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 (AL) sheet. EMF is a desirable process because the dynamic nature of the deformation results in benefits which include increased forming limits and reduced springback. The benefits would result in increased use of Al and, therefore, more fuel-efficient vehicles due to mass reduction.

Approach

The project addresses three main technical areas:

- Analysis methods for forming-system design
- Development of durable actuators (coils)
- Industrial embodiment of the EMF process

Accomplishments

- Development of the flat-coil design
  1) Improvement has been made to both simplify and lower the cost of manufacturing flat coils;
  2) The packaging of the flat-coil assembly has been improved for robustness and ease of handling, and

3) A design was completed, and fabrication initiated, on a large prototype tool for EMF process demonstrations.
4) At PNNL, we upgraded the EMF capacitor-bank power-supply system to increase charge rate and decrease testing cycle time.

- Developed new, coupled, numerical models that describe three critical elements of the EMF process
  1) Propagation of the electromagnetic field through the coil-blank system and generation of pulsed electromagnetic pressure in specified areas,
  2) High-rate deformation of the blank and,
  3) Heat accumulation and transfer through the coil with an air-cooling system.
- Completed restrike simulation of an aluminum panel using a newly-developed flat concentrator.

Future Direction

- Complete automotive component tool development and fabrication, and demonstrate ability to form commercially-representative components.
- Develop further modeling capabilities that can assist in the design of EMF systems.
- Perform high-cycle-rate coil testing to demonstrate the commercial embodiment of EMF systems for automotive manufacturing.

Introduction

In the 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 approximately 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 electromagnetic forming of metals has been stimulated by the desire to use more Al in automobiles. The high workpiece velocities achievable using this forming method enhances the formability of materials such as Al. In addition, 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 more complex and has received little attention.

Approach

The project addresses three main technical areas. The first technical area involves establishing analysis methods for designing forming systems. The methods are based on developed knowledge of forming limits and relations between electrical system characteristics and deformation response for specific Al 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 are 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-Al components. Some of the project focus areas and results are discussed in the following sections.

PNNL EMF System

The EMF system at the Pacific Northwest National Laboratory (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.

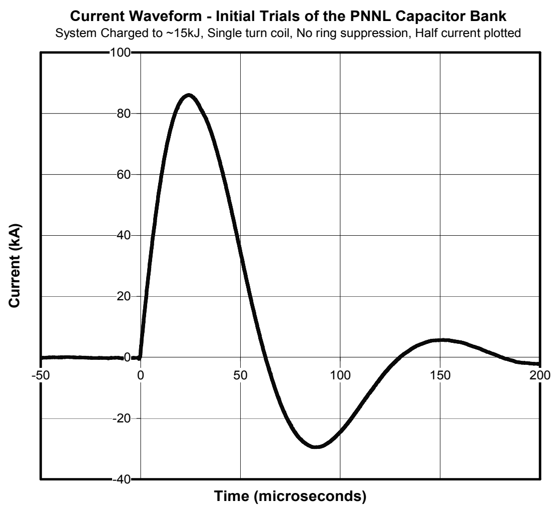


Figure 1. Typical EMF system waveform.

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 fiscal year FY 2006, capacitor-bank control system upgrades were completed that result in significantly higher cycle-to-cycle rates. This upgrade 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 contrast to typical cylindrical coils, sheet forming will require coils with general three-dimensional (3D) 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 FY 2006, PNNL and Ford initiated the design and fabrication of an automotive-component EMF tool for demonstration of commercial applications. Completion of the tooling is currently expected in the second quarter of FY 2007. This tool will be used to demonstrate commercial applications of EMF, through the demonstration of an EMF re-strike process, for a partially-formed Al component.

During FY 2006, additional coil-durability experiments have focused on increasing the frequency of capacitor discharge to simulate high-repetition rate of automotive manufacturing. With the increasing cycle times, experimental work has focused on development of active cooling approaches for managing the thermal conditions of a rapidly-cycled coil. PNNL fabricated the third-generation, actively-cooled coil design. PNNL evaluated the cooling efficiency of this design under short cycle times at high-energy capacitor-bank discharge. Results from experimental cycling of the coil and thermal measurements were provided as input to the related EMF modeling effort.

The second half of FY 2006 was primarily spent on the validation of an EMF process-simulation tool. This predictive EMF process-simulation tool will allow us to design the process by predicting the EMF field, stress-strain behavior, and the temperature distribution in the coil. Another focus area was the continued development of the flat-coil design. Improvements were made to both simplify, and thus lower, the cost of the manufacturing of flat coils. Furthermore, the packaging of the flat-coil assembly has been improved for robustness and ease of handling.

Results of Numerical Simulation of EMF Process

The EMF process is challenging to simulate due to the need to model electromagnetic, thermal, and elastic-plastic deformation of materials simultaneously. Many of the commercial research codes have serious limitations and an inability to predict the results of EMF processes accurately. This project originally focused on integrating portions of existing commercial research codes to predict the important characteristics of a 3D electromagnetic-forming process accurately. However, work that is more recent has focused on more accurate, custom process simulations. The current modeling work involves collaboration with Dr. Nick Bessonov in cooperation with the University of Michigan – Dearborn and Dr. Sergey Golovashchenko at Ford.

The objective of numerical simulation was to assist the development of the efficient coil for the restrike operation of preformed Al blank. Preliminary experimental results indicated that sometimes electromagnetic pressure is applied in the area where plastic deformation is not expected. Therefore, we paid specific attention to the distribution of electromagnetic pressure and formation of the blank. Parameters of the discharge were taken from the experimental results produced using a commercial EMF machine and a single-turn coil made of Al-alloy 6061-T6. The maximum energy of the machine was 22.5 kJ with maximum charging voltage of 15 kV. We simulated two cases: Capacitance (C)=0.0002, Faraday (F) and C=0.00025 F. Figure 2 shows the results of the numerical simulation.

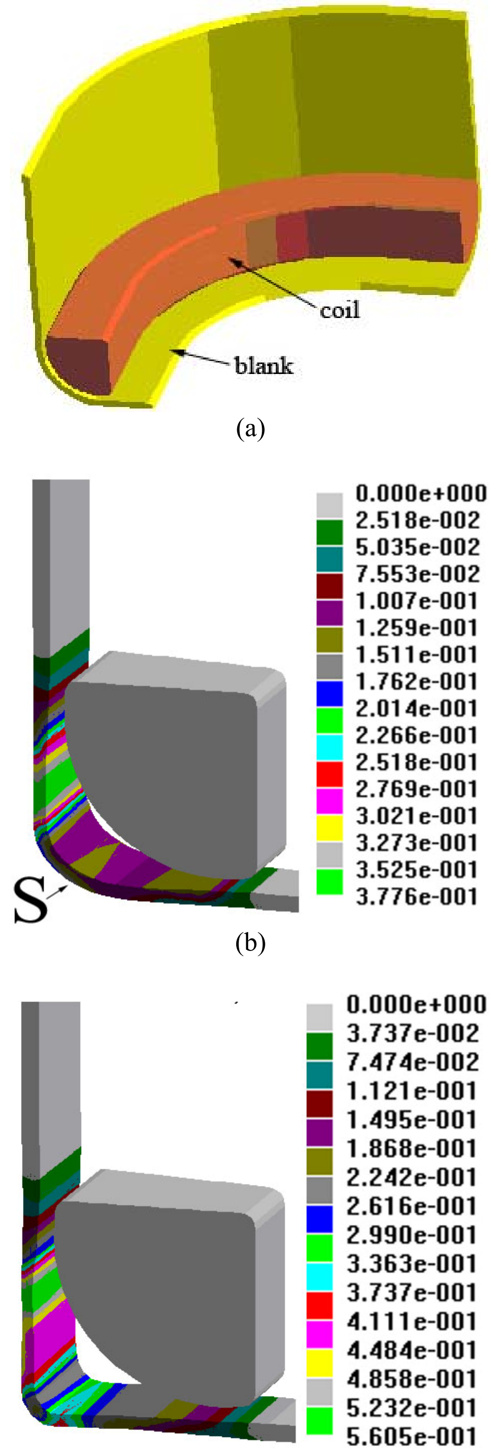


Figure 2. Results of numerical simulation of EMF restrike of 1-mm-thick preformed AA6111-T4 aluminum blank. (a) Initial position of the blank and coil. (b) position of the blank and distribution of plastic strains after the EMF process with the parameters Capacitance (C) =0.0002 Faraday (F) and, Voltage=15 kV.(c) Same as (b) with C=0.00025 F.

Analyzing the strain distribution for two cases, we can conclude that for the case of C=0.00025 F, maximum plastic strains were at the formability limit. Displacement of the point S on the external surface of the blank, facing the die and belonging to the bisecting line of the angle formed, is shown in Figure 3.

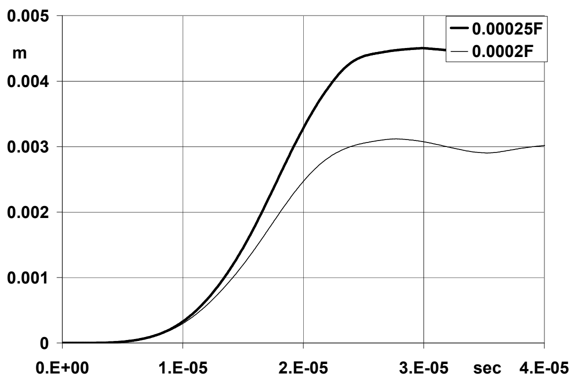
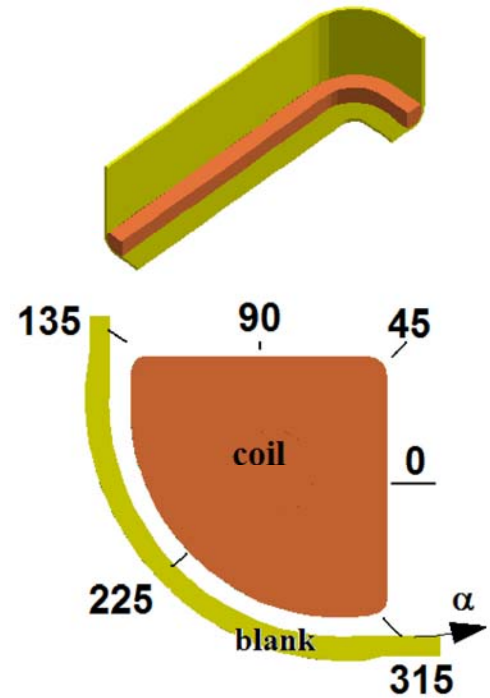


Figure 3. Radial displacements of the point S vs. time for C=0.0002 F and C=0.00025 F.

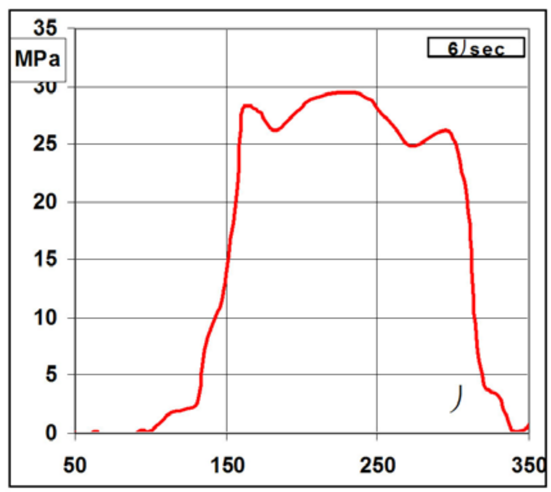
As mentioned before, special attention was paid to the distribution of density of electric current and pressure applied to the blank. Figure 4 shows the distributions for the single-turn coil described above.

An attempt was made to simulate a composite coil, which consists of two parts – copper layer facing the blank and the steel layer reinforcing the coil from electromagnetic pressure. As a result (Figure 5), density of electric current in the area of the cross-section facing the blank can be significantly increased. Even though we expect a composite coil to be more expensive due to the necessity of the layers joining, it may provide better efficiency, higher strength and less heat accumulation compared to the coils made of a homogeneous material.

Accumulation of heat in the coil in high-volume EMF process requires special attention. As in well-known induction-heating processes, electric current in EMF processes tends to run within a relatively thin layer, due to the "skin" effect. Later, the heat is redistributed, due to the material thermal conductivity. After every new discharge of the machine, additional heat is generated in the skin layer. This heat generation process can be considered adiabatic. To define the amount of heat, electric current density was integrated over the duration of the process and



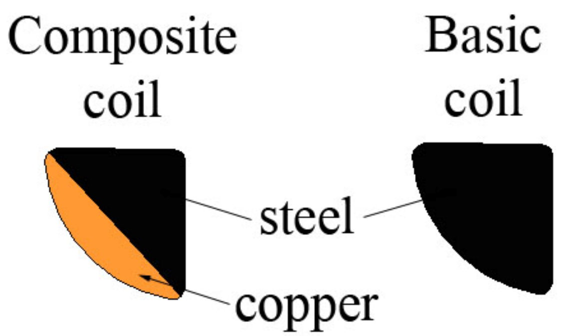
(a)



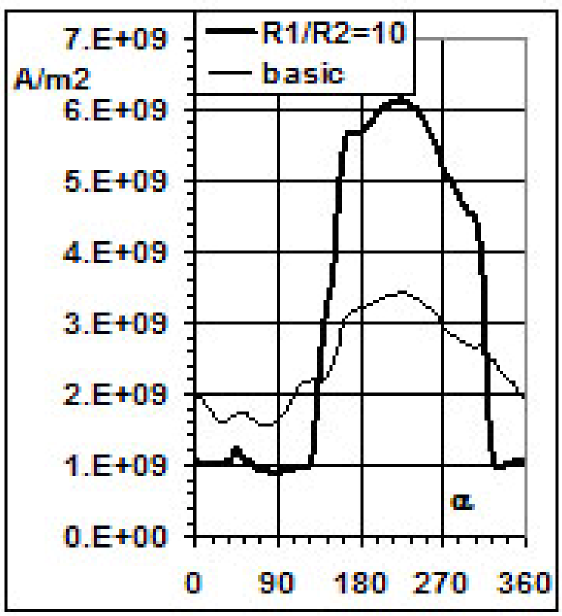
(b)

Figure 4. (a) The coordinate system of a cross-section of the coil and (b) the distribution of EMF pressure at time t=6 μsec.

produced the distribution of heat due to the active resistance of the coil material (Figure 6). Further heat flow and temperature redistribution happens within a much longer period between pulses of the EMF machine. In production conditions, unloading of the stamped blank and loading of the next blank would take place between two discharges.



(a)



(b)

Figure 5. Results of the numerical analysis of the composite (copper-steel) coil compared to the basic steel coil.

In order to develop an efficient cooling system of the coil, a numerical model of the heat transfer through the coil was developed. This model took into account the air-cooling system, which provided the airflow along the coil surface. The parameter, which was expected to drive the cooling process, was the velocity of airflow. According to the results of numerical simulation shown in Figure 7, the airflow with the speed of 20 m/sec could accomplish a satisfactory result, since it provides stabilization of the temperature of the coil. Slower air flows of 15 and 10 m/sec provide stabilization at the higher temperatures, which may not be appropriate for the insulation material and may reduce durability of the coil.

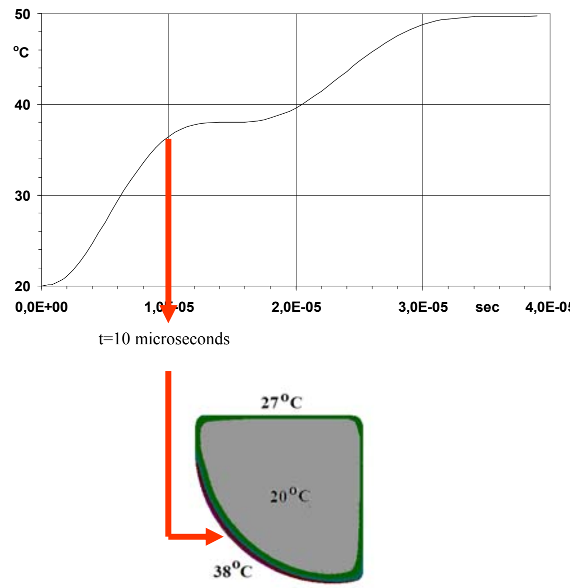


Figure 6. Distribution of maximum temperature vs. time (top) and distribution of temperature in the coil cross-section after 10 microseconds during one discharge of the EMF machine.

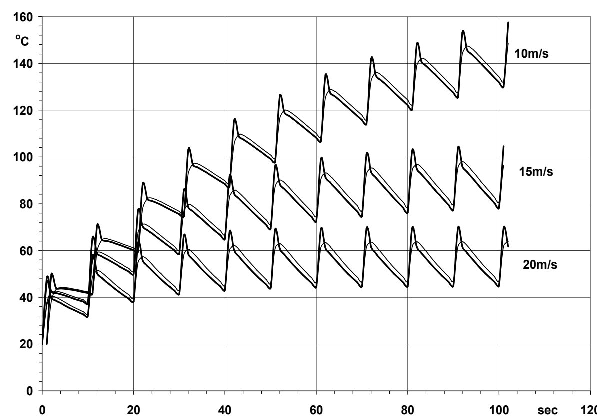
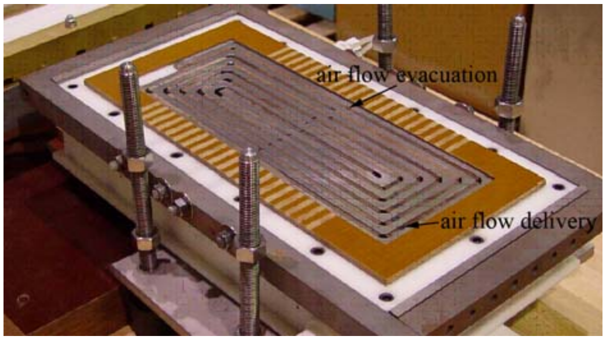
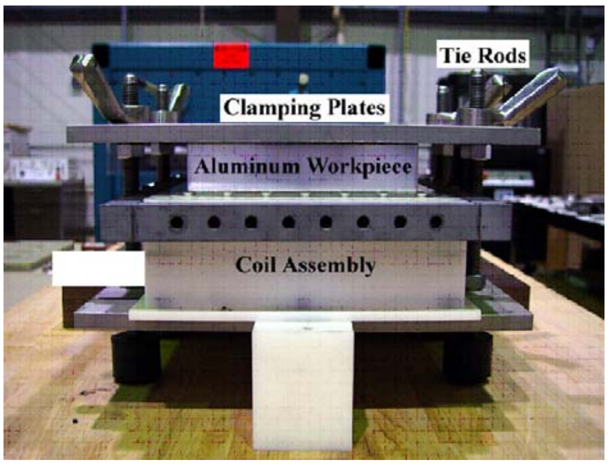


Figure 7. Maximum (thin lines) and average (thick lines) coil temperature vs. time for a production rate of 360 parts/hour with air flow of 10, 15 and 20 m/sec.

Experimental study of the cooling process was conducted using the flat coil made of steel and micarta insulation plates, illustrated in Figure 8. Airflow was delivered through the slots between the micarta plates in the corners of the coil. The spiral surface was insulated from the blank by a thin plate of insulation material. The airflow was directed between the spiral surface and insulation plate, so it would provide cooling of the working surface of the coil where maximum amount of heat is generated.



(a)



(b)

Figure 8. Experimental fixture employed for experimental study of coil durability and heat accumulation. (a) Flat coil with air-cooling system. (b) Assembled fixture ready for testing.

Conclusions

This work has developed numerical models that describe three critical elements of the EMF process: 1) propagation of the electromagnetic field through the coil-blank system and generation of pulsed electromagnetic pressure in specified areas, 2) high-rate deformation of the blank and, 3) heat accumulation and transfer through the coil with an air-cooling system. The process models provide capability to analyze EMF restrike processes from the perspective of coil design, blank deformation, and cooling systems for the coil.