaluate coil durability.
- Established a CRADA to include Ford, PNNL, and Oxford Automotive.
- Performed cyclic testing of an EMF coil assembly for durability assessment and achieved more than 5,000 cycles.
- Developed conceptual layouts for industrial embodiment of EMF process.
- Demonstrated ability to improve formability of aluminum sheet by a factor of two-to-three times over conventional forming.
- Completed evaluation of EMF coil assembly cooling effectiveness.
- PNNL fabricated an enhanced coil assembly for improved coil cooling and durability.
- Established minimum cycle time limitations of the existing coil design assembly at PNNL.
- Developed EMF calibration process that reduces springback of parts.
- Design and experimental testing of flat coil with flat concentrator.
- Developed numerical simulation of the coil current density and pressure distribution on the blank during EMF restrike operation.

Future Direction

- Improve coil design to improve the thermal characteristics of the prototype coil assembly.
- Scale-up laboratory testing to include commercially-representative components.
- Further develop modeling capabilities that can assist in the design of EMF systems.
- Continue to investigate the industrial embodiment of EMF systems for automotive manufacturing.

Introduction

In the electromagnetic forming (EMF) process, a transient electrical pulse of high magnitude is sent through a specially designed forming coil by a low-inductance electric circuit. During the current pulse, the coil is surrounded by a strong transient magnetic field. The transient nature of the magnetic field induces current in a nearby conductive workpiece that flows opposite to the current in the coil. The coil and the workpiece act as parallel currents through two conductors to repel one another. The force of repulsion can be very high, equivalent to surface pressures on the order of tens of thousands of pounds per square inch. Thin sheets of material can be accelerated to high velocity in a fraction of a millisecond.

A recent interest in understanding the EMF of metals has been stimulated by the desire to use more aluminum in automobiles. The high workpiece velocities achievable using this forming method enhances the formability of materials such as aluminum. Also, the dynamics of contact with the forming die can help reduce or mitigate springback, an undesired effect that cannot be avoided in other forming techniques such as stamping. The commercial application of this process has existed since the 1960s. The large majority of applications have involved either the expansion or compression of cylinders (tubes). The forming of sheet materials is considerably more complex and has received relatively little attention.

Project Deliverables

At the end of this project, methods and data to assist the economical design of EMF sheet forming systems will be documented. This will include materials information and design methods for durable coils, coil durability test data for selected materials and design concepts, dynamic and hybrid formability data, methods for modeling the forming process, and concepts for the industrial implementation of the technology in an automotive manufacturing environment.

Approach

This project addresses three main technical areas. The first technical area involves establishing analysis methods for designing forming systems. These methods will be based on developed knowledge of forming limits and relations between electrical system characteristics and deformation response for specific aluminum alloys of interest. The second area of technical challenge is in coil durability. Existing knowledge of electromagnetic forming and relevant knowledge from pulsed-power physics studies will be combined with thermo-mechanical analyses to develop durable coil designs that will be tested experimentally. Until a more thorough understanding is achieved of economic factors determining required durability, a nominal level of 100,000 cycle coil life will be the goal for this project. Finally, the third technical area involves the industrial embodiment of the EMF process. In this project, EMF is expected to be hybridized with conventional sheet metal stamping. Different approaches to hybridization will be analyzed for issues affecting the economic implementation in a modern stamping plant. Different system concepts will be developed and studied. Existing knowledge of the EMF process and technical achievements in this project will be combined to establish a methodology for designing hybrid forming systems that can be readily integrated into modern manufacturing facilities for the economic production of automotive sheet aluminum components. Some of the project focus areas and results are discussed in the following sections.

PNNL EMF System

The EMF system at PNNL has been operational since 2001. The system is typically operating at 6,500 V and current levels in excess of 225 kA have been demonstrated. Figure 1 shows a typical response of the EMF system during a 15 kJ discharge of the capacitor bank. The figure shows that the half-current (measuring half the total system current) of the system is approximately 86 kA, so that a total current of 172 kA passed through the load coil within 26 µs.

The system has also been cycled several thousands times at high current levels while supporting our coil durability experimental work. The custom designed control system was also successfully demonstrated in automated cyclic loading operating modes. During FY05, capacitor bank control system upgrades were complete that increased cycle-to-cycle reliability, and improved the efficiency of the data acquisition system used to sample the electrical response of the entire system as well as the changing response of the coil assembly.

Coil Design Concepts and Durability. During EMF, the high-intensity electromagnetic forces are applied to the turns of the coil. The coil, insulators and support structure must resist these forces, as well as related thermal cycles, without significant permanent deformation or material failure. In

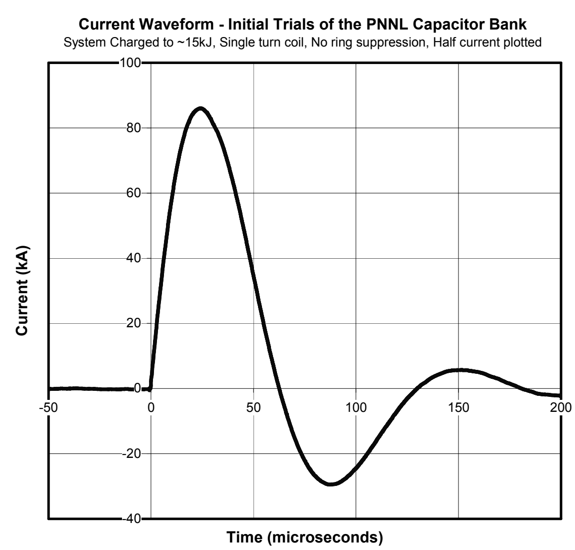

Figure 1. Typical EMF system waveform.

contrast to typical cylindrical coils, sheet forming will require coils with general three-dimensional shapes that are inherently less resistant to forces induced during forming. The key issues involve materials selection and design. Materials must be selected for both electrical conductivity and mechanical properties, and they must lend themselves to manufacturing. Materials may also need to be compatible with the presence of coolants and the forces generated during hybrid forming that combines conventional stamping and EMF. The design must integrate these elements while delivering the primary function of a spatial and temporal load distribution that achieves the desired deformations. Coil systems will have to be low-cost, modular, and have high durability (nominally 100,000 cycles) if they are to be relevant to automotive manufacturing.

During the first half of FY03, PNNL evaluated the performance of the original Ford and PNNL coil assembly designed and fabricated under this project. The experiments consisted of evaluating the forming effectiveness, measuring the coil's thermal characteristics, and starting durability tests under cyclic loading of the coil system. Figure 2 shows photographs of the forming die used, and the resulting formed aluminum sheet after testing. In this figure, the coil is directly below the aluminum sheet and the holes in the die are three inches in diameter. After a single EM pulse through the coil, the system forms three domes as shown in Figure 2 and Figure 3. These forming experiments were conducted to learn the necessary pulse magnitude in order to effectively form aluminum sheet. Subsequent to determining this critical EM pulse magnitude, PNNL initiated cyclic loading experiments on the coil system to determine the thermal and mechanical characteristics of the coil assembly to determine long-term durability. This original assembly has undergone cyclic testing at PNNL, and has achieved greater than 5000 cycles with no signs of coil degradation.

The PNNL coil durability experiments have focused on increasing the frequency of capacitor discharge to simulate high-repetition rate of automotive manufacturing. PNNL has increased the charge rate of the capacitor bank and refined the control system to achieve cyclic discharge rates to less than one per 10 seconds. This has allowed the project team to

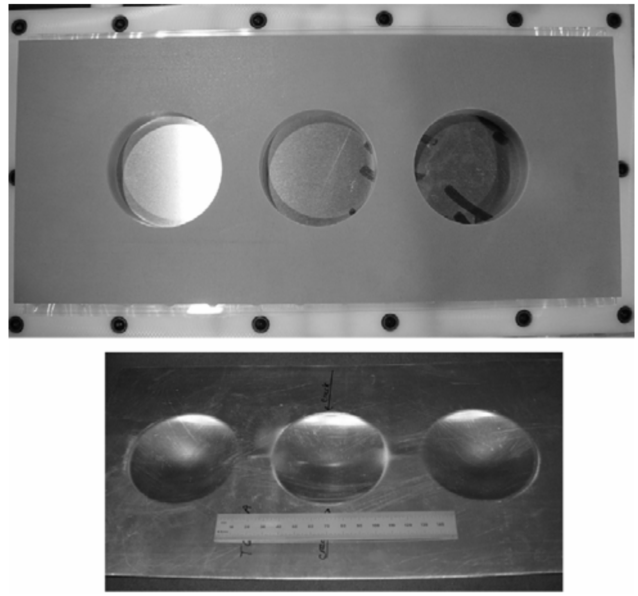

Figure 2. (top) Top view of the glass fiber reinforced plastic tooling on the coil assembly with aluminum sheet metal between the coil and the tool. (bottom) Photograph of the deformed sheet after one EM pulse through coil.

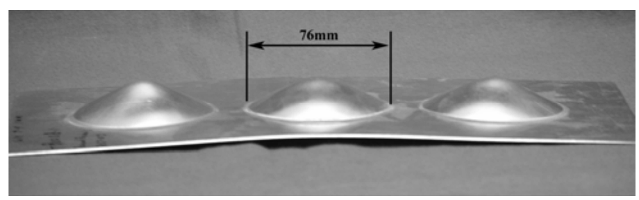

Figure 3. A formed aluminum sheet after a single EMF operation.

evaluate the structural performance of the coil and better understand the effect of coil operating temperature. One major focus at PNNL during the first half of FY04 was investigating the influence of coil assembly temperature and the ability to remove heat from the coil. Figure 4 shows the results of experiments at PNNL to evaluate the ability to remove heat from the coil using various proprietary techniques.

In the second half of FY04, PNNL redesigned the original coil assembly to increase the efficiency of cooling. The original design had limited cooling capacity and materials that had operating temperature ranges insufficient to support 10-second cycle times at high energy capacitor bank discharge. The redesigned coil incorporated a series of material substitutions and design refinements to increase the cooling efficiency, while attempting to retain the

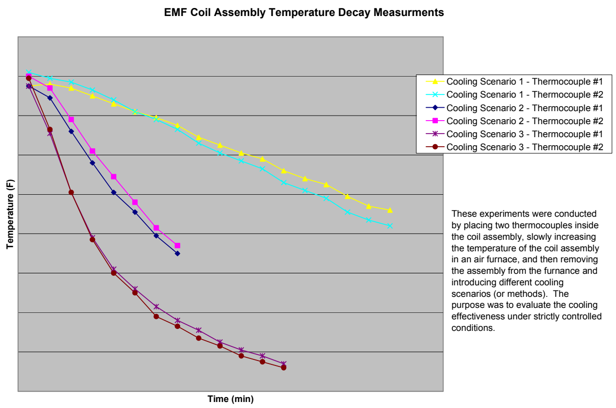

Figure 4. Plot showing the experimental results of heat removal from the coil assembly using three proprietary cooling scenarios. These experiments evaluated the rate of heat removal under controlled conditions to establish the effectiveness of each of the three cooling techniques.

successful mechanical support from the original design. This second-generation design was fabricated at PNNL. PNNL evaluated the cooling efficiency of this second-generation design under short cycle times at high energy capacitor bank discharge. During FY05, PNNL completed evaluations of this second generation coil assembly, and is making further design refinements to successfully maintain high repetition rates and suitable coil assembly temperatures.

Ford developed an EMF calibration process. The use of an EMF calibration process results in reduced springback of parts as shown in Figure 5.

Figure 5. Improvement in springback by using EMF calibration process. (top) before, (bottom) after.

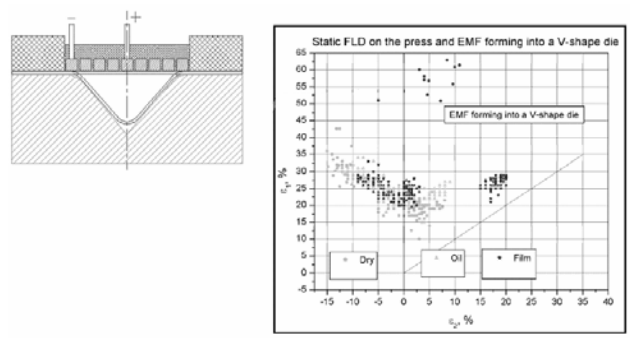

Figure 6. (left) A cross-section through a V-shaped die showing the coil, die, and workpiece before and after deformation. (right) Strain grid formability data showing the improvement in aluminum formability under these forming conditions.

Formability of Aluminum During EMF. Ford Motor Company has conducted laboratory experiments to investigate the formability of aluminum alloy sheet during EMF. These laboratory experiments included free forming of domes and forming of sheet metal into V-shaped die cross-sections. Figure 6 shows a cross-section through a V-shaped forming die showing the coil, die, and the workpiece before and after deformation. This figure also shows the results of a typical strain grid analysis and the two-to-three times improvement in formability under these forming conditions. However, the experimental data have shown that the formability is sensitive to the shape of the die being used to evaluate the formability. Further investigation may be required in this area to better define the forming limits of the material under the varying biaxial and triaxial states of stress that develop during electromagnetic forming.

Numerical Simulation of EMF Process. The EMF process is challenging to simulate due to the need to simultaneously model electromagnetic, thermal, and elastic-plastic deformation of materials. Many of the commercial research codes have serious limitations and an inability to accurately predict the results of EMF processes. This project originally focused on integrating portions of existing commercial research codes to accurately predict the important characteristics of a three-dimensional electro-magnetic forming process. However, more recent work has focused on more accurate, custom process simulations.

The current work involves collaboration with Dr. Nick Bessonov in cooperation with University of Michigan – Dearborn. Figure 7 illustrates an example of a two-dimensional simulation of EM forming of aluminum sheet into a conical die with a fully-coupled electromagnetic-elastic plastic model. These models are currently being extended for use as a fully three-dimensional numerical simulation approach.

A numerical simulation of the current and the electromagnetic forces for the EMF restrike operation has been developed in support of the coil and concentrator work ongoing at Ford. The simulation accurately predicts the coil temperature rise, the current density in the coil cross-section, the electromagnetic pressure on the aluminum blank and the plastic strain distribution in the aluminum blank. Figure 8 shows a typical result of the numerical simulation for specific coil geometry.

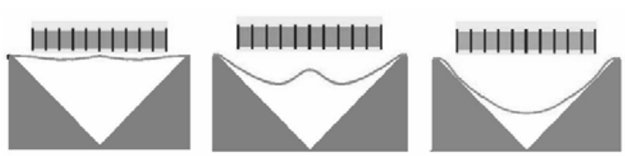

Figure 7. Example of a two-dimensional simulation of EM forming of aluminum sheet into a conical die with a fully-coupled electromagnetic-elastic plastic model. (Produced by Dr. Bessonov in cooperation with University of Michigan – Dearborn).

Industrial Embodiment. Oxford Automotive completed a study of the industrial embodiment of the EMF process, which is designed to analyze the potential methods to incorporate EMF into the highly-integrated manufacturing of automobiles. The study investigated integration into conventional sheet-metal stamping production facilities and the potential to create an entirely new and separate production line based on EMF technology for aluminum alloy sheet. Several variations of industrial deployment were identified and studied. One possible scenario is where the EMF system would be used as a separate forming station to perform a restrike function. This restrike operation would be employed to increase deformation in local regions requiring greater formability than conventional stamping will permit.

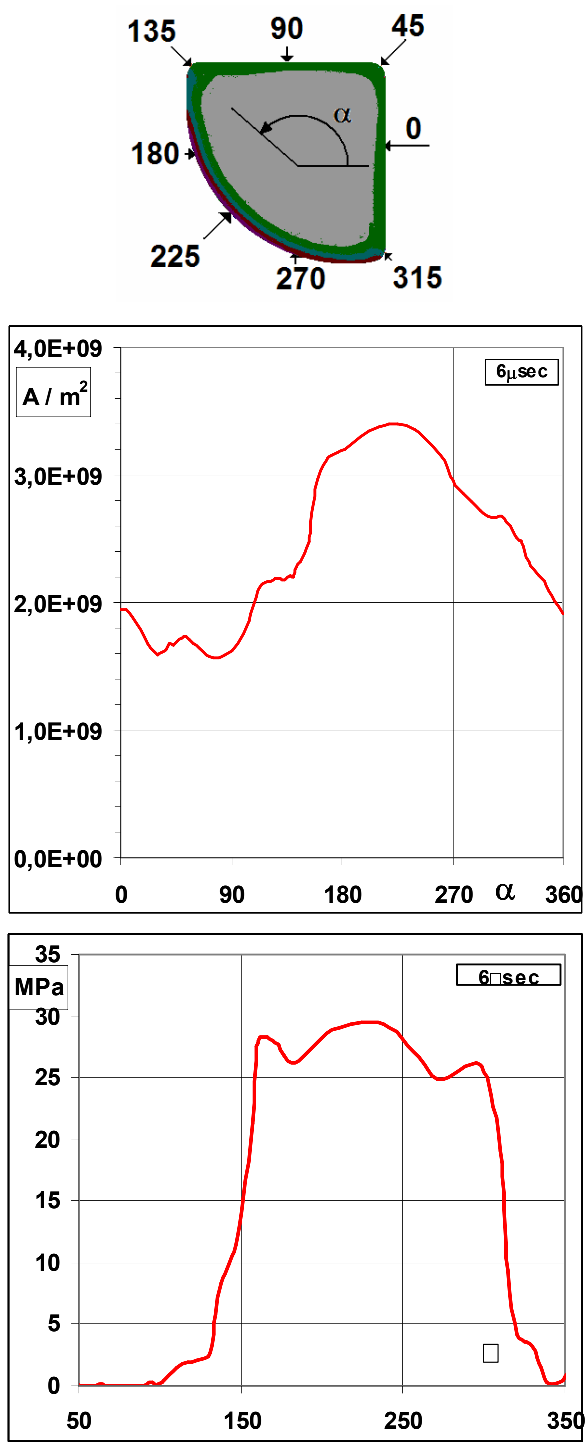

Figure 8. Numerical simulation of the (middle) coil current density and (bottom) pressure distribution on the blank during EMF restrike operation using the coil geometry (top).

Conclusions

Technical feasibility of EMF for aluminum sheet in an automotive application has been demonstrated, during both this project and prior USCAR projects. The durability of relevant coils systems and methods for the economical design, construction and implementation of forming systems are yet to be demonstrated. However, the current project has made significant progress in demonstrating coil durability at commercially relevant conditions. There is also a need for additional dynamic formability data of relevant aluminum alloys. This project targets these issues. Progress has been made in assessing the current state of knowledge for materials, coil design, formability, and system design. Also, a pulsed power system has been designed and fabricated to serve in experimental testing of coil systems. This project has also shown that EMF can be performed using aluminum sheet while achieving intermediate coil life (~5,000 cycles). As this project progresses, a balanced combination of analysis and experiment will be applied to demonstrate more durable coil systems that meet the performance requirements of automotive manufacturing. A numerical simulation tool has been developed that accurately predicts the coil temperature rise, the current density in the coil cross-section, the electromagnetic pressure on the aluminum blank and the plastic strain distribution in the aluminum blank. This tool contributes to developing modeling capabilities that can assist in the design of EMF systems.