C. Electromagnetic Forming of Aluminum Sheet

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Objective

- 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 (Figure 1) at Los Alamos National Laboratory (LANL).

Figure 1. Photograph of the capacitor bank and load cables connected to the forming coil.

- Found that Ford Motor Company designed an integrated forming coil system for high-volume automotive stamping.
- Established that LANL completed a literature review of patents, relevant coil materials, and the design of EMF coils.
- Installed the 150-kJ pulsed power supply at Pacific Northwest National Laboratory (PNNL), demonstrated operation, and installed an 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 Cooperative Research and Development Agreement (CRADA) that includes 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 2-3 times more than conventional forming.
- Completed evaluation of EMF coil assembly cooling effectiveness.
- Observed that PNNL has fabricated an enhanced coil assembly for improved coil cooling and durability.

Future Direction

- Increase the cyclic testing rate to better evaluate the thermal characteristics of the industrial 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 EMF 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 are being 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.

*EMF System Commissioning***.** The initial testing and trials of the new EMF system at PNNL were conducted in September and October 2001. The trials consisted of assembling the new EMF power supply system, load cables, and inductive load coil. The apparatus used to conduct the experiments is illustrated in Figure 1. This figure shows the four parallel coaxial conductors connected between the power supply and the EMF coil. The coil used was a single-turn, low-inductance aluminum alloy coil made from AA6061-T6. Not shown in the figure is the coil containment shroud and associated supports. The experiments involved multiple cycles of charging and discharging of the capacitor bank through the load coil at various known energy levels. The capacitor bank was controlled via the custom system developed for the unit. The sequence of testing consisted of charging the capacitor bank, isolating the charging power supply, triggering (releasing) the capacitor charge, and monitoring the response of the system. The system response was recorded using a high-speed digital oscilloscope. Figure 2 illustrates the typical response of the system during a 15-kJ discharge of the capacitor bank. This figure shows that the half-current (measuring half the total system current) of the system is approximately 86 kA, so

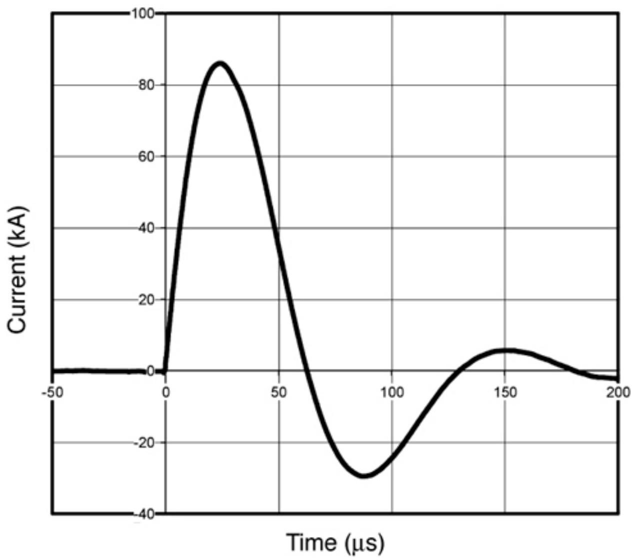

Figure 2. The current waveform that resulted during the initial system trials at PNNL.

that a total current of approximately 172 kA passed through the load coil. The system rise time was shown to be approximately 26 μs. This EMF system has been commissioned and demonstrated with an automated cyclic testing during sheet metal forming. During the first half of FY 2003, the EMF capacitor bank was demonstrated at current levels in excess of 225 kA. 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 the last half of FY 2004, the capacitor bank control system was upgraded to increase cycle-to-cycle reliability and to improve 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 contrast to typical cylindrical coils, sheet forming will require coils with general three-dimensional (3-D) 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 second quarter of FY 2002, LANL generated a technical report containing a conceptual coil design to perform in a high-volume manufacturing system. This particular design is considered modular and would likely require multiple coils to execute any singular forming operation. This modular coil approach may require further study of coil-to-coil interaction and durability before it can be commercially implemented. In contrast, Ford Motor Company designed an integrated forming coil system for high-volume automotive stamping of complex components. This Ford-designed system has evolved into the system currently being tested for high-cycle forming trials at PNNL. The design integrates features that enhance the stiffness and durability of the coil during cyclic forming operations.

Beyond these trials on the Ford-designed coil system, PNNL has developed a system to evaluate these potential coil materials under high-cycle EMF conditions. PNNL has designed and fabricated a coil durability test apparatus, which was used early in the project for EMF testing. Figure 3 shows a photograph of the coil configuration that is part of the apparatus (copper alloy shown). Removed from this coil photograph (for clarity) are insulating sheets of Mylar that retard cross-coil sparking. This coil is connected to the EMF capacitor bank and control system via cables that connect on the bottom side of the coil shown. This coil is designed to be placed in close proximity to a stationary aluminum alloy plate and to be subject to cyclic pulse loading at different power levels and frequencies to determine the number of cycles to failure. The objective was to make coils from multiple materials and compare the coil durability across several samples from each population. This early work has evolved into testing of a full-scale coil assembly at PNNL.

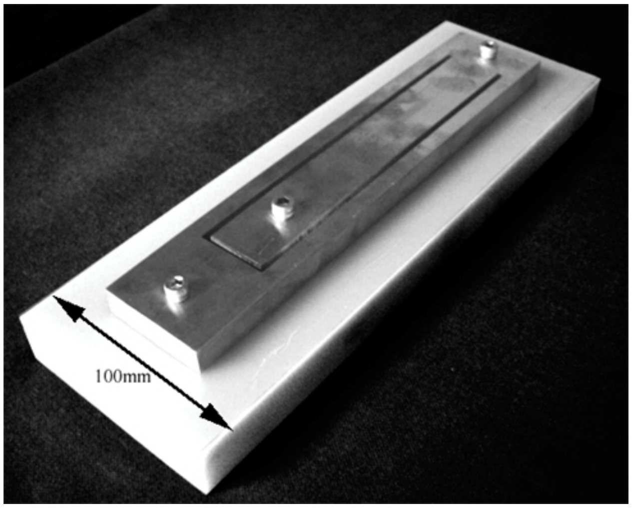

Figure 3. Photograph of the coil system originally used for testing different candidate coil materials.

Coil Durability Experiments. During the first half of FY 2003, PNNL evaluated the performance of the original 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 4 shows a photograph of the Ford- and PNNL-designed coil assembly. Figure 5 shows photographs of the forming die used as well as 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 3 in. in diameter.

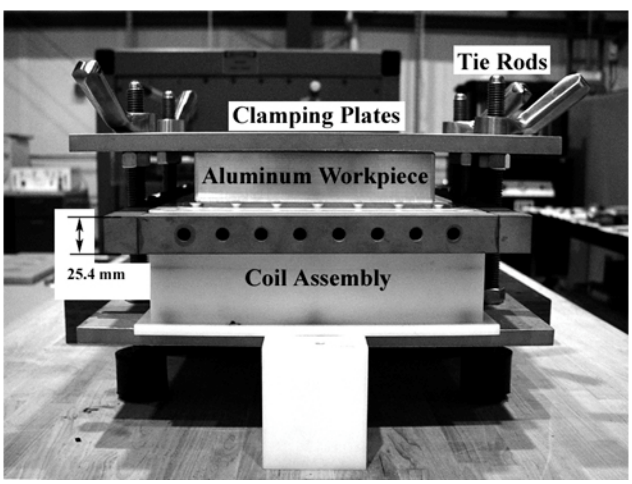

Figure 4. Photograph of the Ford and PNNL designed coil assembly. This assembly has undergone cyclic testing at PNNL and achieved greater than 5000 cycles with no signs of coil degradation.

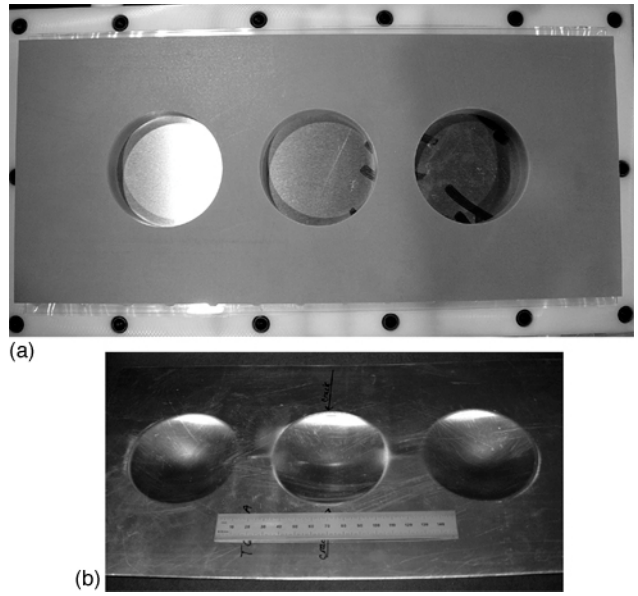

Figure 5. (*a*)Top view of the glass-fiber-reinforced plastic tooling on the coil assembly with aluminum sheet metal between the coil and the tool. (*b*) Photograph of the deformed sheet after one EM pulse through coil.

After a single EM pulse through the coil, the system forms three domes as shown in Figures 5 and 6. 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 5,000 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 fewer than 10 s. This has allowed the project team to evaluate the structural performance of the coil and better understand the effects of coil operating temperature. One major focus at PNNL during the first half of FY 2004 was investigating the influence of coil assembly temperature and the ability to remove heat from the coil. Figure 7 shows the results of experiments at PNNL to evaluate the

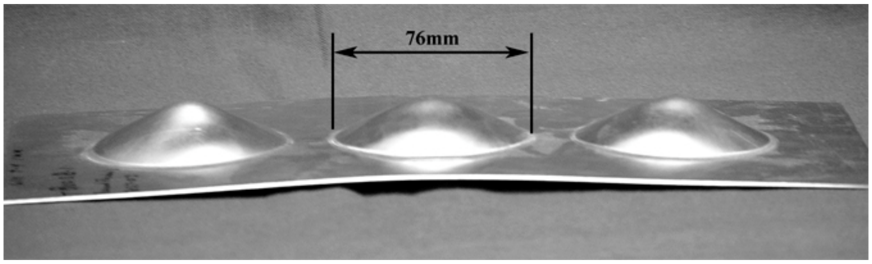

Figure 6. A formed aluminum sheet after a single EMF operation.

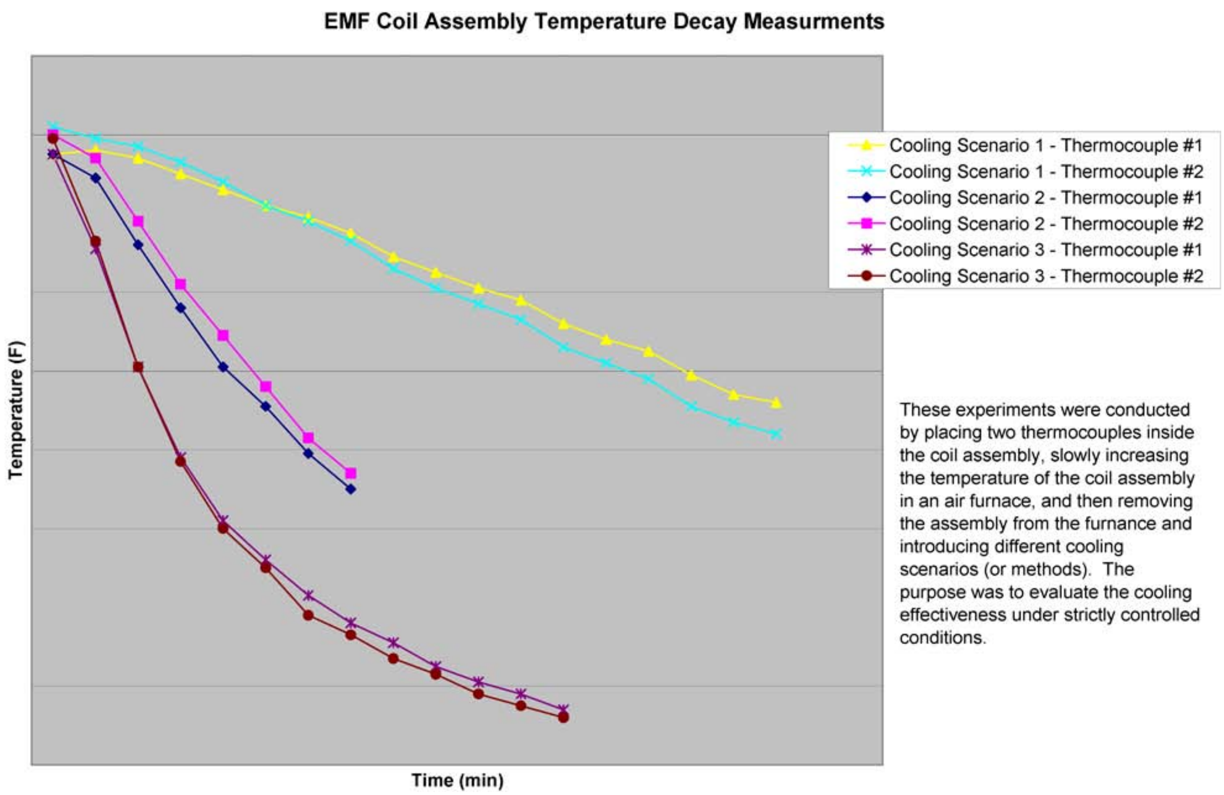

Figure 7. Plot showing the experimental results of heat removal from the coil assembly using three proprietary cooling scenarios. These experiments evaluated the rate of heat removal under controlled conditions to establish the effectiveness of each of the three cooling techniques.

ability to remove heat from the coil using various proprietary techniques.

In the second half of FY 2004, PNNL redesigned the original coil assembly to increase the efficiency of cooling. The original design had limited cooling capacity and included materials that had operating temperature ranges insufficient to support 10-s cycle times at high-energy capacitor bank discharge. The redesigned coil made a series of material substitutions and design refinements to increase the cooling efficiency, while attempting to retain the successful mechanical support from the original design. This second-generation design has been fabricated at PNNL. PNNL is currently evaluating the cooling efficiency of this second-generation design under short cycle times at high-energy capacitor bank discharge.

*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 8 shows a cross-section through a v-shaped

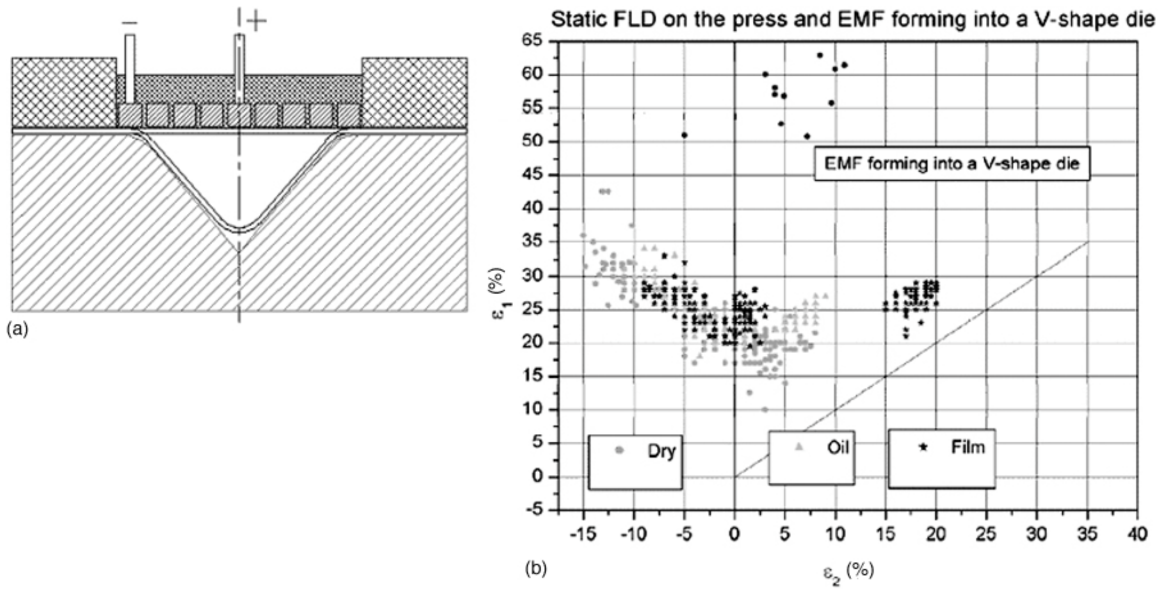

Figure 8. (*a*) A cross-section through a v-shaped die showing the coil, die, and workpiece before and after deformation. (*b*) Strain grid formability data showing the improvement in aluminum formability under these forming conditions.

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 EMF.

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 has focused on integrating portions of existing commercial research codes to accurately predict the important characteristics of a 3-D EMF process. The current work involves collaboration with Dr. Nick Bessonov in cooperation with University of Michigan–Dearborn. Figure 9 illustrates an example of a 2-D simulation of EMF 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 3-D numerical simulation approach.

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

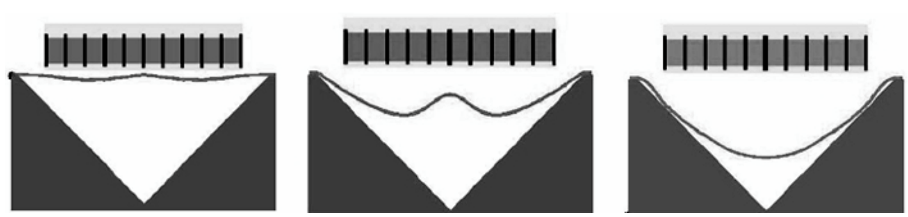

Figure 9. Example of a 2-D simulation of EMF of aluminum sheet into a conical die with a fully coupled electromagnetic-elastic plastic model. *Source:* Produced by Dr. Bessonov in cooperation with the University of Michigan–Dearborn.

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. Figure 10 shows a conceptual industrial embodiment of the EMF process as produced by Oxford. The system shown involves an EMF station located in conjunction with conventional mechanical presses. In the scenario shown in Figure 10, 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.

Conclusions

Technical feasibility of EMF for aluminum sheet in an automotive application has been demonstrated, during both this project and prior U.S. Council for Automotive Research 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 is 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 (~5000 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.

Presentations and Publications

"Pulsed Electromagnetic Forming of Aluminum Body Panels." Accepted for publication by 2005 TMS Annual Meeting and Exhibition, San Francisco, California, February 13–17, 2005.

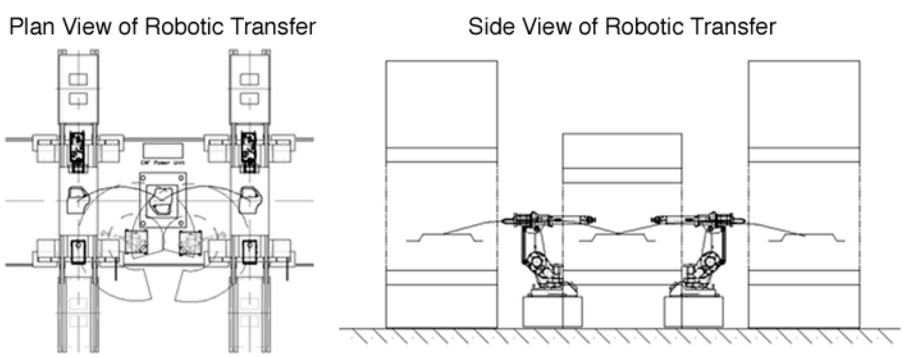

Figure 10. Conceptual industrial embodiment of the EMF process. The system shown involves an EMF station located in conjunction with conventional mechanical presses.