Multi-Layer Aluminum Formability Assessment Using Composite Shells in LS-DYNA® with the Linear Fracture Line Approach

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Abstract

Multi-layer aluminum sheet offers exciting design possibilities for automotive applications due to the outer layer having a ductility that suppresses fracture in drawing processes involving a high degree of bending. Formability assessment of multi-layer aluminum products such as AF200 thus offer a challenge to traditional techniques used in the industry such as Forming Limit Diagrams, owing to this large resistance to bending dominated fracture. A modelling technique using standard LS-DYNA release features is set forth and discussed.

Introduction

Advanced aluminum composites are available with multiple layers to offer customized surface properties for processes such as remote laser brazing, heat-exchanger brazing and very deep drawing. The advanced forming aluminum grade AF200 is the topic interest for this paper, specifically offering a technique using standard LS-DYNA R10.0 features to predict fracture during deep drawing simulations of this particular grade. Such a grade of aluminum is well suited to deep drawn parts such as door inners, as well as outer panels with very aggressive styling involving tight radii.

The product and its application in processes involving tight radii in forming operations poses a problem for automotive body engineers in so far as the conventional Forming Limit Diagram (FLD) approach is only valid when one can assume a state of plane stress. A different approach is described and evaluated using recent feature development in LS-DYNA.

Characterization of the constitutive material model is summarized for AF200 in the T4 condition, where it is most formable. An additional feature to such a grade of aluminum owes itself to the 6xxx core, which allows for a strong paint bake response; during which the age hardening offered by precipitation nucleation and growth strengthens the grade. The 5000 alloy clad layer is soft and suppresses shear fracture seen during forming operations with a high degree of bending.

Modelling Approach

The modelling approach relates to methods detailed in the work of Gorji [1] implemented in a user defined subroutine. The approach outlined in this work uses only standard features of LS-DYNA to achieve comparable results.

Consideration was given to approaches outlined by Erhart [2] that rely on the control card *PART_STACKED_ELEMENTS to discretize the thickness of the multi-layered sheet. The approach was discarded after the new features in *PART_COMPOSITE that allow one to specify, in a simple manner, multiple layers to a composite shell, without necessitating user defined integration rules and such. Figure 1 below shows the control card in LS-PrePost®. Timesteps are comparable to standard shell techniques and other benefits such as unaffected contact definitions allow less model changes when simulation engineers evaluate monolithic aluminum grades side by side with products such as AF200 during die development.

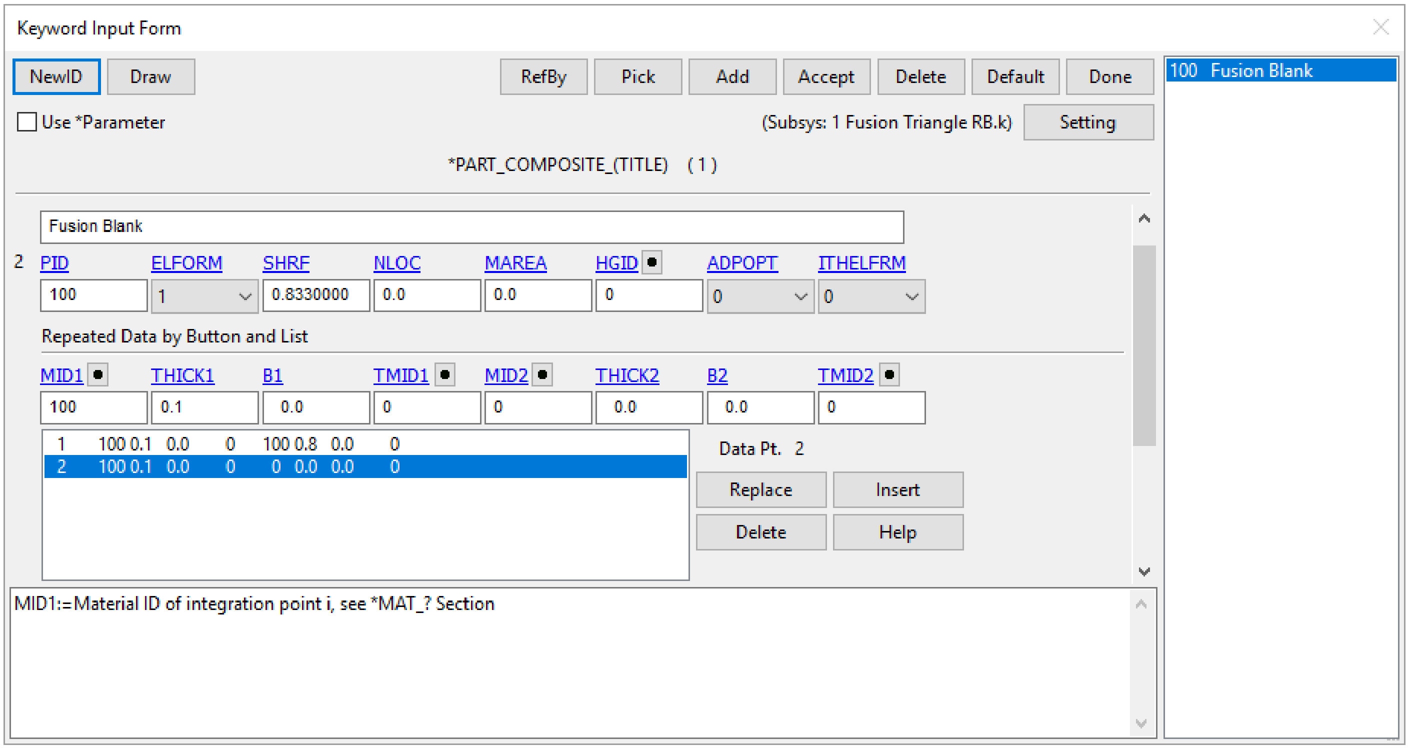

Figure 1: *PART_COMPOSITE control card showing freedom to easily define multiple aluminum layers.

Fracture characteristics are implemented using *MAT_ADD_EROSION, as shown below in figure 2. Specifically the author has turned off damage accumulation to avoid the conversion of measured data into triaxiality space and so on, and instead supplying engineering major and minor strains to failure from experimental measurements using the LCFLD option.

Gorji [1] offers additional options for defining fracture to the one discussed here using a Linear Fracture Line (LFL) approach, namely Johnson-Cook, constant effective plastic strain to fracture and a shear stress approach. The conclusion in this reference is that the LFL approach was most effective. Since publication of the aforementioned work, further work by Gorji *et al* [3] offers a technique to use the Hosford-Coulomb fracture model, as favored by the International Fracture Consortium. The decision to implement the LFL approach in the present paper surrounds the use of shells and their modelling efficiency, as well as ease of implementation in the automotive industry.

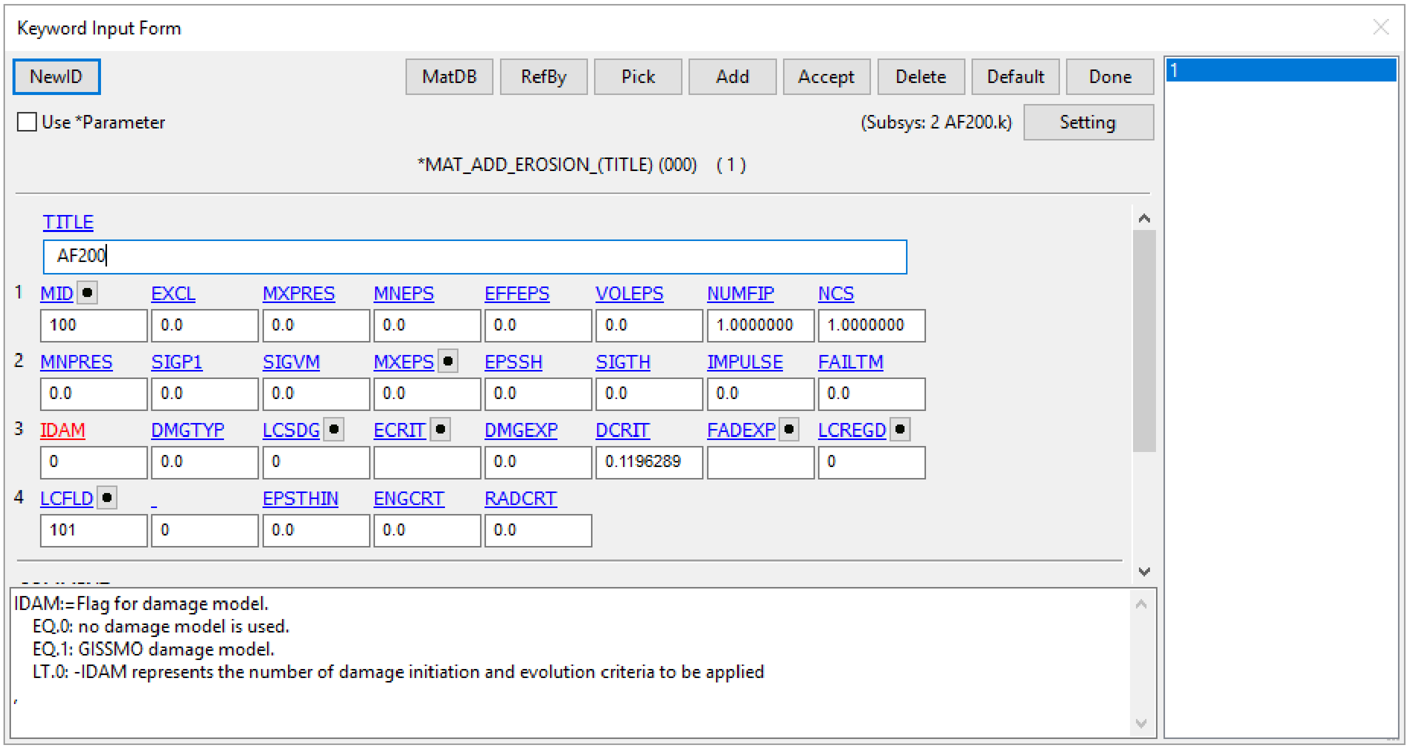

Figure 2: *MAT_ADD_EROSION card to define fracture characteristics for individual layers.

Experimental techniques are discussed in the following section on input data, and the published work by Gorji [1] and Gorji *et al* [4] offers the reader a detailed description. Similar techniques for defining fracture data into LS-DYNA do exist in material models such as *MAT _TRANSVERSELY_ANISOTROPIC_ELASTIC _PLASTIC by activating the option NLP_FAILURE, though one has to sacrifice the most appropriate yield locus definition for common aluminum alloy grades seen in the automotive industry, namely YLD2000 by Barlat *et al* [5].

Input Data

Gorji *et al* [4] offer a thorough treatment of the methods used necessary for the characterization of layered aluminum composite grades such as AF200. Firstly one must supply the necessary coefficients for the *MAT_BARLAT_YLD2000 constitutive material model card. Such non-quadratic yield functions offer good description of the plasticity behavior of sheet aluminum during plane stress forming operations [5]. Figure 3 below shows the coefficients published for AF200 [1].

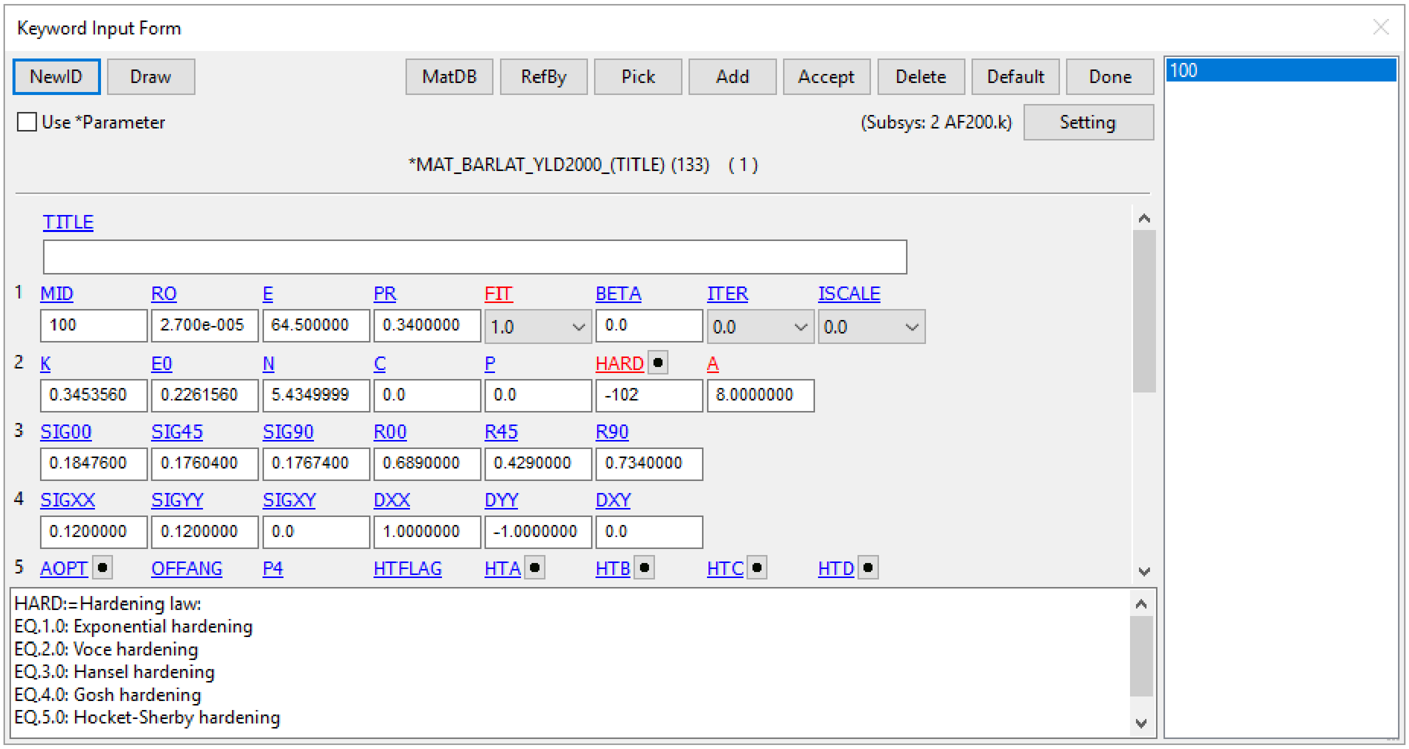

Figure 3: *MAT_BARLAT_YLD2000 material card with coefficients for characterized sheet AF200. Hydraulic bulge test results can be used for input to define work hardening.

LS-DYNA offers the flexibility for the user to input a work hardening curve. Aluminum differs from mild steel in so far as the work hardening is not of a consistent rate, making fitting using a Holloman power law equation difficult for example. Best practice is use of Hydraulic Bulge test data [7, 8] and extrapolation using a modified Voce equation like below [9]:

$$\tau = \tau_0 + (\tau_1 + \theta_1 \,.\, \gamma)\,(1 - \exp\,(\,-\theta_0 \,.\, \gamma \,/\, \tau_1))$$

Fracture and failure definition is more involved than standard Forming Limit Curve (FLC) measurements [10] and needs extension to approximate strains at fracture, rather than localization limit as is more traditionally the case. Below, figure 4 shows the results from such an experimental technique with strain paths from Nakajima experiments and final strain to fracture shown above the FLC line. A cup test is used to attain failure information for the extreme left.

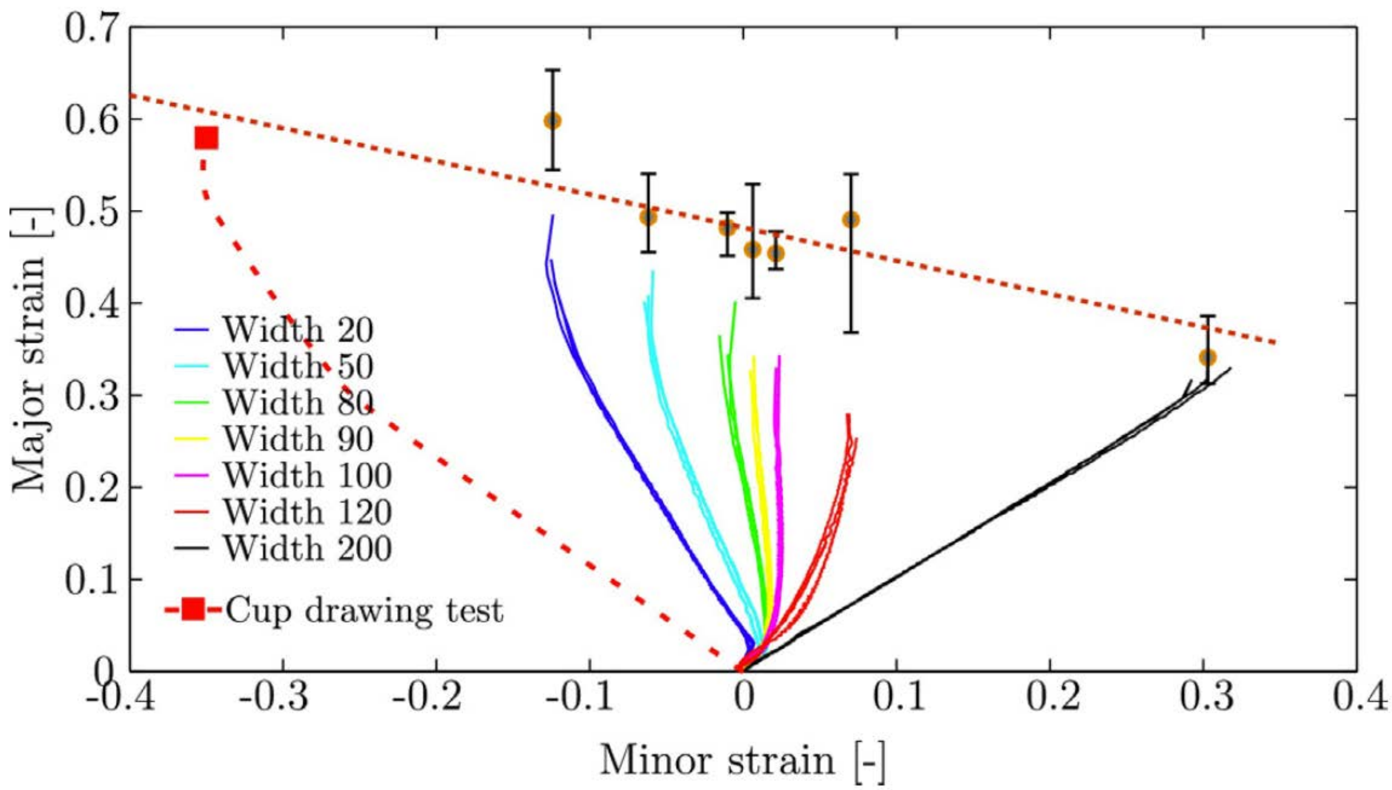

Figure 4: Gorji *et al* offer a description of fracture characterization methods required and the referenced author's results are shown here. The method requires Nakajima and cup specimens to be analyzed for strain paths and final thinning in the necked region. [4]

The Linear Fracture Line seen in the above figure 4 is used for fracture definition as was described in the modelling approach section. LS-DYNA demands input of these fracture major strain and minor strain combination in *engineering strain* and thus becomes curvilinear. The resulting simulation using the modelling approach will subsequently be covered in the following section.

Results

The geometry chosen to trial out the modelling approach defined in the prior sections of this paper is described in the thesis of Gorji [1], as is the blank dimensions. Figures 5a, 5b and 5c show progression of the deep drawing simulation detailed in the previous section with a fringe plot of effective plastic strain. For each step in the process the corresponding strain distribution is shown on the right hand side.

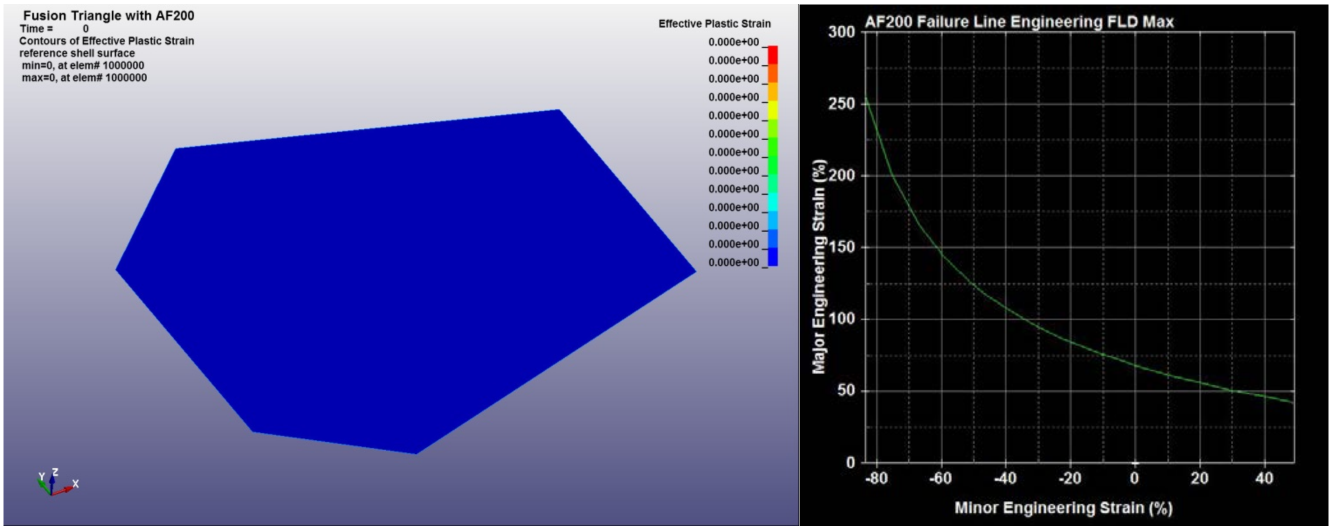

Figure 5a: initial blank shown alongside limit strain diagram for fracture. Strain is engineering and plotting is described below.

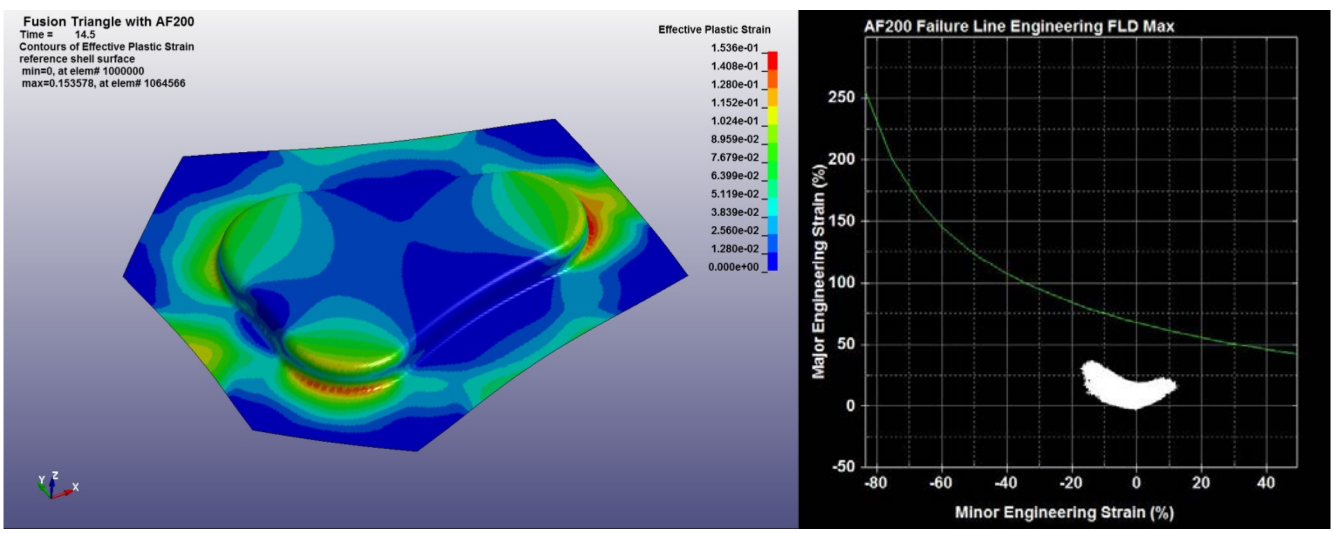

Figure 5b: partially formed blank shown alongside limit strain diagram for fracture.

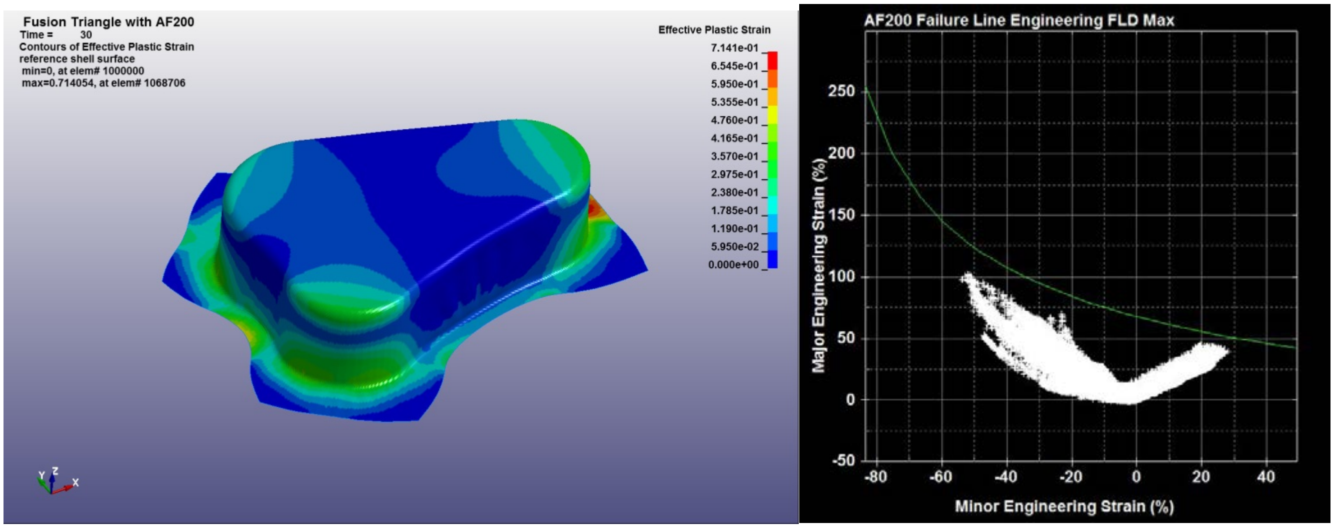

Figure 5c: part at depth of 55mm shown alongside limit strain diagram for fracture.

Post processing of the simulation has been performed in LS-PrePost, using its ability to optionally plot engineering strains as opposed to true strains on the FLD. LS-PrePost offers the user the option to specify the same curve as was used in the failure definition as LCFLC.

The simulation behaves as expected and at 55mm punch depth the part is still safe. Punch travel limits the ability to crack the AF200 in this case, though AA6016 will have cracked at approximately 45mm in the same nominal 1.0mm gauge [4].

Discussion and Conclusion

The Linear Fracture Line technique has been successfully implemented in LS-DYNA using release features and functionalities of R10.0. The LFL shows promise as a suitable technique for assessing fracture propensity of formed sheet metal components from layered aluminum alloy composites, such as AF200. Previously published work [1, 4] had relied on user defined subroutines not available to all users of LS-DYNA. Though at time of publication a fractured specimen was difficult to attain, a new die with 100mm draw depth will be implemented at Novelis Global Research Development and Technology Center. Further work with this experimental die will deep draw AF200 to a point of fracture, and will thus allow more conclusive evidence that the LFL technique and the modelling approach described herein is predictive.

The NLP_FAILURE option, as implement in *MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC _PLASTIC, for instance, would offer additional functionality by taking account of non-linear strain paths seen in the forming of complex parts. Though the author is not aware if its implementation to non-quadratic constitutive models pertinent to aluminum alloys such as *MAT_BARLAT_YLD2000, though such functionality would potentially be beneficial.

References

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