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Application of a Uniform Pressure Actuator for Electromagnetic Processing of Sheet Metal

Scott Golowin, Manish Kamal, Jianhui Shang, Jake Portier, Ahmad Din, Glenn S. Daehn, John R. Bradley, Keith E. Newman, and Steve Hatkevich

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High-velocity electromagnetic sheet-metal forming and processing has many potential advantages over more conventional techniques, including: higher-forming limits, resistance to wrinkling and springback, one-sided tooling, and physical contact to only one side of the work piece. Traditional electromagnetic actuators are flat spirals that produce a nonuniform pressure distribution, limiting the types of parts that can be formed. A new type of electromagnetic actuator, the uniform pressure (UP) actuator, has been developed. The UP actuator can uniformly and efficiently accelerate conductive sheet metal to velocities on the order of 200 m/s or greater over distances of a few millimeters. When the material is arrested by impact with a tool, high-forming pressures can be imparted to it. The utility of the UP actuator is illustrated here by demonstrating its ability to form sheet metal components with intricate shape, to shock harden, and also to pick up nearly arbitrarily small details from a die surface. Thus, electromagnetic processing with the use of the UP actuator offers the unprecedented ability to simultaneously form and engineer the surface morphology and microstructure of sheet metal samples.

Keywords aluminum, joining, stamping

1. Introduction

Electromagnetic forming (EMF) is a technique whereby large forces are imparted to a conductive-metallic work piece by electromagnetic interaction (Ref 1). EMF of sheet metal entails discharging a capacitor bank through a coil that, in turn, induces electrical current in a nearby metal workpiece blank. The mutually repulsive force that results between the stationary coil and the workpiece causes the workpiece to be accelerated to high velocities toward, and impact upon, a nearby die surface. This paper discusses the use of an efficient, uniform pressure (UP) electromagnetic actuator to form nominally flat components with detailed or fine surface features. One example is that of a metal bipolar plate for a hypothetical polymer membrane fuel cell. It is useful to begin by reviewing the fundamentals of electromagnetic sheet metal forming, and the attributes and advantages of this technology.

High-velocity EMF is fundamentally different, and offers several advantages over, conventional metal forming. At sufficiently high sample velocities and/or strain rates, stretching limits are not bounded by the restrictions of a traditional forming limit diagram (FLD). Instead, if launch and boundary conditions are properly chosen, ductility far beyond typical quasi-static forming limits can be achieved. Enhanced ductility under EMF conditions is discussed in detail elsewhere (Ref 1-5).

Electromagnetic metal forming also has an advantage in that it can enable much more agile manufacturing processes. For example, if traditional metal stamping is compared to a high velocity approach, (Fig. 1), only a single sided tool is needed for high velocity forming. The metal sheet comes in contact with a tool only on one side and the other side sees only magnetic pressure. This avoids a host of issues related to tool-to-tool tolerances, machining and alignment. Also, die change becomes trivial, and die modification and 'tuning' is greatly simplified as only one surface is touched. Furthermore, the systems required for this kind of forming are much simpler than traditional press systems.

Another advantage of EMF is that light tooling and equipment can be used. Since large static forces are not reacted, the forming system can be a fraction of the size used in conventional press systems. The tooling and supports need only to be sufficient to accelerate and decelerate a workpiece, which typically has a low mass.

Lastly, high-velocity impact between a deformable sheet metal blank and a hard die with surface features can provide surface embossing to yield depth, texture, and sharp or intricate surface features at the same time. The impact gives good dimensional accuracy in the formed part and the entire process is amenable to integration and automation.

Electromagnetic forces to date have been used almost exclusively to form crimped assemblies from round tubes (Ref 1). Traditional electromagnetic actuators for forming flat sheets use a flat spiral or some similar coil path to induce a current in the sheet metal. The fields from the primary and

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Scott Golowin, Manish Kamal, Jianhui Shang, Jake Portier, Ahmad Din, and **Glenn S. Daehn,** The Ohio State University, Columbus, OH; **John R. Bradley,** General Motors Research & Development Center, Warren, MI; **Keith E. Newman,** General Motors Fuel Cell Activities, Honeoye Falls, NY; **Steve Hatkevich,** American Trim Corporation, Lima, OH. Contact e-mail: daehn.1@osu.edu.

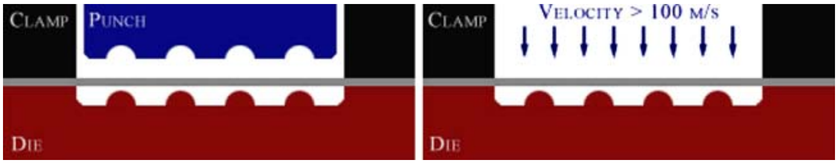

Fig. 1 Comparison of traditional matched tool forming (left) and impact forming of nominally flat components (right)

induced currents act generally to repel the workpiece from the coil. There are two important limitations of traditional EMF coils. First, the electromagnetic pressure distribution is not uniform, which severely limits the types of parts that can be formed. Second, the electromagnetic pressures that can be produced are limited by coil robustness and are not nearly as high as can be obtained in tube compression coils. The present work is based on the development of a novel concept of a uniform-pressure electromagnetic actuator (UP actuator), which adds several degrees of freedom in designing and producing a part (Ref 5).

This paper will focus on how this technology and its specific advantages might be applied to forming, shock hardening, and embossing sheet-metal components. In some cases a small coupon resembling a fuel cell bipolar plate was used for forming demonstrations. However, the attributes of the UP actuator can easily be applied to a wide variety of components.

2. Background

2.1 Uniform Pressure Actuator

Until recently there has not been an actuator coil system for EMF capable of accelerating a sheet metal workpiece at velocities greater than 100 m/s in an efficient and spatially uniform manner. The UP actuator introduced here offers a uniform pressure distribution as well as high efficiency for flat sheet forming. A detailed description of the design, construction and analysis of the UP actuator can be found elsewhere (Ref 5-7). Figure 2 shows a schematic section through the UP coil. When the energized capacitor bank is discharged, the primary current (typically few tens of kA) flows through the primary coil, which is well insulated from the outer conductive channel. The outer channel and the sheet metal workpiece form a closed circuit through which the induced current flows. Repulsive Lorentz forces established between the opposed primary and induced currents cause the sheet metal to be accelerated away from the coil at high velocity. Since, in this case, the induced current path completely encircles the coil, there is little loss of the magnetic flux energy, hence the coil's high efficiency. Also, since the primary coil is repelled from both the sheet and channel, it can be forced onto a strong rigid central mandrel, which results in a more durable coil design. The essential utility of this device is that it can efficiently and uniformly accelerate a piece of sheet metal, e.g., aluminum sheet about 1 mm thick, greater than 200 m/s over a distance of several millimeters.

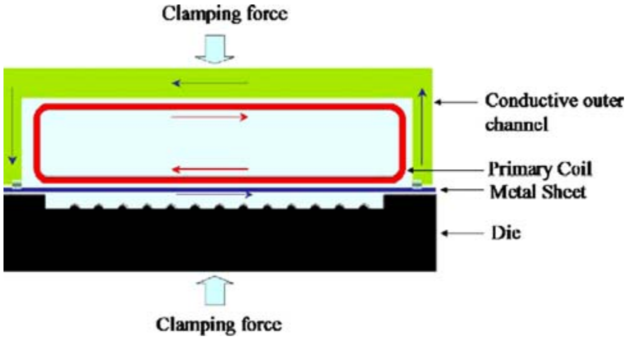

Fig. 2 Schematic of a uniform pressure coil. The primary coil has many turns going into the plane of the figure

2.2 Impact Pressure

Much of the literature on the impact of solids addresses ballistic velocities of 750 m/s or greater. Upon impact at these velocities all metals experience severe plastic deformation and work of this nature is often concerned with penetration mechanics. At lower workpiece velocities, however, the impact can be fully elastic. Using linear elasticity, the impact pressure, P_i, developed when two semi-infinite elastic bodies 1 and 2 collide at an impact velocity V_i is given as (Ref 8):

$$P_i = \frac{\rho_1 \rho_2 C_1 C_2}{\rho_1 C_1 + \rho_2 C_2} V_i$$

Here, ρ is the density and C is the longitudinal wave speed for each material. Longitudinal wave speeds are on the order of 7,000 m/s for most structural metals. For aluminum-steel and steel-steel combinations, impact pressures of about 2 GPa and 5.6 GPa, respectively, result from impact at 200 m/s. Of course, higher pressures are available by varying the materials or by increasing the impact velocity. Despite the fact that there are significant deviations from linear elastic behavior at these pressures, simulations show that, due to the planar constraint, the elastic equations work well even beyond the elastic limit (Ref 5).

2.3 Shock Hardening

Aside from forming operations, the effect of the impact-induced pressure wave on the material can be important and useful in other ways. Shock pressures up to 10 GPa are possible when the UP actuator is used to accelerate a sheet to strike a die surface. This is similar to the pressures available in the laser shock processing (LSP) of metals. A review (Ref 9) of microstructural effects of LSP showed that peak pressures in LSP are typically between 3 and 10 GPa and that significant changes in materials strength and hardness can be produced using an LSP shock wave. There is a critical pressure that must be reached for shock hardening, and the hardening increment increases with increasing pressure. For 2024 aluminum, pressure thresholds of about 2.5 GP are reported for an underaged alloy, and about 7.5 GPa for an overaged alloy

(Ref 9). For 304 stainless steel, significant shock hardening was available at pressures of 4.9 GPa (Ref 10). Thus, the pressures achieved at impact during electromagnetic processing should also be sufficient to induce shock hardening. Alternately, straining materials at strain rates above $10^3\ s^{-1}$ can also significantly increase rates of dislocation accumulation and strain hardening. This has been persuasively argued by Follansbee and Kocks (Ref 11).

2.4 Embossing

The high sheet-die pressures can also cause the sheet to conform to micro-contours of the die, thus establishing the basis for electromagnetic embossing processes. Prandtl's 1920 analysis (Ref 12), which provide a clear understanding of the pressures required to cause a deformable body to take the shape of a nondeformable body, is the foundation for hardness testing. In general, in order to make one plastic body fully conform to another, the interface pressure must reach a level about three-times the flow stress of the deforming material. This simple rule has recently also been found to be roughly true in coining for microgeometry (Ref 13). Reaching sufficiently high pressures over macroscopic areas usually requires very large presses. This is the reason conventional coining is only performed on small articles. Since electromagnetic impact forming using the UP actuator can provide uniform pressures up to 10 MPa, we should be able to emboss very fine features in sheets. In theory, arbitrarily small features can be embossed and these features can be imparted to a relatively large total sheet area, so long as it can be accelerated to a sufficient velocity. This distinguishes this approach from coining.

3. Experimental Procedure

3.1 Uniform Pressure Actuator

Figure 3 shows components of the UP actuator prior to potting the windings in urethane. In this case, it consists of a coil with eleven turns enclosed within the outer channel. The coil and outer channel were machined from ASTM B16 brass, which was strong enough to enable the actuator to withstand the high forming pressures. The actuator used here, an improved version of earlier UP actuator designs, was manufactured by American Trim Corporation of Lima, Ohio. Urethane potting was then used to provide insulation and structural support.

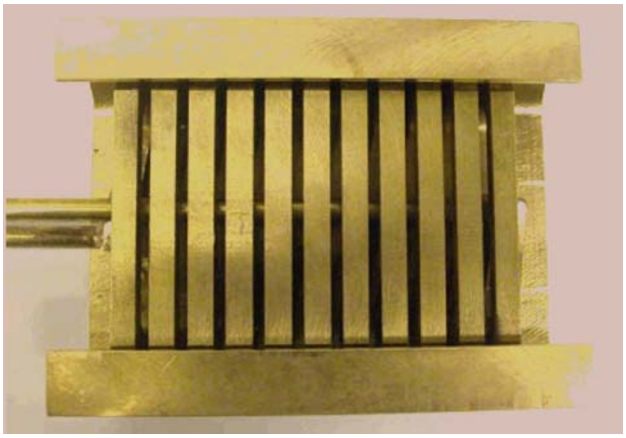

Fig. 3 The machined brass coil and return path used in this study. The length of the active region of the coil is about 10 cm

A vacuum chamber (typical vacuum levels are a few torr) with an adjustable standoff distance between the workpiece and the die surface was fabricated to allow good control over these experiments. Further details can be found in (Ref 5). The actuator-workpiece-die assembly is then clamped together using an arrangement of six nuts and bolts with a typical total clamping force of 80 kN. The actuator system is then connected to a commercial Magneform capacitor bank (Ref 14). The capacitor bank stores a total of 16 kJ of electrical energy at a full charging voltage of 8.3 kV.

3.2 Forming

Several workpiece materials were used in this study, but most forming experiments were carried out with 0.1 mm thick annealed 316L stainless steel as the workpiece sheet. Since austenitic stainless steels have low electrical conductivity, a 0.13 mm thick annealed OFHC copper driver sheet was used in conjunction with it. When used as a driver sheet, the more highly conductive copper sheet is positioned between the coil and the stainless steel workpiece sheet. Forces generated between the coil and the copper sheet drive the copper sheet into the stainless steel which is, in turn, forced into the die cavity. In some instances the copper sheet was also used as the workpiece material and formed on its own.

Forming trials were conducted using a tool steel die representing typical features of a fuel cell bipolar plate. In this particular case, the tool was the female die half of a conventional punch and die stamping tool set. Overall dimensions of the formed area of the plate were about 80 mm × 30 mm. The female die surface had a pattern of multiple channels with a spacing of 2.2 mm and a draw depth of 0.38 mm.

The standoff between the sheet metal and the die was varied initially to evaluate its effect on part definition. Based on the experiments a standard standoff of 2.3 mm was used. If the gap was much smaller, the sample did not have the opportunity to accelerate to peak velocity. Forming trials were carried out over a range of launch energies.

Inspection of formed plate features was carried out using a Cobra model noncontact laser scanning device manufactured by optical gaging products (OGP), Rochester, NY to measure the depth and profile of the formed channels in 5-micron steps.

3.3 Shock Hardening

As discussed previously, it can be expected that the impact velocities used here (estimated to be 150-250 m/s) can produce significant shock hardening. The potential for electromagnetic shock hardening was evaluated experimentally. The UP actuator was used to accelerate 316L stainless steel and copper sheets (the same materials used in the forming trials) so as to impact against smooth steel plates. The Vickers hardness of both materials was measured before impact and after striking the flat steel surface at several energy levels from 0.8 to 4.7 kJ.

3.4 Embossing

To demonstrate the ability to transfer extremely fine features from a tool surface to the workpiece, several experiments were carried out to accelerate 0.13 mm thick Alloy 110 electronic-grade copper sheet and 0.25 mm thick AA5082-H32 sheet samples so as to impact upon a tool surface with optical-diffraction gratings. The standoff distance and discharge energy were varied systematically in order to establish the conditions for which the diffraction gratings with micron-size features could be reproduced on the samples.

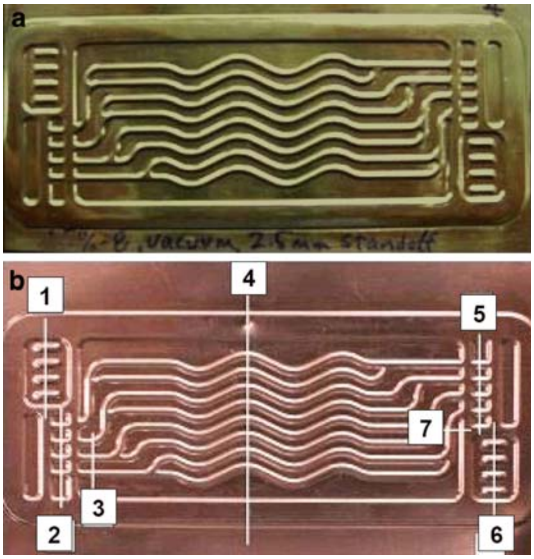

Fig. 4 (a) A 316L stainless steel sample formed electromagnetically using the uniform pressure actuator at 7.2 kJ. (b) A stainless steel sample formed by conventional metal stamping. The numbers (1-7) show profile tracked during laser scan measurements in Fig. 5(a-d)

4. Results and Discussion

4.1 Forming

Figure 4a shows a 316L stainless steel plate sample electromagnetically formed using the UP Actuator with launch energy of 7.2 kJ. Figure 4b shows a conventionally stamped sample made from the same tooling. Figure 4b also shows the locations of the seven laser scan traces done on the baseline stamped sample and on the EMF samples formed at various discharge energies.

Figure 5 compares the channel dimensions for the stamped and EMF samples at scan locations 1, 3, 4, and 6. At the higher-energy levels, the channel depth of the EMF samples essentially matched that of the stamped part. None of the EMF samples

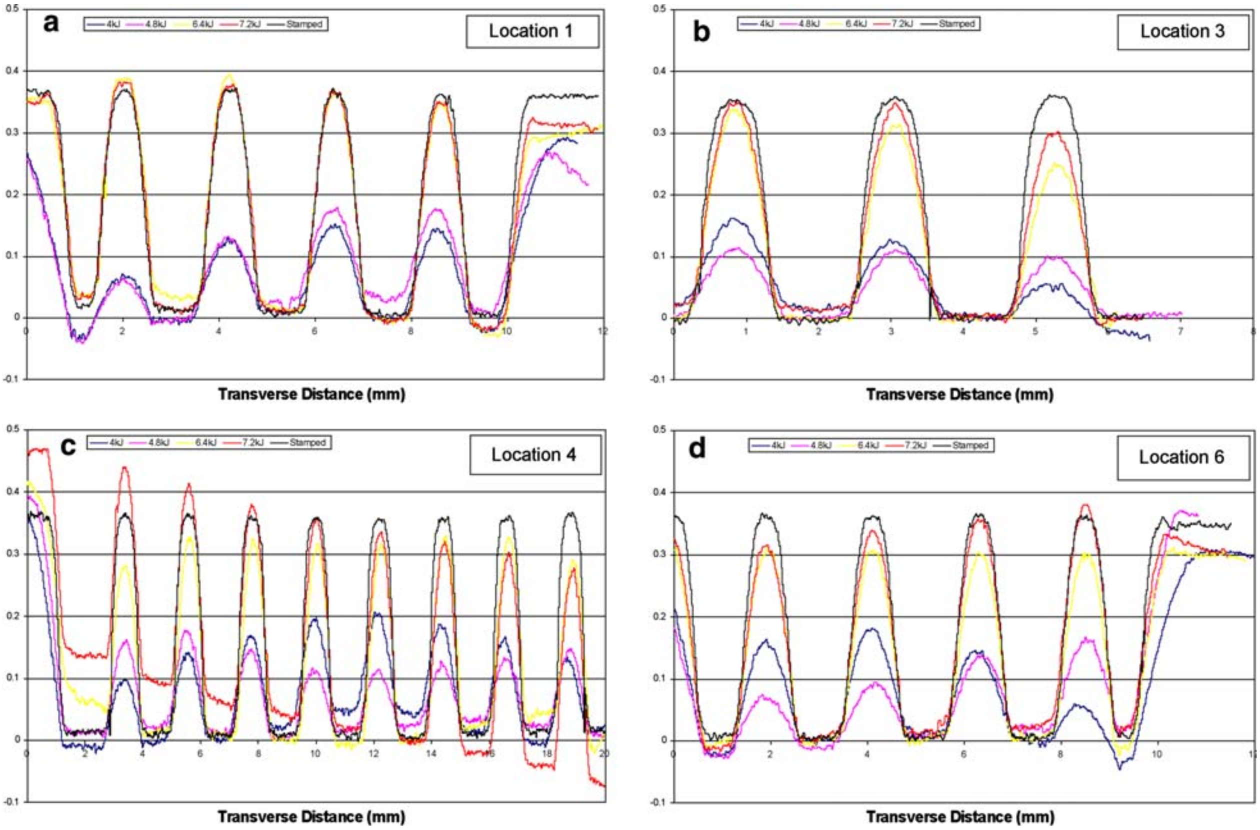

Fig. 5 (a) Laser scan measurements of channel profiles along trace 1 for a stamped 316L part and similar parts electromagnetically formed at 4.0, 4.8, 6.4 and 7.2 kJ. (b) Laser scan measurements of channel profiles along trace 3 for a stamped 316L part and similar parts electromagnetically formed at 4.0, 4.8, 6.4 and 7.2 kJ. (c) Laser scan measurements of channel profiles along trace 4 for a stamped 316L part and similar parts electromagnetically formed at 4.0, 4.8, 6.4 and 7.2 kJ. (d) Laser scan measurements of channel profiles along trace 6 for a stamped 316L part and similar parts electromagnetically formed at 4.0, 4.8, 6.4 and 7.2 kJ

formed to date have exhibited tearing or perforation within the area of the flow field channels. Achieving fully formed channels that conform exactly to the shape of the tool will require working at higher discharge energies, and is the focus of ongoing research.

4.2 Shock Hardening

The potential for electromagnetic shock hardening was initially investigated by impacting flat sheets of 316L stainless steel and copper against smooth steel plates with varying energy. Figure 6 plots the Vickers hardness for each material as a function of launch energy. The average value and the standard deviation for each experimental condition are plotted for both materials. Note that at launch energies above about 4 kJ significant hardness increases are observed, in the absence of macroscopic plastic strain.

4.3 Embossing

Figure 7 presents the results of electromagnetic embossing of micron scale features on the copper and aluminum sheets.

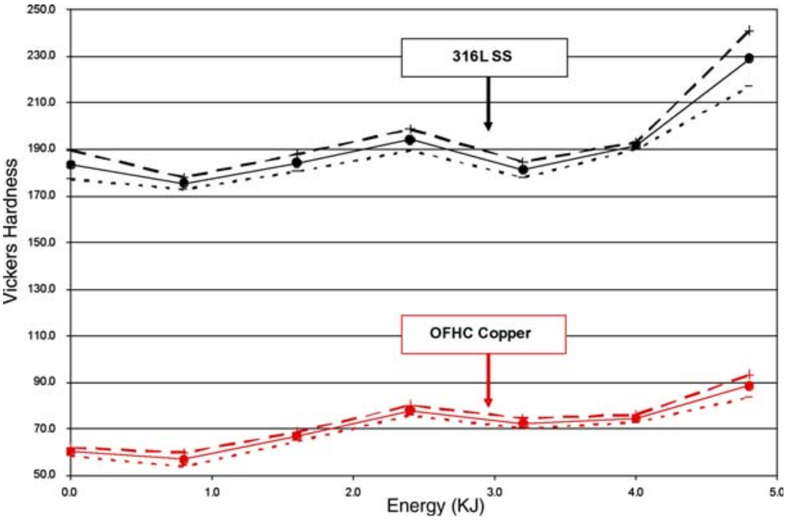

Fig. 6 Surface hardness of 316L and OFHC copper as a function of launch energy after striking a flat hardened steel plate with 2.3 mm standoff (dotted lines indicate ± standard deviation)

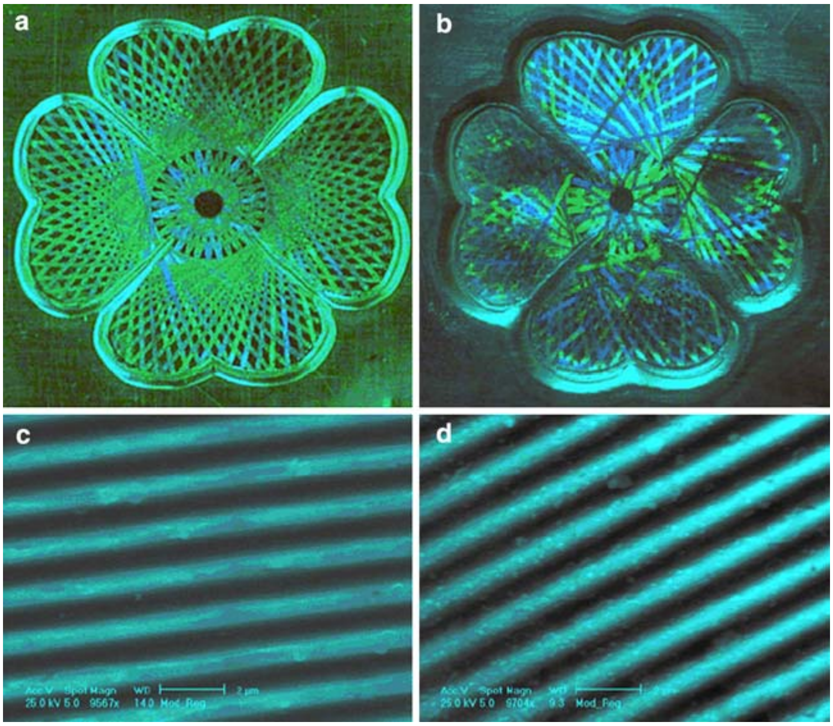

Fig. 7 Examples of embossing sheet metal using a die with a holographic optical diffraction grating image about 2.5 cm across. The copper (a) was formed at 2.4 kJ; the aluminum (b) was formed at 4.0 kJ. In both cases the entire area formed was about 100 × 75 mm. SEM images compare the original holographic die surface (c) and the pattern embossed in the copper (d)

For the 0.13 mm thick copper sheet, a standoff distance of 2.3 mm and launch energy of 2.8 kJ were sufficient to reproduce the diffraction grating by impact embossing. Those conditions produced a peak primary current of 66 kA with a rise time of 18 μs. Based on the simple estimation procedures in (Ref 5), this resulted in an impact velocity of about 208 m/s. The 0.25 mm thick aluminum alloy sheet was impacted in a similar way using a discharge of 4.0 kJ and, again, a standoff distance of 2.3 mm. This produced a peak primary current of 78 kA, a rise time of 18 μs, and an estimated impact velocity of about 250 m/s.

Figure 7 shows the resultant impact-formed part for copper (Fig. 7a) and aluminum (Fig. 7b). In both cases the entire area formed was about 100 × 75 mm. The formed sheets replicate the features of the die and show the optical diffraction grating effect. The original holographic surface of the nickel tool is shown in the SEM image of Fig. 7c. Figure 7d is an SEM image of the embossed pattern on the copper sample showing excellent replication of the micron level features of the tool surface due to the high impact pressures attainable by EMF which would be difficult to achieve by conventional forming. It is also significant that this can be carried out over large surface areas by use of the UP actuator.

5. Conclusions

The use of the UP electromagnetic actuator is demonstrated in the forming of an exemplary fuel cell bipolar plate. This technique is fundamentally different than conventional stamping in that the sheet metal is formed by first accelerating it to a velocity between 100 m/s and 300 m/s, followed by impact with a single-sided tool with the desired geometry. Impact between the workpiece and tool provides very high levels of transient pressure and forming takes place at very high strain rates. Additional examples of EMF demonstrate the ability of the high impact to reproduce surface features from the tool and to provide enhanced strain hardening. Further, this method using single-sided tools offers much greater agility and flexibility than traditional stamping methods.

Acknowledgments

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References

1. G.S. Daehn, High Velocity Metal Forming, *in ASM Handbook, Volume 14B, Metalworking: Sheet Forming*, Published 2006, ASM International, p 405–418
2. G.S. Daehn, Electromagnetically Assisted Stamping – A Vision of a Future for Metal Forming, www.osu.edu/hyperplasticity, April, 2005
3. M. Seth, V.J. Vohnout, and G.S. Daehn, Formability of Steel Sheet in High Velocity Impact, *J. Mater. Process. Technol.*, 2005, **168**, p 390–400
4. J.D. Thomas, M. Seth, G.S. Daehn, J.R. Bradley, and N. Triantafyllidis, Forming Limits for Electromagnetically Expanded Aluminum Alloy Tubes: Theory and Experiment, *Acta Mater.*, 2007, **55**, p 2863–2873
5. M. Kamal, A Uniform Pressure Electromagnetic Actuator for Flat Sheet Forming, Ph.D. Dissertation, The Ohio State University, 2005
6. "Electromagnetic Formation of Fuel Cell Plates," United States Patent #7,076,981, 18 July 2006
7. "Electromagnetic Metal Forming," United States Patent #7,069,756, 4 July 2006
8. W. Johnson, *Impact Strength of Materials*. Edward Arnold, London, 1970
9. A.H. Clauer, Applications of Laser-Induced Stress Waves, *presented at ASM Conf. on Laser Solid Interactions*, 1979, Washington, DC
10. A.H. Clauer, J.H. Holbrook, and B.P. Fairland, Effects of Laser Induced Shock Waves on Metals, in *Shock Wave and High Strain Rate Effects in Metals*, M.A. Myers and L.E. Murr Ed.,. Plenum, 1981, p 675–702
11. P.S. Follansbee and U.F. Kocks, *Acta Metall.*, 1988, **36**, p 81–93
12. L. Prandtl, Über die Hä rte Plastischer Kö rper. Nachr. Akad. Wiss. Göttingen. Math-Physik. Kl., 1920
13. H. Ike and M. Plancak, Coining Process as a Means of Controlling Surface Microgeometry, *J. Mater. Process. Technol.*, 1998, **80-1**, p 101–107
14. www.magneform.com, April, 2005