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Material Formability and Coil Design in Electromagnetic Forming

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Pulsed electromagnetic forming is based on high-voltage discharge of capacitors through a coil. An intense transient magnetic field is generated in the coil and through interaction with the metal work-piece; pressure in the form of a magnetic pulse is built up to do the work. Data on formability of two aluminum alloys employed for exterior (6111-T4) and interior (5754) automotive body panels will be shown. Comparison of traditional Forming Limit Diagrams obtained by stretching of aluminum sheet with hemispherical punch to the results on formability, where hemispherical punch is replaced by a coil will be provided. It will be shown that material formability in high-rate forming conditions can significantly depend upon interaction with the forming die: electromagnetic forming into an open round window provides only slight improvement in formability, while forming in a V-shape die or into a conical die indicates a significant improvement. An important part of the electromagnetic forming technology is the design of the coil. The coil failure modes and measures preventing them are discussed.

Keywords aluminum alloy, electrical discharge, sheet metal stamping

1. Introduction

During the last 10 years, the important targets in automotive industry were to reduce fuel consumption and air pollution. Decreasing of vehicle weight serves both of these objectives; therefore, aluminum alloys are being used more and more in automotive body construction. Improvement in formability would further promote the application of aluminum alloys in production of body panels of automotive vehicle. Currently there are several approaches to achieving this improvement by: employing superplastic forming technology (Ref 1), increments of forming followed by heat treatment (Ref 2), and warm forming (Ref 3). All of these technologies are based on the physical principles that ductility can be significantly increased by forming metals at the temperature of hot deformation or by dividing the deformation process into several stages and annealing metal in between those stages. These approaches have the following drawbacks: heating metal adds to the cost of the stamping process and makes the environment less pleasant for people involved in production; thin blanks quickly cool down if they are not formed in isothermal conditions; and currently used lubricants cannot keep their properties at such elevated temperatures. As a result, there are problems of cleaning lubricant from metal before heating it and then applying it again to continue the deformation process. In this paper we study the alternative approach of employing high-rate forming processes without preliminary heating of blanks.

The idea of using a pulsed electromagnetic field to generate sufficient force to form metals and join tubular parts has been known since 1924 (Ref 4). Pulsed electromagnetic forming is based on high-voltage discharge of capacitors through a coil. An intense transient magnetic field is generated in the coil and through interaction with the metal work-piece, pressure in the form of a magnetic pulse is built up to do the work. The schematic of pulsed electromagnetic forming of sheet is shown in Fig. 1. The electric power is accumulated in the bank of capacitors 1 through a charging circuit including a high-voltage transformer 2 and a set of diodes 3. Charging voltage is typically between 3 and 25 kV. It can be adjusted by changing the charging time. A low inductance high voltage switch 4 or a set of switches are employed in order to discharge the capacitors through the coil 5. The blank is usually positioned in a close vicinity to the coil. The efficiency of the process is better if the distance between the coil and the blank is minimal. However, the coil is usually insulated in a way that short-circuit would not be possible in between its turns or onto the blank. Therefore, the clearance between the coil and the blank is usually dictated by the voltage of the discharge and the properties of the insulation.

Additional benefit of electromagnetic forming can be reduced springback due to the impact between the die and the blank (Ref 5). In addition, pulsed electromagnetic field can be used for low energy calibration of conventionally stamped part by eliminating the root cause of springback: residual stresses in the blank, accumulated at the end of the stamping process (Ref 6, 7).

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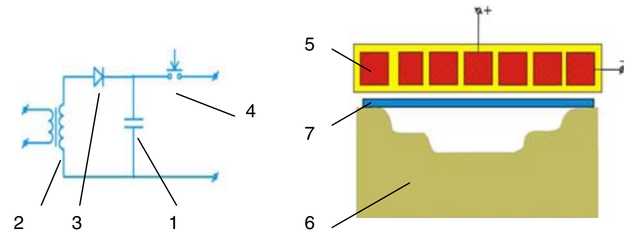

Fig. 1 Schematic of pulsed electromagnetic forming of sheet material: 1—high-voltage capacitors; 2—transformer; 3—set of diodes; 4—high-voltage switch (usually ignitron or vacuum switch); 5—flat coil; 6—die; 7—sheet being formed

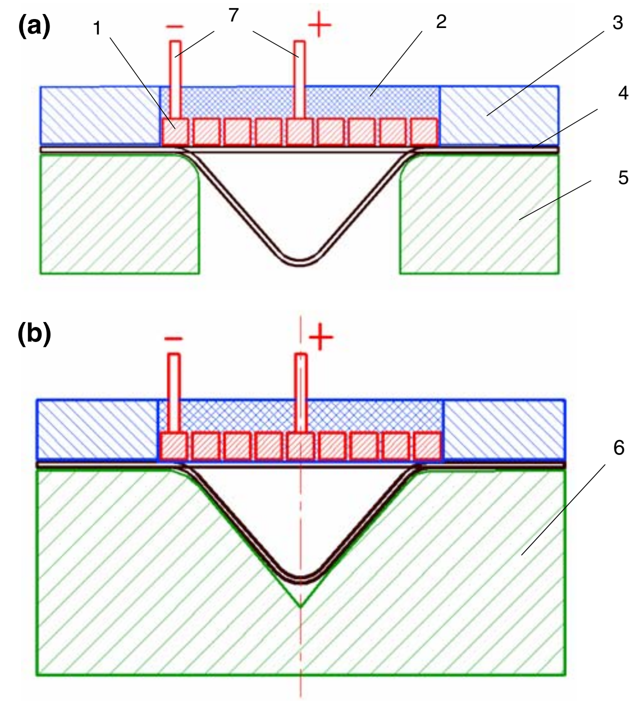

Fig. 2 Schematic of the testing procedure to study formability of sheet metal with electromagnetic forming: 1—coil; 2—insulation block; 3—steel ring; 4—blank being tested; 5—die with an open round window (Ø100 mm); 6-conical or V-shape die; 7—leads

2. Description of Experimental Equipment and Tools for Pulsed Electromagnetic Forming

The experimental work was performed using a Magnepress System manufactured by IAP Research, Inc. This system has the following characteristics: capacitance—200 μF (including four Aerovox capacitors of 50 μF each), inductance—230 nH, maximum energy storage—22.5 kJ at 15 kV charge, maximum peak current capability—100 kA. The Magnepress is built on a modular principle, so several modules can be connected in parallel with cables and add their electric current to an electromagnetic coil. In our experimental work we just used one module. In order to improve the system performance, the custom cable connection of the module with the coil was developed. It is comprised of three 1.5 m long-coaxial cables connected in parallel in order to minimize the system's inductance. This modification reduced the useless cable inductance and related loss of energy. Such a connection is six times more efficient than a three-meter-long conventional one-cable connection of the Magnepress system with the coil.

The testing procedure is schematically shown in Fig. 2a, where a flat coil 1 is acting instead of a hemispherical punch in a standard FLD test. The coil 1 is mounted inside the insulation block 2, which is press-fit into a steel ring 3, serving the following dual purpose: as a bandage for the coil, preventing its expansion, and as a flat upper binder for the blank 4 being tested. A die 5 with an open-round window 100 mm in diameter and an entry radius of 10 mm, typical for formability testing fixtures, serves as a lower binder for the first set of experiments. In order to study formability of aluminum alloys in corner filling operations, the die with an open round window 5 can be replaced by a conical die or a V-shaped die 6, schematically shown in Fig. 2b. Both conical and V-shaped dies had entry radii of 10 mm. The coil 1 has leads 6, connecting it to the Magnepress.

The flat coils for these experiments were fabricated from a solid piece of brass in order to improve their durability. The experience of fabricating coils by winding a bar around a mandrel showed that such a coil normally stops functioning near the central electrode after a few discharges. Two layers of insulating strips were filling the space between the turns of the flat spiral (Fig. 3a). The sheet to be formed was insulated from the coil by an insulating plate of 1 mm thick. Such a coil without a blank or top insulating plate is shown in Fig 3b. A steel bandage was expected to prevent expansion and fracture of the insulation block. However, insulating blocks fabricated from delrin (Fig. 3b) did not perform really well during the testing program. Therefore, in later generation coils, insulating blocks were fabricated from micarta (Fig. 4a). The die with an open round window, serving as a lower flat binder, is shown in Fig. 4b. This die was employed for original set of experiments on 6111-T4. However, it required special effort to prevent the material flowing into the die cavity from the flange area, for example bending of the sample over the exterior edge of the die. In order to prevent the flange drawing into the die cavity, a die with the circular draw bead, shown in Fig. 5, was employed. Both V-shape and conical die (Fig. 4c and d) were attached to the same flat coil shown in Fig. 4a.

Two types of flat coils were used in this study: coils with round flat spiral and coils with rectangular flat spiral. Schematic of the testing procedure in Fig. 2 can serve for both of them. Similar to the circular flat spiral, the first generation rectangular flat spiral was machined from a single piece of metal. Such a coil was connected to the Magnepress with two legs, similarly as it was done for circular flat coils. Rectangular coils were also mounted inside the insulation block and press-fit into a steel bandage, as shown in Fig. 6. The rectangular coils were necessary to test the narrow samples for the drawing side of the Forming Limit Diagram. The attempts to employ circular flat spirals for testing of samples 25.4 mm wide did not produce positive results. In our opinion it happened due to nonuniform distribution of pressure, specifically a significant drop in pressure in the area close to the center of the coil (Ref 8). Employment of a rectangular flat coil, shown in Fig. 6 together with the die with rectangular open window provided an opportunity to deform samples with wide variety of width, especially narrow samples (25.4 mm wide or less). The die had an entry radius of 10 mm and had an opening 100 mm wide, providing the same length of the narrow sample as the diameter

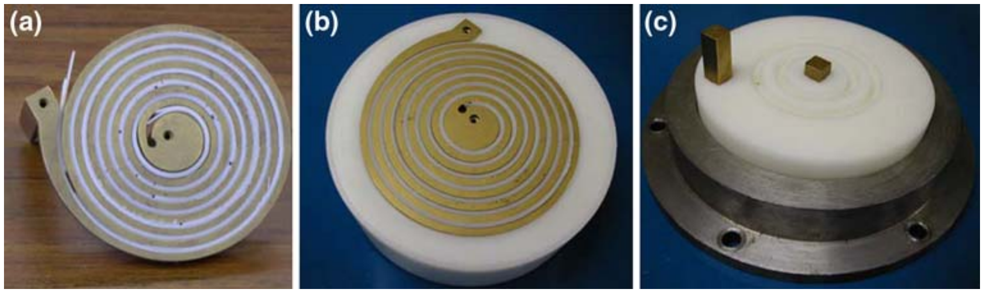

Fig. 3 Design of the flat coil employed for formability experiments: (a) brass spiral machined from a solid piece insulated with mylar strips; (b) mounted into a mylar block; (c) press fitted into a steel bandage

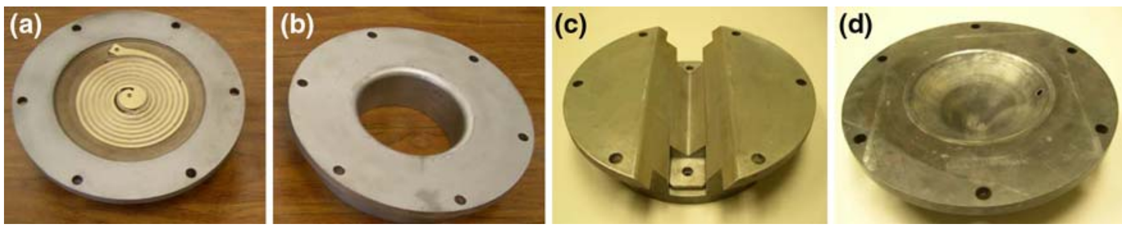

Fig. 4 The coil (a), mounted into an insulation block an press-fit into a steel bandage for electromagnetic forming of sheet metal samples into the die with an open round window (b), V-shape die (c) and conical die (d)

Fig. 5 The die for forming into an open round window with the draw bead: (a) in open position; (b) in closed position

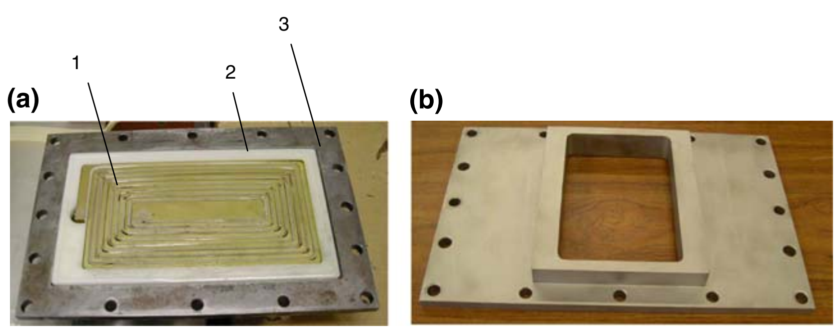

Fig. 6 (a) a rectangular flat coil 1, mounted inside the insulation block 2 and press-fit into a steel bandage 3; (b) a steel die with rectangular open window and an entry radius for forming of strip samples

of the fully clamped sample formed into an open round window. This became possible because the pulsed current was induced in the die and in the blank (Fig. 7), so, due to the electrically conductive connection between the blank and the die, the induced current made a closed loop going partly through the die and partly through the blank. Position of the strip sample relatively to the rectangular coil and the die is shown in Fig. 7, where the insulation plate is removed in order to visualize the mutual position of the sample and the coil. Placing the sample in such a fashion provided symmetrical deformation of the sample. Such tooling configuration allowed varying the width of the sample using the same coil and providing approximately the same-pulsed load duration. In our opinion, it is particularly important, since it provides approximately the same pattern of strain rate history during the test for the samples with different width.

In order to make a fair comparison of formability in conventional and pulsed forming conditions, we reproduced the

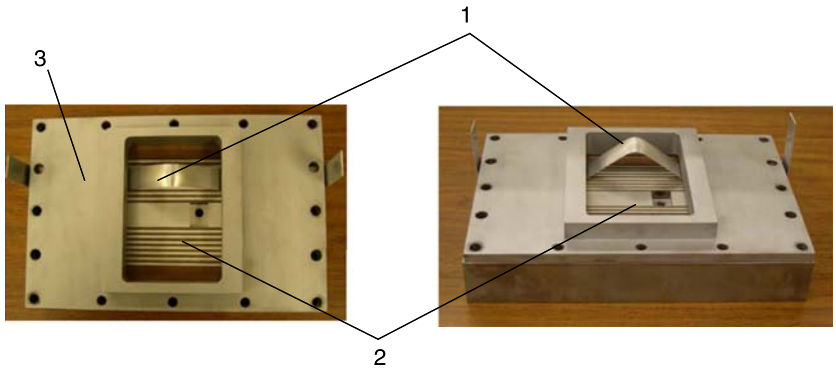

Fig. 7 Strip sample 1, deformed with the rectangular flat coil 2 into the die 3 with an open rectangular window

Fig. 8 Samples after testing formability with pulsed electromagnetic field driving samples into the dies with an open round or rectangular window

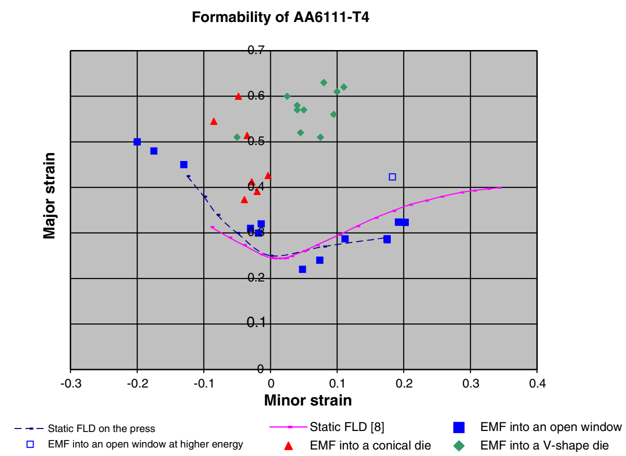

Fig. 9 Results on formability of AA6111-T4: solid line—generalized data from current study; broken line—FLD diagram developed in (Ref 8); rectangular dots—samples after EMF forming into an open round and rectangular window; triangular dots—samples formed with EMF into a conical die (Ref 8); diamond dots—samples formed with EMF into a V-shape die

FLD test by forming aluminum sheets with a 100 mm diameter hemispherical punch into a round die cavity. Blanks of the following dimensions were used: 165 mm × 165 mm; 165 mm × 114 mm; 165 mm × 64.5 mm, and 165 mm × 25.4 mm. In order to create a wide variety of ε_1 and ε_2 strain combinations, dry, oil, and plastic lubricating conditions were analyzed. In plane strain condition, we could not exceed 0.27 deformation. On a drawing side of the diagram, the points of maximum strain were (0.43, −0.13) and (0.36, −0.15). On the double stretching side the maximum deformation was (0.29, 0.20). However, in the practice of stamping, increasing the maximum strain over 0.15 for 6111-T4 is not recommended because dry lubrication conditions may happen in some local area of the tool.

The same sheet of 6111-T4 was used for testing of formability in electromagnetic forming conditions. As it was indicated above, coils were replacing the punch, while the length of the samples being deformed was the same as for the widely accepted FLD testing. Samples after the testing of formability into an open round or rectangular window are shown in Fig. 8.

Testing procedures for electromagnetic forming of aluminum sheet into V-shape and conical die were similar to the procedure of forming into an open round window. The samples were 165 mm × 165 mm and completely covered the cavity of the dies. The V-shape die and later the conical die (Fig. 4c and d) were attached with the bolts to the same flat coil with the steel bandage (Fig. 4a). Energy of the discharge was adjusted to have the blank inertial deformation stopped before fracture occurred.

3. Experimental Results on Formability of AA 6111-T4 and AA5754

The initial approach was to define the minimum energy of discharge needed to fracture the blank. To define this level, we incrementally increased the energy in the capacitors by adjusting the charging voltage. With this approach, we obtained the results shown with squares in Fig. 9. One point in Fig. 9 (0.18, 0.43), shown as a nonshaded square, was obtained by increasing the energy over a minimum limit, at which fracture occurs (3.3 kJ). In this case, we were able to increase the maximum level of strains; however, the central section of the sample was fractured and separated from the rest of the sample driven by the inertia forces. Comparison of samples formed at the minimum level of energy when fracture occurs and samples formed at the higher levels of energy is shown in Fig. 10. It indicates that the diameter of the fracture line is growing with the increase of the energy level from 4.9 to 7.2 kJ.

Increase in maximum strains of samples formed at higher energy and, as a result, with higher strain rates brought us the idea that if the die is positioned in a way that it prevents further free-forming of the blank, increased strains without fracture of the metal can be obtained. In such a way we formed samples into conical die or into a V-shape die. As it can be seen from Fig. 9 for AA6111-T4 and from Fig. 11 for AA5754, material maximum strains after forming into an open round and rectangular window are in some cases slightly exceeding the strains after static forming on the press. Strains after forming into a conical die or a V-shape die significantly exceeded the strains in static FLD test and forming into an open window. Detailed explanation of potential reasons of such significant difference is provided in (Ref 8) for forming into a conical die based upon numerical simulation of the material damage during the forming process. In general, two important reasons can be formulated, which may be responsible for the formability enhancement: increased strain rate and high-rate impact with the tooling, where significant growth of hydrostatic pressure and bending-unbending of the sheet may be observed. Also, an important point of difference between static forming with hemispherical punch and dynamic forming with nonuniformly distributed electromagnetic field is in nonmonotonic character of deformation in electromagnetic forming. The shape of the sample formed with EMF in conditions close to plane strain is shown in Fig. 12, where a fold in the center of the sample is observed. This shape is different from typical dome shape of samples after FLD testing. Also, the plastic waves propagating from the die periphery towards the center of the blank can play significant role in distribution of strains and fracture initiation.

The results on effect of high strain rate on formability shown in Fig. 9 and 11 are different from the data published earlier in (Ref 9) for the common structural aluminum alloy 6061 formed into a conical die: even though the general trend was the same, the effect of strain rate observed in (Ref 9) was more significant than in the current study. A possible reason of such a difference is in heat treatment of AA6061 in (Ref 9), while in our experiments the AA6111-T4 sheet was used in as-received condition.

4. Lessons Learned in Performance of Coils for Electromagnetic Forming

Several coils were built at Ford Research & Advanced Engineering during testing of formability of sheet materials using EMF. In this section we discuss the failure modes

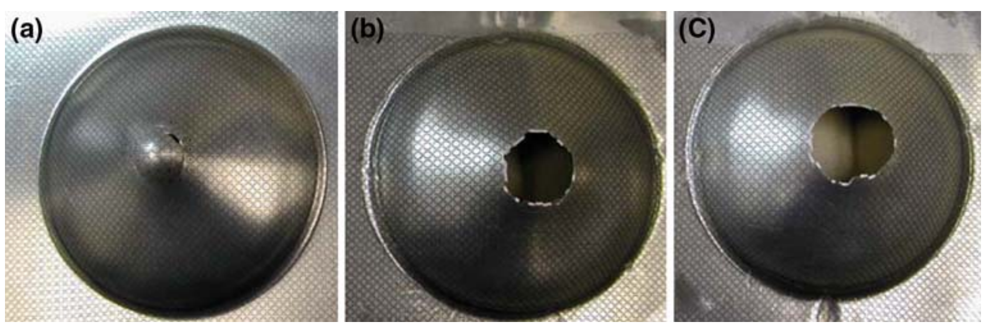

Fig. 10 Samples of 6111-T4 deformed with electromagnetic forming into a die with an open round window at different levels of energy: (a) 3.3 kJ; (b) 4.9 kJ; (c) 7.2 kJ

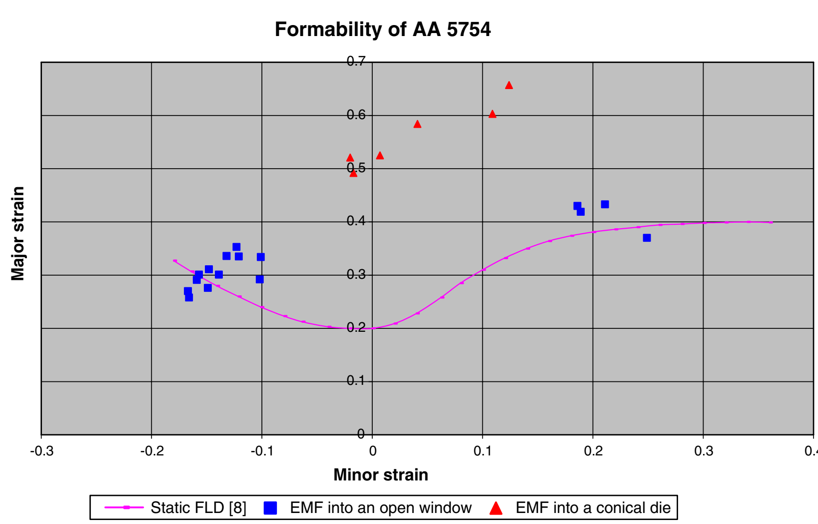

Fig. 11 Results on formability of AA5754: solid line—FLD diagram developed as a result of static tests on the press (Ref 8); rectangular dots—samples after EMF forming into an open round and rectangular window; triangular dots—samples formed with EMF into a conical die (Ref 8)

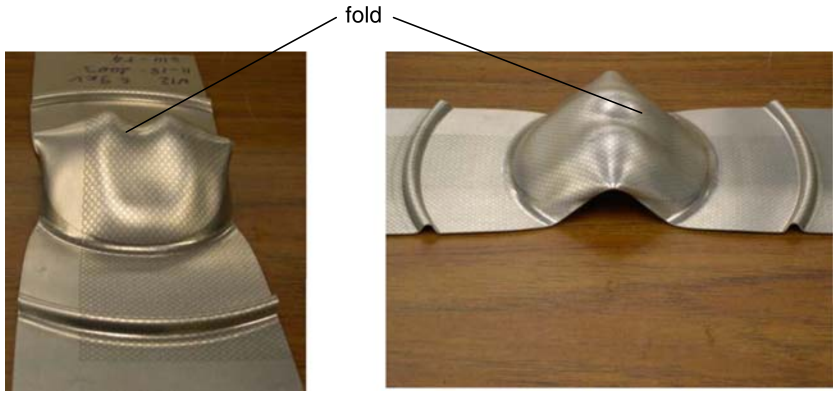

Fig. 12 Sample of 6111-T4 formed in conditions close to plane strain

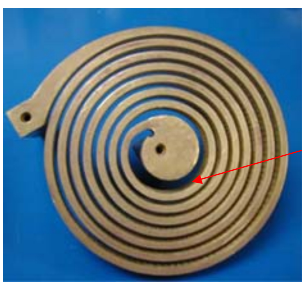

Fig. 13 The spiral of the circular flat coil with deformed central turn

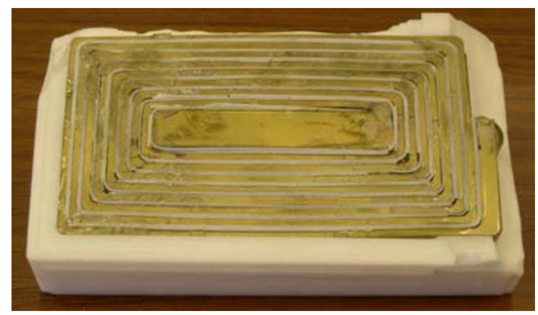

Fig. 14 Rectangular flat coil with fractured insulation block

observed in earlier coil designs and modification of the design leading to significantly higher durability of the coils, which may serve as a prototype for future production coils. Typical failure mode of both circular and rectangular coils was in deformation of the central turn of the coil and expansion of the clearance between the first and the second turns, as it is shown in Fig. 13. If the coil is not properly bandaged, expansion of the central turn may lead to the expansion of the bandage and fracture of the insulation block, as shown in Fig. 14. The observed failure mode indicated that the bandage, shown in Fig. 6, did not provide sufficient stiffness. After the coil failure, a visible curvature was seen originally at rectangular bandage block. Also delrin, from which the insulation block was fabricated, did not perform well from strength point of view; therefore, micarta was later on employed for coils construction.

If the bandage block performs appropriately, the telescoping failure mode was observed in experimental coils. In this case, the coil was loosing its flatness when the central turn was deforming outside the original coil plane increasing the distance between the blank and the tested sheet, as it can be seen in Fig. 15. The insulation sheet separating the sheet sample from the coil in this case was typically pierced in the center, resulting in a short circuit between the coil and the blank. Further attempts to use a telescoped coil resulted in a short circuit between the turns of the coil and its further mechanical failure.

One more important aspect of the coil strength was to provide proper insulation and reinforcement between the turns of the coil. For this purpose, the thickness of insulation should be the same as the clearance between the turns. Violating this condition leads to a failure mode, observed in Fig. 16. In this case the coil was machined from cold rolled steel, providing more mechanical strength for the spiral compared to the coils fabricated from brass. The clearance between the turns was exceeding the standard thickness of the insulation material and did not allow putting two-layers of insulation. An attempt to use this coil resulted in its very short life. Improper insulation of the coil, when the space between the turns is not filled properly, results in coil deformation due to significant forces between the parallel turns in the mode shown in Fig. 16. An important lesson was learned from this case: the strength of the coil is not defined by the strength of the material of the spiral; it is mostly dictated by the reinforcement of the coil against observed failure modes.

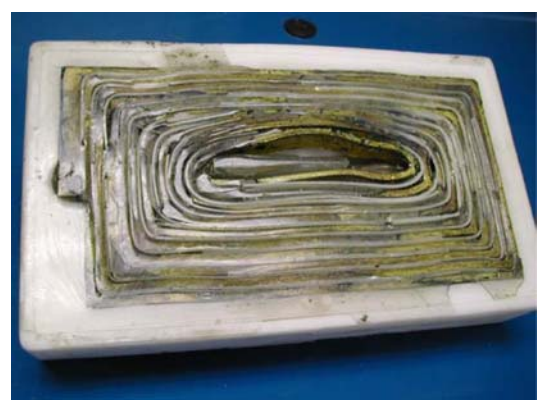

Fig. 15 Coil fractured due to the deformation of the central turn and gradual telescoping of the turns

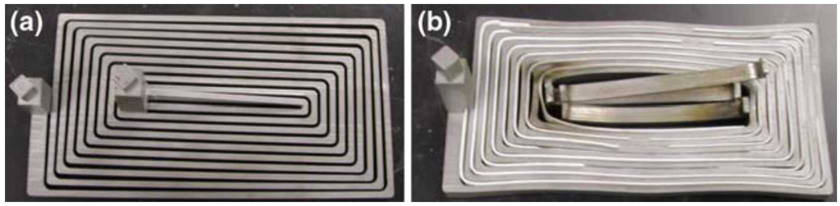

Fig. 16 Rectangular flat coil: (a) original new spiral; (b) fractured spiral

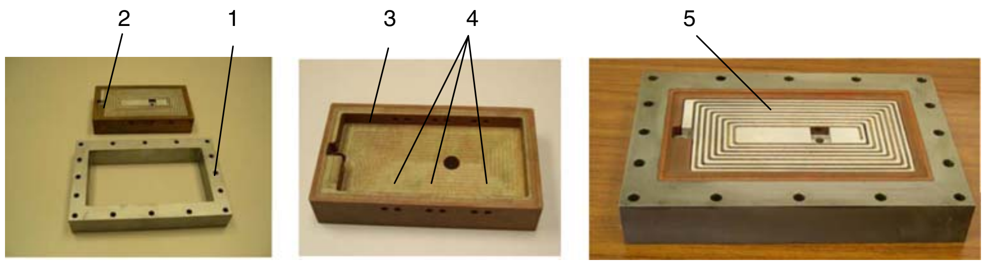

Fig. 17 Next generation flat coil used for formability testing of sheet metal (without a blank or insulating plate): 1—coil bandage; 2—assembled coil with reinforcing bars, made of non-conductive material, crossing the coil; 3—insulating block, made of micarta; 4—holes for the reinforcing bars; 5—assembled coil

Based upon these lessons, more durable coil design was developed (Ref 7). It was fabricated from a flat plate using water-jetting technology. The design of the coil included reinforcement of the spiral with a system of nonconductive bars. Insulation between the turns of the coil (Fig. 17) was made of micarta sheet, which thickness was identical to the clearance between the turns. The coil was mounted inside the insulation block also made of micarta. Reinforcing cylindrical rods were inserted through the coil and the insulation block. Then the coil was positioned inside the steel bandage to prevent its expansion.

5. Conclusions

1. Formability of aluminum alloys, employed for the auto industry for interior and exterior panels (including 6111-T4) like many other materials, can be improved by using electromagnetic forming.
2. Electromagnetic forming into an open-round and rectangular window provides relative improvement in maximum deformation of the blank in the range of 10-15%. Electromagnetic forming of aluminum sheet into V-shape and conical die may provide a significant increase in local strains.
3. Mechanical strength of the coil is not defined by the strength of the material of the spiral; it is mostly dictated by the reinforcement of the coil against observed failure modes. A new generation coil design, addressing the observed failure modes, has been developed.

References

1. J.C Benedyk, Superplastic Forming of Automotive Parts from Aluminum Sheet at Reduced Cycle Times, *Light Metal Age*, 2002, **60**(6), p 28–31
2. S. Golovashchenko and A. Krause, Improvement of Formability of 6xxx Aluminum Alloys Using Incremental Forming Technology, *J. Mater. Eng. Perform.*, 2005, **14**(4), p 503–507
3. B. Avitzur, *Handbook of Metal Forming Processes*. John Willey & Sons, New York, 1983 1020
4. P. Kapitsa, A Method for Producing Strong Magnetic Fields, *Proc. Roy. Soc., Ser. A*, 1924, **105**, p 691–710
5. S.F. Golovashchenko, Numerical and Experimental Results on Pulsed Tubes Calibration, *Proceedings of a 1999 TMS Symposium "Sheet Metal Forming Technology"*, San-Diego, 1999, p 117–127
6. S.F. Golovashchenko, Springback Calibration Using Pulsed Electromagnetic Field, *Proceedings of the 6th International Conference and Workshop on Numerical Simulation of 3D Sheet metal Forming Processes Numisheet 2005*, Detroit, Michigan, 2005, p 284–285
7. S.F. Golovashchenko, V. Dmitriev, P. Canfield, A. Krause, and C. Maranville, Apparatus for Electromagnetic Forming with Durability and Efficiency Enhancements, US Patent Application US2006/086165A1, April 27, 2006
8. J.M. Imbert, S.L. Winkler, M.J. Worswick, D.A. Oliveira, and S.F. Golovashchenko, The effect of Tool-Sheet Interaction on Damage Evolution in Electromagnetic Forming of Aluminum Alloy Sheet, *Transactions ASME*, *J. Eng. Mater. Technol.*, 2005, **127**(1), p 145–153
9. V.S. Balanethiram and G.S. Daehn, Hyperplasticity: Increased Forming Limits at High Workpiece Velocity, *Scripta Metall. Mater.*, 1994, **30**, p 515–520