Contributing Factors to the Increased Formability Observed in Electromagnetically Formed Aluminum Alloy Sheet*

J.M. Imbert[1], M.J. Worswick[1], S. Golovashchenko[2]

[1] Dept. of Mech. Engineering, University of Waterloo, Waterloo, Ontario, Canada
[2] Ford Motor Company, Scientific Research Laboratory, Dearborn, MI

Abstract

This paper summarizes the results of an experimental and numerical program carried out to study the formability of aluminum alloy sheet formed using electromagnetic forming (EMF). Free-formed and conical samples of AA5754 aluminum alloy sheet were studied. The experiments showed significant increases in formability for the conical samples, but no significant increase for the free-formed parts. It was found that relatively little damage growth occurred and that the failure modes of the materials changed from those observed in quasi-static forming to those observed in high hydrostatic stress environments. Numerical simulations were performed using the explicit finite element code LS-DYNA with an analytical EM force distribution. The numerical models revealed that a complex stress state is generated when the sheet interacts with the tool, which is characterized by high hydrostatic stresses that create a stress state favourable to damage suppression increasing ductility. Shear stresses and strains are also produced at impact with the die which help the material achieve additional deformation. The predicted peak strain rates for the free formed parts were on the order of 1000 s^{-1} and for the conical parts the rates are on the order of 10,000 s^{-1}. Although aluminum is typically considered to be strain-rate insensitive, the strain rates predicted could be playing a role in the increased formability. The predicted strain paths for the conical samples were highly non-linear. The results from this study indicate that there is an increase in formability for AA5754 when the alloy is formed into a die using EMF. This increase in formability is due to a combination of high hydrostatic stresses, shear stresses, high strain rates, and non-linear strain paths.

Keywords:

Electromagnetic sheet metal forming, Formability, Aluminum alloy sheet, AA5754

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1 Introduction

Interest in electromagnetic forming (EMF) has increased recently due to the potential formability increases that high speed forming can offer for low formability materials. The exact nature of the mechanisms that contribute to the increased formability observed remains an open question. Daehn and co-workers [1,2,3] studied the phenomenon and reported that the formability increases were due to inertial suppression of necking and inertial ironing. The present authors have proposed that the increases in formability are due to the complex stress state and strains produced by tool/sheet interaction [4, 5, 6, 7]. The importance of the tool/sheet interaction becomes apparent since no significant increases in formability have been observed by the current authors in free-formed parts where the material does not contact a die. In contrast, significant increases in formability have been observed in parts formed into a conical die. Similar observations have been made by Oliveira [8] and Golovashenko et al [9]. Imbert [7] contains an in-depth review on the available literature on this subject.

This paper summarizes the results of a project whose aim was to determine which factors were affecting the formability of sheet material in EMF. The preliminary findings of the project were presented by the authors in the 1st International Conference on High Speed Forming [6]. Both AA5754 and AA6111 were studied, however, for the sake of brevity only the data for AA5754 will be presented in this paper. The reader is referred to Imbert [7] for the complete findings of the project.

2 Experimental procedure

2.1 Formability experiments

The experiments consisted of forming 1mm AA5754 sheet into free-form and conical dies of 34°, 40°, and 45° side angle, using a spiral coil. The yield stress of the material was 98 MPa. An IAP Magnepress [10] system with a maximum storage capacity of 22.5 kJ at 15 kV was used. Figure 1 shows a schematic of the tooling used in the experiments.

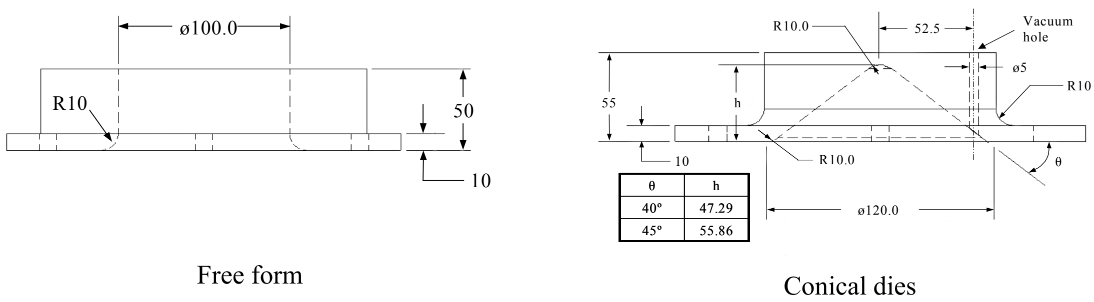


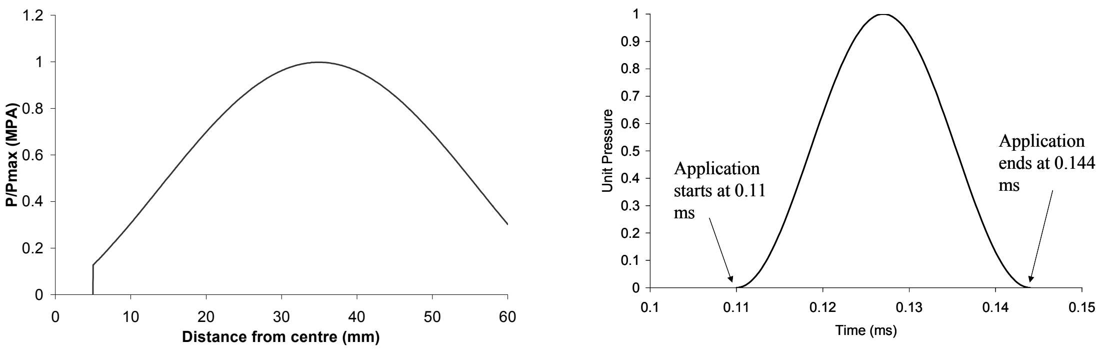
Figure 1*: Schematic of the dies used*

Circle grids were used to measure the engineering strains in the rolling direction. Metallographic and scanning electron microscopy was carried out to measure the damage levels in the material and to study the failure modes present in the material. A detailed description of the experimental procedures can be found in ref [7].

3 Numerical models

Numerical simulations of the experiments were carried out using the explicit dynamic finite element code LS-Dyna [11]. The EM force was modeled using an analytical pressure distribution. This approach was deemed appropriate since the general behavior of the sheet as it interacts with the tool would not change dramatically with the analytical pressure distribution when compared to the pressure distribution of an actual spiral coil. Constant stress solid elements were used for the sheet in order to capture the trough thickness normal and shear stresses. The die and blank holder were modeled using rigid shell elements.

The EM pressure was modeled with an analytical pressure distribution for an "ideal" spiral coil (i.e. one formed of concentric circles) from Al–Hassani [12]. This results in a radial pressure distribution that does not vary in the circumferential direction. To simplify the load application, no load was applied within a 5 mm radius of the center since the actual loads are very low at this point. A sinusoidal profile was used for the time history of the pressure (Figure 2). The time at which the peak pressure was reached corresponded to the average value observed in the experiments, that is 0.017 ms. The material was modeled using a modified version of the Gurson-Tvergaard-Needleman (GTN) constitutive model [13,14,15]. An in-depth description of the model and its validation is presented in [7].



a b

***Figure 2**: Radial pressure distribution (a) and time history of pressure application (b)*

4 Experimental Results

So-called safe parts that did not fracture were produced with the 34 ° and 40° cone. All the parts formed with the 45° cone fractured. For the purpose of this work, a part that showed no indication of fracture or necking is considered safe; otherwise it is considered to have failed. Figure 3 shows representative free formed and conical parts.

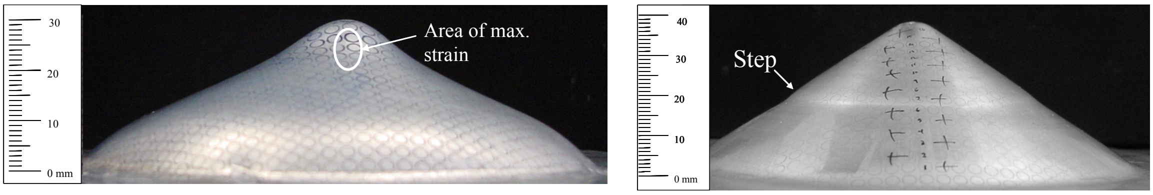


***Figure 3**: Samples formed using the free form (left) and 34° die (right)*

4.1 Formability data

Figure 4 shows the measured strains for the safe and failed conical parts. It can be seen that strains above the conventional forming limit curve (FLC) were achieved. In contrast to the conical die results shown, none of the free-formed samples exhibited measured strains that lay above those obtained using conventional stamping methods [7], indicating that enhanced formability was only observed for the parts formed into conical dies.

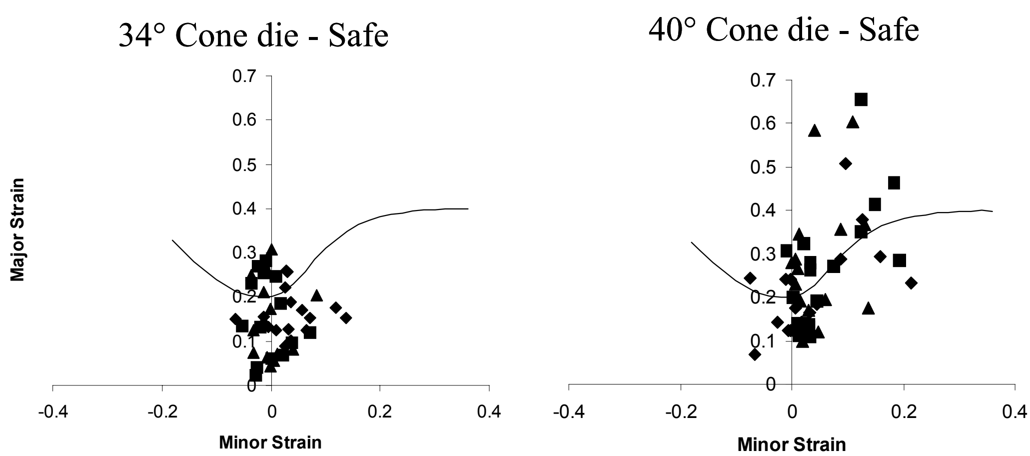


***Figure 4**: Measured strains for the 34 ° and 40° conical parts in FLD form. The curve represents a typical FLC for 1.0 mm AA5754 [16]. Each FLD contains the data of three samples*

4.2 Damage measurements

In the areas where safe strains beyond the conventional FLD were recorded the material showed little increase in damage relative to the as-received condition of 0.01% void volume fraction. Thus, the data for the conical die experiments showed relatively small increases in damage. Safe areas in the conical parts with strains in the range of 25-30% under near plane strain conditions showed damage levels between 0.01 to 0.02%. Relatively larger increases were measured in the tip area of the 40° sample where 0.067% void volume fraction was measured for major and minor strains of 60% and 10%. The area of the neck has a void volume fraction of 0.15% for similar strains, the higher value is consistent with the localized thinning.

4.3 Observed failure

Micrographs comparing the fractured region of a conical EM formed part to fractures under quasi static and high strain rate tensile loading are shown in Figure 5. It can be seen that the material formed with EMF thinned considerably before fracture, in a manner more consistent with plastic collapse than with ductile fracture. The amount of thinning is significantly higher than that observed in quasi-static testing and higher than that observed in Hopkinson bar testing at 1500 s^{-1}.

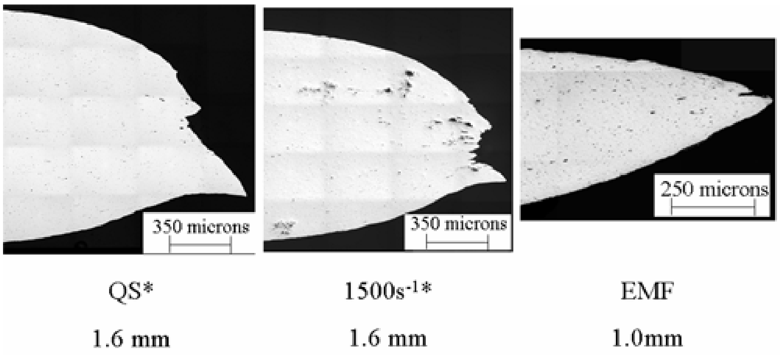


Figure 5: *Micrographs of failure of AA5754 for tensile quasi-static (QS), high strain rate Hopkinson bar testing at 1500 s^{-1}, and EM forming, (* Taken from Smerd et al. [17]*

Scanning electron microscope images of the EMF failure are shown in Figure 10. There are some areas of dimpling and void sheeting which indicate ductile fracture, with limited areas exhibiting shear fracture. This is non consistent with the quasi-static fractures of the material, which were primarily ductile-shear failures [7]. The dramatic reduction in area and failure modes present in the EMF samples are consistent with damage suppression mechanisms and the presence of large hydrostatic stresses [7].

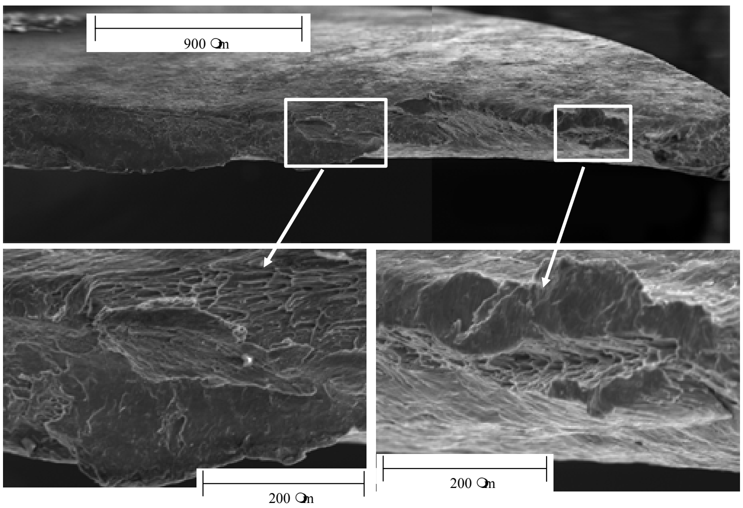


Figure 6: *Scanning electron microscope images of the failure of the conical parts. Insets show ductile and shear fracture (bottom right) and shear fracture and void sheeting (bottom left)*

5 Numerical results

The numerical analysis yielded considerable insight into the deformation processes of the free-formed and conical parts. In general, the free-formed parts deformed in essentially a plane-stress manner. Details of this deformation can be seen in [7]. In contrast to the free-formed parts, the forming history of the conical parts was characterized by a complex three dimensional stress and strain state. In region A, the sheet is deforming in plane stress. In region B, the sheet impacts the die, resulting in a complex stress state. Just prior to impact the sheet bends and then straightens as it hits the die. In region C, the sheet is deformed to its final state, but bounces off the wall of the die. The model agrees well with the experimental observations; a more detailed comparison can be seen in [7].

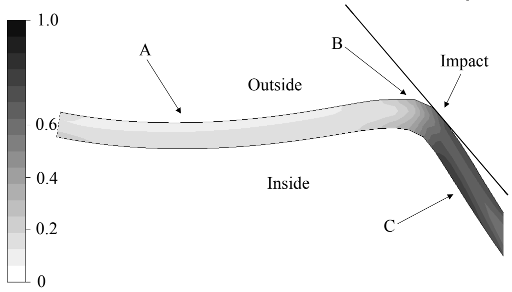


Figure 7: *Predicted impact zone. Contours are of true effective plastic strain*

5.1 Through thickness stresses

The stress at impact is dominated by large through thickness-stresses. Figure 8 shows the predicted through-thickness stresses and strains for an element on the sheet that makes contact with the die.

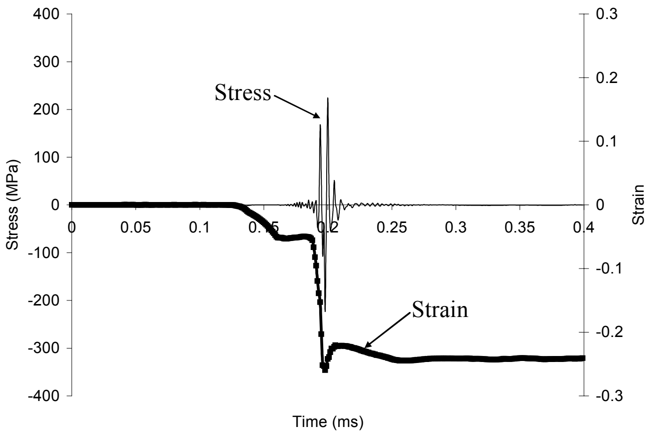


Figure 8: *Predicted through-thickness stresses and plastic strains for elements that make contact with the sheet*

The through-thickness stresses are very high and contribute to the production of high compressive hydrostatic stresses. The through-thickness stresses vary significantly throughout the thickness of the sheet, being an order of magnitude lower on the inside of the sample. Figure 9 shows a comparison between the triaxiality history predicted for free-formed and conical parts. The triaxiallity of the free-formed parts increases relatively monotonically as forming takes place, indicating a plane stress state. The conical part is characterized by a very high negative triaxiality produced by the presence of the through-thickness stresses.

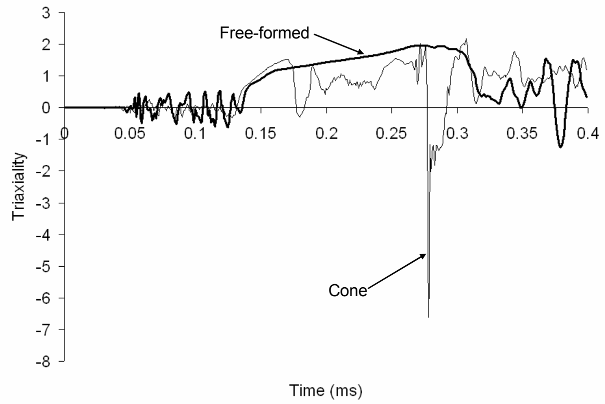


Figure 9: *Triaxiality for free-formed and conical part*

5.2 Shear stresses

A distinctive feature of the stress state history is the presence of significant shear stresses. Figure 10 shows the predicted shear stress and strain for an element on the outside of the sheet. The maximum predicted shear stresses are on the order of the yield stress of the material. These produce shear strains that contribute to the overall deformation of the material.

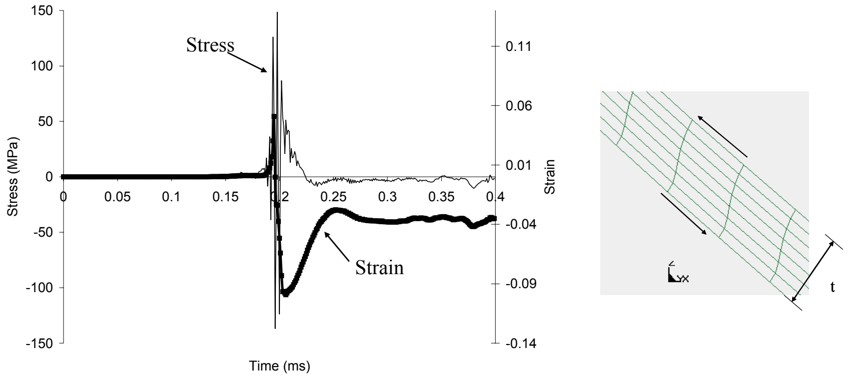


Figure 10: *Predicted shear stresses and strains for an outside element. The direction of shear is shown on the left of the figure.*

5.3 Strain rates

A careful examination of Figure 7 shows that the majority of the deformation of the sheet happens at impact, the duration of the impact is roughly 10 µs, producing strain rates on the order of 10,000 s^{-1}. This strain rate is very high and no material data are available for AA5754 sheet under these conditions to the authors' knowledge. It is likely that these high rates of strain are affecting the formability, but further work is required to determine any constitutive and thermal effects that might be present. In contrast, for the free-formed samples the predicted strain rates were on the order of 1,000 s^{-1}. It has been shown by Worswick et al [17] that AA5754 experiences some increase in flow stress and increased elongation at strain rates on the order of 1,000 s^{-1} (Figure 11). If this trend holds for higher strain rates, some of the increased formability observed could be explained.

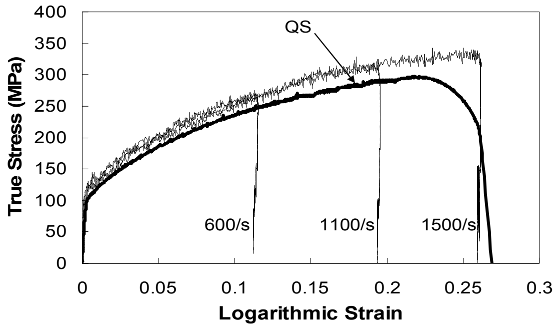


Figure 11: *Effect of strain rate on flow stress and elongation for AA5754-O [17]*

Strain paths have a significant effect on formability [18,19]. The predicted strain paths for the conical parts are highly non-linear and could also be affecting the formability. More details on the predicted strain paths can be found in [4, 7].

6 Discussion

The experimental evidence suggests that the material formed into conical dies is subject to high hydrostatic stresses that suppress damage and change the failure mode of the material. This is supported by the numerical analysis, which shows that a complex stress state is produced with high through-thickness stresses that lead to high compressive triaxiality. These stress states have been shown to reduce damage and improve ductility. Sheet metal through-thickness stresses have been suggested as a possible mechanism for improving formability, as further discussed by Imbert [7].

The presence of large through-thickness and shear stresses and strains also contributes to the increased levels of deformation observed. For numerical simulations of these processes the shear stresses combined with the through-thickness stresses have significant implications to the choice of elements used. In particular, shell elements should not be used since they do not account for transverse shear stresses.

The effects of the strain rates and strain paths on formability are the subject of ongoing research. Although the available evidence suggests that these may have an effect on formability, data on the properties of the materials studied are not available for the extremely high strain rates encountered in the EMF conical die forming operations.

7 Conclusions

The following conclusions are drawn:

- EM forming of sheet into a die results in non-plane-stress conditions due to the high compressive trough-thickness stresses and transverse shear stresses produced.
- Very high strain rates are predicted for which material data are not available for the alloys studied.
- The above mentioned factors combine to produce the increased formability observed.

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