Predicting FLDs Using a Multiscale Modeling Scheme

Z. Wu, C. Loy, E. Wang and V. Hegadekatte*

Novelis Global Research & Technology Center
1950 Vaughn Road
Kennesaw GA 30144 USA

*vishwanath.hegadekatte@novelis.adityabirla.com

Abstract. The measurement of a single forming limit diagram (FLD) requires significant resources and is time consuming. We have developed a multiscale modeling scheme to predict FLDs using a combination of limited laboratory testing, crystal plasticity (VPSC) modeling, and dual sequential-stage finite element (ABAQUS/Explicit) modeling with the Marciniak-Kuczynski (M-K) criterion to determine the limit strain. We have established a means to work around existing limitations in ABAQUS/Explicit by using an anisotropic yield locus (e.g., BBC2008) in combination with the M-K criterion. We further apply a VPSC model to reduce the number of laboratory tests required to characterize the anisotropic yield locus. In the present work, we show that the predicted FLD is in excellent agreement with the measured FLD for AA5182 in the O temper. Instead of 13 different tests as for a traditional FLD determination within Novelis, our technique uses just four measurements: tensile properties in three orientations; plane strain tension; biaxial bulge; and the sheet crystallographic texture. The turnaround time is consequently far less than for the traditional laboratory measurement of the FLD.

1. Introduction

Novelis is the world’s largest producer of flat rolled aluminum products. Increasingly the automotive industry is using aluminum sheet for skin panel and structural applications to reduce the weight of the cars in order to meet strict environmental regulations. The sheet is formed into components using deep drawing, stretching, flanging, bulging, hemming etc. As a result, an understanding of the formability of aluminum sheet is of paramount importance to the automotive industry. Formability in the most general sense is the ability of a metal sheet to undergo plastic deformation without failure. Often, localized necking is considered as failure. Going by this definition, one of the best known ways of assessing formability is the forming limit diagram (FLD) [1]. FLDs are often included in Novelis’ automotive product data sheets provided to customers, as well as being used to study the formability of our products for internal research and development purposes. The concept of the FLD originated from the pioneering work of Keeler and Backhofen [2] and Goodwin [3]. Shortly after publication of the Forming Limit Diagram concept, on the basis of experimental investigations concerning the strain localization of some specimens subjected to hydraulic bulging or punch stretching, Marciniak and Kuczynski [1, 4] developed a limit curve prediction model. In the present work we use the Marciniak-Kuczynski (M-K) criterion implemented in the commercial finite element (FE) package, ABAQUS/Explicit for predicting the FLD.
With the advent of high performance computers and the concurrent development of the finite element method (FEM), computer simulations of the component forming process and the in-service performance are increasingly being employed by automakers to cut developmental costs. The quality of the results from these computer simulations almost entirely depend on the material constitutive model. von Mises yield criterion is the most popular isotropic material model in use today. However, for sheet materials, accounting for the anisotropy in the material properties becomes important. In recent times, anisotropic materials models especially the ones developed by Barlat & coworkers and Banabic & coworkers have become very popular in the sheet metal forming simulation community as they are implemented into commercial FE packages (see [5] for an in-depth analysis on various constitutive models used in sheet metal forming simulations). Though the modeling scheme we have developed is applicable to any anisotropic yield criteria, in the present work, we use Banabic and co-workers’ BBC2008 yield criterion [6, 7] to model the anisotropic material behavior of aluminum alloy AA5182 in the O temper which is implemented as a user subroutine\(^1\) for ABAQUS/Explicit.

Within Novelis, we use FEM for modeling at the continuum (component) length scale. However, it is often necessary to understand the material behavior (e.g., crystallographic texture evolution) at the microstructural length scale. Various theories and modeling methods have been developed to predict the plastic anisotropy and texture evolution by simulating the yielding and hardening characteristics and crystal reorientations at the grain level. The visco-plastic self-consistent (VPSC) model [8] is one of the most widely used microstructural length scale models to provide a detailed description of the anisotropic plastic behavior of aluminum alloys. In the present work we use the VPSC model to predict the material parameters used by the BBC2008 anisotropic yield criterion.

2. Laboratory measurement of sheet crystallographic texture, FLD and mechanical properties

In this section we present laboratory measurement of the sheet crystallographic texture, forming limit diagram and the mechanical properties using uniaxial tensile and bulge (equi biaxial) testing.

2.1. Texture measurement of AA5182-O sheet

![Figure 1](image)

Figure 1. Measured initial texture of AA5182-O sheet at 1 mm gauge represented by the \(\{111\}\) \(\{200\}\) \(\{220\}\) \(\{311\}\) pole figures.

The crystallographic texture input to the visco plastic self-consistent (VPSC) crystal plasticity model was measured using X-ray diffraction (XRD). We employed a Panalytical X’pert Pro multi-purpose diffractometer operating at 40 kV and 45 mA with Cu Kα radiation, utilizing the Schultz reflection method to minimize defocusing at higher \(\chi\) tilts. Incomplete (\(\nu = 0-80^\circ\)) pole figures at \(\{111\}\), \(\{200\}\), \(\{220\}\) and \(\{311\}\) were collected. Background subtraction, defocusing corrections and normalization

\(^1\) The ABAQUS user subroutine, VUMAT code shared by Prof. Dorel Banabic is gratefully acknowledged
were carried out using the MTeX MATLAB toolbox, and MTeX was further used to generate complete orientation distributions functions (ODF) and full pole figures. Raw data were smoothed using a Gaussian filter of 5° in order to remove spurious intensity spikes. Figure 1 shows the measured initial texture of the sheet represented by the \{111\} \{200\} \{220\} and \{311\} pole figures.

2.2. Measurement of FLD of AA5182-O sheet
For measurement of the Forming Limit Diagrams (FLDs), we worked within the bounds of ISO 12004-2. The ISO standard works as a guide for establishing high quality results that best represent a materials forming limit [9]. We used the Nakajima hemispherical punch. In the following, a concise explanation of the measurement process we use for generating forming limit diagrams is described.

![Figure 2](image)

**Figure 2.** (a) Speckle pattern on the sample surface for DIC and (b) measured FLD for AA5182-O sheet at 1 mm gauge.

Thirteen geometries were used with a minimum of three samples per geometry. Even though the ISO requirements are much lower, within Novelis, we use thirteen geometries to get a better fit for the measured FLD. All samples were laser machined which was cost and time efficient without sacrificing edge quality. Often, commercially produced material comes with a pre-applied lubricant that must be removed prior to preparing the surface for testing. We degreased the samples with Simple Green®, a nontoxic, biodegradable degreaser. The samples were then painted with a white base coat. The final step in the surface preparation was to apply the speckle pattern (stochastic grid) with a graphite spray (Figure 2 (a)).

Lubrication at the contact surface of the sample is achieved by using a composite consisting of a thin Teflon membrane, a thick pad of butyl rubber sandwiched between layers of lanolin grease, topped off with a final piece of Teflon. Samples are then clamped with a knurled binder in a double action press. The binder force is adjusted to suit the sample gauge and strength. The GOM ARAMIS² system is used for collecting major/minor strain data through Digital Image Correlation (DIC) from the deforming sample surface. To collect the DIC data efficiently, we use signal triggers and time delays to tailor our data collection at the onset of necking. The forming limit diagram is as shown in Figure 2 (b) and final curve fitting is accomplished using a sum of two exponential equations and a quadratic equation, as presented in [9]. The curve fitting is only done to obtain a smooth curve for input to FE models and the exponential equation has no physical meaning. In the present work, we use the plane strain tension data for calibrating our model and the rest of the generated data is used for validation. In the current work, we use the plane strain tension limit strain (FLD₀) for calibrating our model while the rest of the measured limit strains are used for validating our model.

2.3. Measurement of mechanical properties of AA5182 O temper sheet
To obtain the bulge test data in Figure 3 (a), a 300 × 300 mm (12” × 12”) aluminum sheet sample was clamped inside a custom built servo-hydraulic machine and a maximum pressure of approximately

² [link]

```
6.25 MPa (905 psi) was applied hydraulically to deform the sample in an equi-biaxial stress state. We neglect the bending stresses since the thickness of the sheet is significantly smaller than the in-plane dimensions. Images of the sample’s central region were recorded for DIC. The DIC data was then used to compute the in-plane strain components. Major strain is aligned with the transverse direction and minor strain is aligned with rolling direction of the sheet. The biaxial r-value was calculated using \( \tau_b = \frac{\varepsilon_{90}}{\varepsilon_0} \) at an effective strain of 0.6 (maximum measured strain).

The stress-strain curves and the r-values of the sheet were measured using uniaxial tensile testing following the ASTM standard B557-15. The tensile tests were done on samples cut at 0° (longitudinal), 45° (diagonal) and 90° (transverse) to the rolling direction as shown in Figure 3 (b). The measured r-values are averaged values between 9% and 11% strain. The measured yield strengths and the r-values in the three orientations and that from bulge test are discussed in the following section along with the VPSC model predictions.

3. Crystal plasticity modelling
As discussed in the introduction, in the current work we have used the BBC2008 yield criterion [6, 7] to predict the finite element based FLD in combination with the Marciniak-Kuczynski (M-K) criterion [1, 4]. The BBC2008 yield criterion has 16 coefficients which are determined from the yield strengths and r-values measured every 15° to the rolling direction, and the biaxial yield strength and r-value. As described in the above section, we only measured the uniaxial mechanical properties at 0°, 45° and 90° to the rolling direction, along with the biaxial mechanical properties. To predict the rest of the anisotropic material properties required for the BBC2008 yield criterion, we employed the visco-plastic self-consistent (VPSC) model [8].

3.1. Visco-plastic self-consistent (VPSC) modelling
During plastic forming, the contribution to deformation from elasticity is negligible in comparison to the plastic component. In addition, once the elasto-plastic transition is over, the evolution of stress in the grains is controlled by crystallographic slip activity. As a consequence, in the VPSC formulation, elasticity is disregarded and only the plastic contribution to the deformation is taken into account [8].

In the VPSC model, a polycrystalline material is represented by means of weighted orientations. The orientations represent grains and the weights represent their volume fractions. The latter are chosen to reproduce the initial texture of the material. Each grain is treated as an ellipsoidal visco-plastic inclusion [10, 11] embedded in an effectively visco-plastic medium. Both inclusion and medium have fully anisotropic properties. The effective medium represents the ‘average’ environment ‘seen’ by each grain [12, 13]. Deformation is based on crystal plasticity mechanisms (slip) activated by a resolved shear stress. During each deformation increment, the single crystal constitutive behavior describes the grain-level response which is then solved simultaneously with the self-consistency criterion. This maintains the grain-level stresses and strain rates to be consistent with the boundary conditions imposed on the surrounding polycrystalline aggregates. Realistic hardening evolution is accounted for in the VPSC code by using an extended Voce law to describe the evolution of the critical resolved shear stress with deformation as shown below:

\[
\tau = \tau_0 + (\tau_1 + \theta_1 \gamma) \left( 1 - e^{-\frac{\theta_0}{\tau_1}} \right)
\]

where \( \tau \) is the critical resolved shear stress, \( \gamma \) accumulated shear in the grain, \( \tau_0 \) is initial critical resolved shear stress, \( \theta_1 \) is the asymptotic hardening rate and \( \tau_1 + \tau_1 \) is the back extrapolated threshold stress.

3.2. Calibrating the parameters in the VPSC Model
Plastic deformation of a crystal is facilitated by crystallographic slip in various slip systems. For aluminum alloys, which have a face centered cubic (FCC) crystal structure, \{110\} < 111 > slip system is considered to accommodate the plastic deformation at room temperature: This slip system is defined
using a set of single-crystal plasticity parameters. We estimated the hardening parameters (see Equation 1) in the constitutive behavior used in the VPSC model by curve fitting the bulge test results, as shown in Figure 3 (a). The values of the hardening parameters found by this procedure are summarized in Table 1.

Table 1. Voce hardening fitting parameter in VPSC model.

| $\tau_0$ | $\tau_1$ | $\theta_0$ | $\theta_1$ |
|---------|----------|------------|------------|
| 62      | 133      | 650        | 20         |

The calibrated VPSC model was then used to predict the flow curves in uniaxial tension in the longitudinal, transverse and diagonal orientations relative to the rolling direction. As can be seen from Figure 3 (b), the predictions are in good agreement with the measured stress-strain curves.

![Figure 3](image_url)

Figure 3. (a) Fit of the measured bulge test results using the VPSC model to calibrate the fitting parameters; (b) Measured stress-strain curves and the prediction of the flow curves in uniaxial tension in the longitudinal (L), transverse (T) and diagonal (D) orientations relative to the rolling direction using the calibrated VPSC model.

The calibrated VPSC model was then used to predict the yield strength and $r$-value every 15° to the rolling direction. The predicted results and measured data for the uniaxial case at 0°, 45° and 90° orientations to the rolling direction, as well as for the biaxial case, are presented in Table 2. The yield strengths correspond to an equivalent stress at 0.2% strain for both the uniaxial and biaxial deformation. The $r$-values were calculated at a strains of 10%.

Table 2. Yield strengths and $r$-values predicted using the VPSC model along with the measured data where available.

|       | $\sigma_{0^\circ}$ | $\sigma_{15^\circ}$ | $\sigma_{30^\circ}$ | $\sigma_{45^\circ}$ | $\sigma_{60^\circ}$ | $\sigma_{75^\circ}$ | $\sigma_{90^\circ}$ | $\sigma_{bl}$ |
|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------|
| VPSC  | 123.04            | 122.26            | 118.95            | 117.04            | 117.93            | 120.15            | 121.02            | 123.16      |
|       | 124.65            | 117.43            | 123.82            |                   |                   |                   |                   |             |

|       | $r_{0^\circ}$ | $r_{15^\circ}$ | $r_{30^\circ}$ | $r_{45^\circ}$ | $r_{60^\circ}$ | $r_{75^\circ}$ | $r_{90^\circ}$ | $r_{bi}$ |
|-------|--------------|----------------|----------------|----------------|----------------|----------------|----------------|---------|
| VPSC  | 0.58         | 0.67           | 0.87           | 0.99           | 0.99           | 0.87           | 0.76           | 1.04    |
|       | 0.62         | 1.00           | 0.737          | 1.09           |               |               |               |         |

In the next section, we show how the above VPSC predicted results and the measured data, where available, is used to identify the 16 parameters in the BBC2008 yield criterion.
4. Finite element based prediction of FLD
In the commercial FE package ABAQUS/Explicit, the M-K criterion for FLD prediction can only be used with the isotropic von Mises yield criterion. In order to use the anisotropic BBC2008 yield criterion we have devised a workaround for this limitation. Our technique involves a sequentially coupled, two stage FE model of a square piece of aluminum sheet (meshed using a single shell element, S4R) being deformed along various strain paths with strain ratios ranging from -0.5 (uniaxial tension) to +1.0 (equibiaxial tension) in steps of 0.1. In the first stage, we model the deformation of the sheet sample for the above strain ratios using the anisotropic BBC2008 yield criterion. At the end of this stage, the output flow curves from the various strain paths are extracted and fed into a second stage. In the second stage, for a given strain path, the model uses the corresponding flow curve from the first stage and computes the limit strain using the M-K criterion. The limit strains for the strain ratios ranging from -0.5 to +1.0 are collected and plotted in principal strain space to obtain the FLD, as shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** The flow chart for the prediction of the FLD using a multi-scale technique that makes use of limited mechanical testing, VPSC modeling, FE modeling using the BBC2008 anisotropic yield criterion and the M-K criterion.

The first stage of the FE model uses the BBC2008 yield criterion. A BBC2008 formulation was developed to provide an accurate description of the yield surface of aluminum alloys. As described in the previous section, the mechanical properties predicted using the VPSC model along with the mechanical test results where available (i.e., the data presented in Table 2) are used to identify the 16 coefficients using the procedure described in [7]. The first stage only serves to identify the flow curves for the strain ratios ranging from -0.5 to +1.0.

The second stage FE model uses the identified flow curves from the first stage for the corresponding strain paths and computes the limit strain using the M-K criterion. In the M-K analysis (see [1] for more details), virtual thickness imperfections are introduced as grooves to simulate preexisting defects in an otherwise uniform sheet material. In the current work we use 100 imperfections oriented at 0°, 45°, 90° and 135° to the rolling direction. ABAQUS/Explicit computes the deformation field inside each groove as a result of the applied loading outside of the groove. Necking is considered to occur when the ratio of the deformation in the groove relative to the nominal deformation (outside the groove) is greater than a critical value, generally taken to be 10. In ABAQUS/Explicit, the M-K criterion can alternatively be solely based on non-convergence of the equilibrium and compatibility equations [14]. We have used the latter approach in the current work. In the following sub-section we discuss the results obtained from our multiscale technique.

4.1. Results
For prediction of the FLD, we used the plane strain tension limit strain (FLDₚ) to calibrate the non-homogeneity parameter in the M-K criterion. Even though, in theory, calibration of the non-homogeneity parameter in the M-K criterion can be done using the limit strain for any strain path, e.g.,
equi-biaxial tension, plane strain tension or uniaxial tension etc, our extensive numerical trials have shown that calibrating with the plane strain tension limit strain is the most robust for FLD prediction. The calibrated model was then used to predict the FLD for the AA5182-O sheet at 1 mm gauge, the result of which is shown in Figure 5 along with the measured FLD. The graph shows that the predicted FLD using our multiscale approach employing the BBC2008 anisotropic yield criterion is in excellent agreement with the measured FLD. The graph also shows the superiority of our technique compared to the prediction using the default von Mises yield criterion available in ABAQUS/Explicit.

![Predicted FLD using the BBC2008 and von Mises yield criteria along with the measured FLD for the AA5182-O sheet at 1 mm gauge.](image)

We applied our technique to predict the FLD for thicker 1.5 mm gauge sheet of the same material (AA5182-O) simply by changing the element shell thickness in the FE model. We used the same non-homogeneity parameter as for the 1 mm sheet because we believe that the imperfections do not change much with gauge since these sheets are commercially produced by flat rolling using the same manufacturing assets. The results are presented in Figure 6(a) which show that the predicted FLD is in reasonable agreement with the measured FLD. Similarly we predicted the FLD for a sheet thickness of 0.85 mm of the same material and compared it with the measured FLD, as shown in Figure 6(b). The prediction is in a fairly good agreement with the measured FLD, although not as good as for the thinner gauge in Figure 6(b), especially in the “stretching” region (right hand side) of the FLD which we believe is probably the limitation of the predictive capability of this technique. Overall though, this shows the robustness and the excellent predictive capability of our multiscale technique for FLD prediction even when the model calibration was done at a different sheet gauge.

It should be noted that although the M-K criterion for predicting limit strain has an intuitive physical background, it also has its own advantages and disadvantages. As shown in the present work, the M-K criterion predicts the limit strains with an engineering degree of accuracy, while taking into account the influence of different process and material parameters. However, the predicted limit strains are very sensitive to the non-homogeneity parameter used in the model. As we have shown in Figure 5, the predicted FLD using the M-K criterion is very sensitive to the constitutive equation (isotropic vs anisotropic) used.
5. Summary
In summary, we have presented a multiscale modeling scheme for FLD prediction. Our technique involves only limited mechanical testings (uniaxial tensile, plane strain tension and equi-biaxial bulge), combined with VPSC modeling and sequentially coupled, two-stage FE modeling employing the BBC2008 anisotropic yield criterion and the M-K criterion for predicting the limit strains. Our predicted FLD for aluminum alloy AA5182-O at 1 mm gauge is in good agreement with the measured FLD, not only at the calibrated gauge, but also at various gauges in its vicinity, the agreement is reasonable.

Instead of using 13 different mechanical tests as in a traditional FLD measurement within Novelis, our technique uses just three test geometries along with the as-rolled sheet texture data. The turnaround time is consequently far less than that for traditional laboratory measurement of the FLD. This is especially advantageous to a metals supplier such as Novelis during alloy design. Moreover, we have shown the superiority of our method compared to using the default isotropic von Mises yield criterion.

In the future we plan to implement the M-K criterion directly into the VPSC code to predict the FLD, thus eliminating the need for the FE computations.

References
[1] Banabic D 2010 Computer Methods In Materials Science 10
[2] Keeler S and Backhofen W 1964 ASM Transactions Quarterly 56 25
[3] Goodwin G 1968 SAE Paper 680093
[4] Marciniak Z and Kuczynski K 1967 International Journal of Mechanical Sciences 9 609
[5] Banabic B 2010 Sheet Metal Forming Processes - Constitutive Modelling and Numerical Simulation
[6] Comsa D-S, and Banabic D 2008 Numisheet 2008, Interlaken, Switzerland
[7] Vhr M, Halikovic M, Starman B, Stok B and Comsa D-S 2014 European Journal of Mechanics A/Solids 45 59
[8] Tome C and Lebensohn R 2009 Manual for VISCO-PLASTIC SELF-CONSISTENT (VPSC) code Version 7c
[9] Hotz W and Timm J 2008 Numisheet 2008, Interlaken, Switzerland
[10] Eshelby J 1957 Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences 376
[11] Eshelby J 1959 Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences 561
[12] Kroner E 1961 Acta Metallurgica 9 155.
[13] Hutchinson J 1976 Proceedings of the Royal Society of London Series a-Mathematical and Physical Sciences 348.
[14] ABAQUS 2016 ABAQUS Documentation, Dassault Systèmes, Providence, RI, USA.