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A COMPUTATIONAL APPROACH FOR FORMING LIMIT DIAGRAM (FLD) EVALUATION AT ELEVATED TEMPERATURES FOR ALUMINIUM ALLOYS

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INTRODUCTION

Formability is the ability of sheet metal to undergo shape change without failure by the through-thickness instability or localized necking (Paul, 2012; Jie et al., 2009). Forming limit diagrams (FLDs) have been extensively used in sheet metals to define the deformation limit. A typical FLD can be divided into two branches (Figure 1) depending on the sign of the loading ratio of major and minor plastic strain increments $\alpha = d\varepsilon_2/d\varepsilon_1$ in a standard forming test (proportional loading paths) (Paul, 2012; Jie et al., 2009; Min et al., 2010).

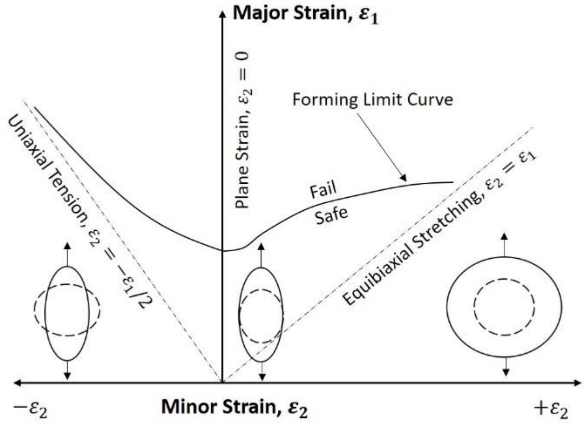


Figure 1. Standard forming limit curve (FLC) covering a range of loading ratios $\alpha = d\varepsilon_2/d\varepsilon_1$. Left branch is from uniaxial tension to plane strain ($-0.5 \leq \alpha \leq 0$), while right branch is from plane strain to equibiaxial stretching ($0 \leq \alpha \leq 1$).

Formability of aluminium alloy sheets has been found to be enhanced with increasing temperature during hot forming process. The strain rate also plays a prominent role but with negative effect. However, determining FLDs experimentally at hot forming conditions is time-consuming and costly. Our aim is to develop reliable computer-based models for FLD evaluation at such conditions. The traditional Marciniak and Kuczynski (1967) model suffers from the sensitivities regarding the choice of the initial geometric imperfection ratio, yield criterion, temperature-dependent hardening exponent and strain rate sensitivity factor, thus it is case-sensitive requiring careful calibration. This study explores the feasibility of combining simpler FLD models with a ductile fracture-based criteria and existing temperature-dependent flow stress curve calculation capability in JMatPro® (Guo et al., 2007, 2008), aiming at tackling the effect of temperature and strain rate on the FLDs of a series of aluminium alloy sheets.

MODELLING FLD AT ELEVATED TEMPERATURES (MODIFIED HBW-CLIFT CRITERIA)

With the Von Mises yield criterion and a power-law constitutive law, Hill's zero extension model (Hill, 1952) is used for the left branch of FLD, assuming a local neck will form at an angle to the direction of the major principal stress. Bressan and William's theory (Bressan & William, 1983) of biaxial stretching is used for the right branch, assuming the shear instability starts when the local shear stress along the pure shear strain direction exceeds a critical value. The joint model is named HBW.

$$\text{Left branch (H):} \quad \begin{cases} \varepsilon_{major} = \dfrac{\varepsilon_p}{1+\alpha} \\ \varepsilon_{minor} = \dfrac{\alpha\varepsilon_p}{1+\alpha} \end{cases} \qquad \text{Right branch (BW):}$$

$$\begin{cases} \varepsilon_{major} = \dfrac{\varepsilon_p}{\sqrt{1+\alpha+\alpha^2}} \left(\dfrac{\sqrt{1+\alpha+\alpha^2}}{\sqrt{1+\alpha}} \right)^{1/n} \\ \varepsilon_{minor} = \dfrac{\alpha\varepsilon_p}{\sqrt{1+\alpha+\alpha^2}} \left(\dfrac{\sqrt{1+\alpha+\alpha^2}}{\sqrt{1+\alpha}} \right)^{1/n} \end{cases} \tag{1}$$

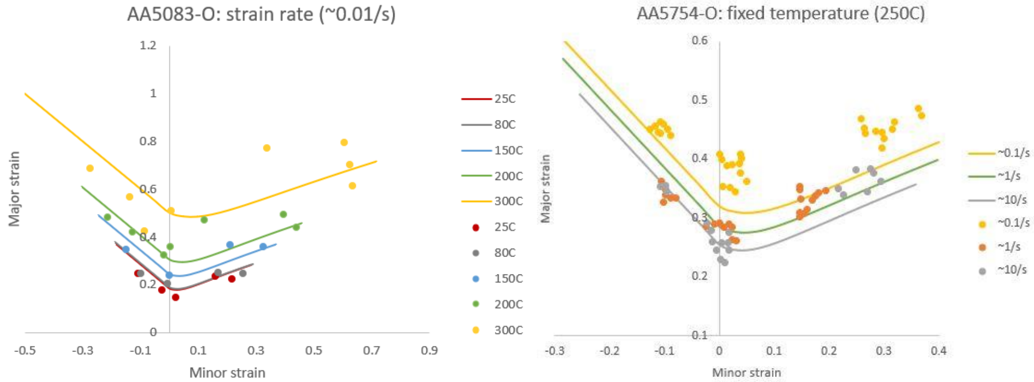
Note we have modified the original HBW criteria for room temperature (RT) FLD calculation by replacing the uniform elongation term (equivalent to the hardening exponent n) with a characteristic elongation term ε_p (the lowest point in a forming limit curve (FLC), or FLC0, at $\alpha = 0$, approximated to be half the uniaxial tensile limit strain in a flow stress curve at $\alpha = -0.5$). This is to provide some flexibility in tackling strain rate and temperature dependence. A similar form to the Clift ductile fracture criteria (Clift et al., 1990) is adopted to determine ε_p based on the flow stress curve at actual temperature and strain rate (Eq. 2).

$$\int_0^{2\varepsilon_p} \sigma d\varepsilon = C \tag{2}$$

where C is a material-specific constant to be approximately calculated from the reference flow stress curve at RT. All the flow stress curves here, particularly the parameters n and ε_p in Eq. (1), are calculated from JMatPro®. The appropriate strain-rate and temperature dependency has been modeled by incorporating high temperature deformation mechanisms such as precipitation strengthening and flow softening stemming from competition between dislocation glide and climb (Guo et al., 2007, 2008).

CASE STUDIES OF FLD CALCULATION FOR ALUMINIUM ALLOYS

The calculated FLDs of two example aluminium alloys (AA5083 and AA5754) at either different strain rates or different temperatures using the above approach are shown in Figure 2. The predicted results agree reasonably well with the reported data in literature. The general trend is captured such that FLC shifts up with increasing temperature or decreasing strain rate, which is attributed to the enhanced flow softening and thus an increased tensile limit strain. The proposed analytical approach provides further insight on the correlation between the tensile flow behavior and formability of aluminium alloy sheets. It can be extended to other materials and further aid the sheet metal formability evaluation and materials selection in industry.



(a) (b)

Figure 2. FLD prediction of two example aluminium alloys: (a) AA5083-O at constant strain rate ~0.01/s but different temperatures (Naka et al, 2001); (b) AA5754-O at constant temperature 250ºC but different strain rates (Shao et al, 2016).

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KEYWORDS

Forming limit curve (FLC), High temperature, Flow stress curve, Characteristic elongation, JMatPro®

A computational approach for forming limit diagram (FLD) evaluation at elevated temperatures for aluminium alloys

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Introduction

Formability is the ability of sheet metals to undergo shape change without failure [1,2]. Forming limit diagrams (FLDs) are used to define the deformation limit (Fig. 1). Formability of Al alloy sheets enhances with increasing temperature. However, experimental FLDs tests at hot forming conditions are time-consuming and costly. The Marciniak & Kuczynski model [3] suffers from case-sensitive requirement for careful parameter calibration. Here a computer-based model at such conditions is developed and validated for FLD evaluation on a variety of Al alloy sheets.

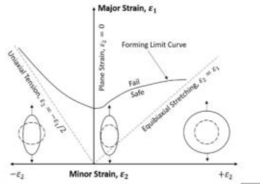


Fig. 1 A standard forming limit curve (FLC) covering a range of proportional loading ratios $\alpha = d\varepsilon_2/d\varepsilon_1$.

Left branch is from uniaxial tension to plane strain ($-0.5 \le \alpha \le 0$).

Right branch is from plane strain to equibiaxial stretching ($0 \le \alpha \le 1$)

Modelling of FLD at elevated temperatures

Modified joint HBW criterion for forming limit curves (FLCs):

1. *Hill's (H) local necking criterion [4] for left branch*

A local neck will form at the zero extension direction, i.e. with an angle $\varphi = \tan^{-1}\sqrt{-\alpha}$ to the direction of the major principal stress.

$$\begin{cases} \sigma_t = K\varepsilon_t^{\,n} \\ \dfrac{d\sigma_t}{d\varepsilon_t} = \sigma_t(1+\alpha) \end{cases} \rightarrow \varepsilon_t = \frac{n}{1+\alpha} \rightarrow \begin{cases} \varepsilon_1 = \dfrac{n}{1+\alpha} \\ \varepsilon_2 = \dfrac{\alpha n}{1+\alpha} \end{cases} \rightarrow \begin{cases} \varepsilon_1 = \dfrac{\varepsilon_p}{1+\alpha} \\ \varepsilon_2 = \dfrac{\alpha\varepsilon_p}{1+\alpha} \end{cases}$$

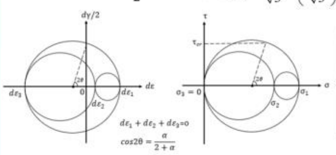
σ_t, ε_t	True stress, strain
K	Strength coefficient
n	Hardening exponent
ε_p	Characteristic elongation

The original uniform elongation ($\approx n$) is replaced by ε_p (lowest point in FLC, or FLC0, at $\alpha = 0$), to provide flexibility in tackling strain rate and temperature dependence.

2. *Bressan and William's (BW) shear instability theory [5] for right branch*

In biaxial stretching, a local neck will initiate in the direction of pure shear when the shear stress exceeds a critical value, determined by matching **BW** with **H** at $\alpha = 0$.

$$\tau_{cr} = \frac{\sigma_1}{2}\sin 2\theta \rightarrow (\tau_{cr})_{\alpha=0} = \frac{1}{\sqrt{3}}K\left(\frac{2\varepsilon_p}{\sqrt{3}}\right)^n \rightarrow \begin{cases} \sigma_1 \\ \sigma_2 \end{cases} \rightarrow \begin{cases} \sigma_{eq} \\ \varepsilon_{eq} \end{cases}$$



$$\begin{cases} \varepsilon_2 = \dfrac{\varepsilon_p}{\sqrt{1+\alpha+\alpha^2}}\left(\dfrac{\sqrt{1+\alpha+\alpha^2}}{\sqrt{1+\alpha}}\right)^{1/n} \\ \varepsilon_1 = \dfrac{\alpha\varepsilon_p}{\sqrt{1+\alpha+\alpha^2}}\left(\dfrac{\sqrt{1+\alpha+\alpha^2}}{\sqrt{1+\alpha}}\right)^{1/n} \end{cases}$$

Modified Clift ductile fracture-based criterion [6] for ε_p or FLC0:

The major strain at $\alpha = -0.5$ ($2\varepsilon_p$ or 2FLC0) at a given temperature and strain rate is approximated to be the uniaxial tensile limit strain in a flow stress curve at the same condition. The original fracture strain in Clift criterion is replaced by $2\varepsilon_p$:

$$\int_0^{2\varepsilon_p} \sigma \, d\varepsilon = C$$

C is a material-specific constant to be determined from the reference flow stress curve at room temperature

Flow stress curve capability in JMatPro®:

Calculate σ_t, ε_t, K and n with temperature and strain rate dependency [7,8]:

1) Dislocation glide hardening
- Precipitate strengthening
- Solution strengthening
- Grain size (Hall-Petch)

2) Flow softening
- Dislocation climb

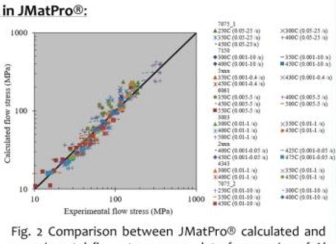


Fig. 2 Comparison between JMatPro® calculated and experimental flow stress curve data for a series of Al alloys at different temperatures and strain rates

Simulation of FLDs at elevated temperatures

FLC0 evaluation of a series of Al alloys over a range of test conditions:

Computational scheme:

Reference flow stress curve at RT with no strain rate dependency (JMatPro®)

Already known FLC0 at reference state → Clift → Material-specific constant C

Actual flow stress curve at a given temperature and strain rate condition (JMatPro®)

Material-specific constant C → Clift → Actual FLC0 → HBW / JMatPro® → Full FLC at the given condition

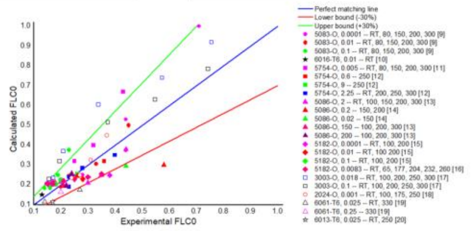


Fig. 3 Comparison between reported and calculated FLC0 for a series of Al alloys at various strain rates and temperatures.

FLC0 consistently increases with increasing temperature at each given strain rate, or with decreasing strain rate at each elevated temperature. Similar trend is also reflected in the entire FLC (Fig. 4). This can be attributed to the enhanced flow softening and thus an increased tensile limit strain. Majority of predicted FLC0 are found to match reasonably well within 30% of the reported values. Improvement is yet needed at relatively very high temperatures with very low strain rates.

Full FLDs for four example Al alloys:

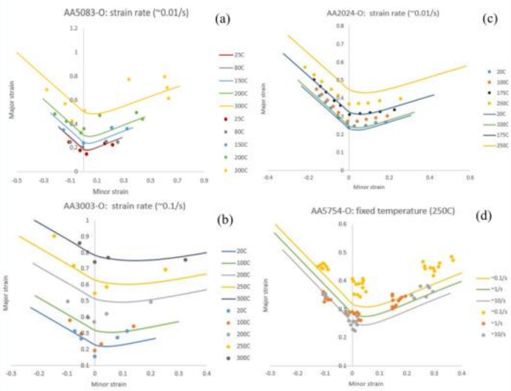


Fig. 4 FLD prediction of four example Al alloys: (a) AA5083-O [9] and (b) AA5182-O [15] at constant strain rate but different temperatures; (c) AA5086-O [13] and (d) AA5754-O [12] at constant elevated temperature but different strain rates

Conclusions

A computational approach based on modified HBW-Clift criteria and JMatPro® flow stress capability is explored to tackle the effect of strain rate and temperature on the evaluation of FLD for Al alloys. The approach provides further insight on the correlation between the tensile flow behaviour and formability. It can be extended to other materials and further aid the materials selection in industry.

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