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Technical Paper

Prediction of complete forming limit diagram from tensile properties of various steel sheets by a nonlinear regression based approach

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ABSTRACT

Experimental Forming Limit Curve (FLC) and tensile properties of various steel grades are collected from literatures to validate the proposed model. The experimental results show that the ultimate tensile stress (σ_{UTS}), total elongation (ε_t), coefficient of normal anisotropy (r), tensile strain hardening exponent (n) and sheet thickness (t) are strongly related to the plane strain forming limit (FLC_0) values for steel sheets. A nonlinear regression equation is proposed to predict FLC_0 from uniaxial tensile properties like σ_{UTS}, ε_t, r, n and t. To verify the predictive capability of the proposed equation, predicted FLC_0 values for fifty six steel grades in various thickness and strength ranges are compared with experimentally measured FLC_0 values. It is observed that the newly developed nonlinear regression equation predicts well the FLC_0 values.

Left side of the strain-based FLC is calculated from a criterion (a line with slope of −1) which is normally well matched with experimental observation. Right side of the strain-based FLC is calculated from modified Keeler–Brazier power equation. In the original Keeler–Brazier power equation for the right side of the FLC the exponent is considered as 0.5, while experimental finding revels that it varies systematically with FLC_0. Complete strain-based FLCs calculated from proposed method are matched well with experimental FLCs for various automotive steel grades like IF, IF 340, DP 780, TRIP 780 and TWIP 940 steels.

1. Introduction

Sheet metal forming is extensively used for producing various automotive and aeronautic structural components [1,2]. Estimation of material formability plays a key role in evaluating the workability of sheet metals and diagnosing production problems in the forming processes. Sheet metal formability is usually limited by the occurrence of localized necking. Forming limit diagram (FLD) is commonly used to experimentally characterize the formability of sheet metals. A schematic of FLD is illustrated in Fig. 1. A typical FLD shows the major in-plane strain on the vertical axis and the minor in-plane strain on the horizontal axis. The FLD is essential to find out whether the amount of deformation exceeds the forming limit at any point of the formed part. Keeler and Backofen [3] and Goodwin [4] are the pioneers of introduction of FLD. Forming Limit Curve (FLC) is a line on FLD and which divide safe levels of strains from unsafe ones. FLC_0 denotes the lowest point of the FLC which lies near the plane-strain state. Limit strains in FLC can be higher than tensile uniform elongation (ε_{UE}), because the geometrical constraints prevent diffuse necking during biaxial sheet deformation.

FLC is experimentally determined by conducting hemispherical/flat-bottom punch stretching tests up to the onset of necking on gridded blanks. The experimental strain measurement procedure form gridded sample is costly, laborious and it involves both skill and care in order to determine accurate FLC. As a consequence, analytical and numerical procedures to determine FLC are developed. FLC prediction by analytical bifurcation method was initially introduced by Swift [5] and Hill [6] for plane stress condition. Latter Storen and Rice [7], and Hutchinson et al. [8,9] also used bifurcation method to determine FLC analytically. Marciniak and Kuczynski [10] used the concept of geometrical imperfection which is introduced by thickness heterogeneity to determine FLC numerically. Keeler and Brazier [11] and Raghavan et al. [12] developed empirical formula to predict FLC. In the present work a nonlinear regression equation is developed to predict the entire FLC for steel sheets. Researchers used regression equations to predict hole expansion ratio [13–15] and FLC_0 [11,12] effectively, but for entire FLC such type of investigation is not noticed by the author. Therefore, the context of present work is justified.

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Nomenclature

FLD	Forming limit diagram
FLC	Forming limit curve
FLC_0	Plane strain forming limit curve
σ_{YS}	Tensile yield stress
σ_{UTS}	Ultimate tensile stress
ε_t	Total tensile strain
ε_{UE}	Uniform tensile strain
n	Tensile strain hardening exponent
r	Coefficient of normal anisotropy
t	Sheet thickness
ε_1	Major strain
ε_2	Minor strain
ε_3	Thickness strain
σ_1	Major stress
σ_2	Minor stress
ε_{eq}	von Mises equivalent strain
σ_{eq}	von Mises equivalent stress
K	Strain hardening coefficient
α	Stress ratio
β	Strain rate ratio
FLSC	Stress based forming limit curve
DD	Deep drawn
IF	Interstitial free
BH	Bake hardened
MA	Micro alloyed
DP	Dual phase
TRIP	Transformation induced plasticity
TWIP	Twin induced plasticity

2. Different empirical equations for prediction of FLC_0

Keeler and Brazier [11] developed a standard-shaped FLC that separates major–minor strain points for safe areas from unsafe areas. The FLC_0 increases with increase in the work hardening exponent (n) and increasing sheet thicknesses (t). Keeler [16] showed that the equation is only valid for thickness values of up to 3.1 mm.

$$FLC_0 = \ln\left[1 + \left(\frac{23.3 + 14.13t}{100}\right)\frac{n}{0.21}\right] \quad (1)$$

where $n \le 0.21$, $t \le 3.1$ and t is in mm.

Eq. (1) indicates a proportional relationship between n and FLC_0. Shi and Gelisse [17] reported that the empirical Keeler and Brazier equation is still popular in press shops in North America.

Raghavan et al. [12] proposed a different approach to predict FLC_0 which increases with increasing total elongation (ε_t) and sheet thickness (t).

$$FLC_0 = 2.78 + 3.24t + 0.892\varepsilon_t \quad (2)$$

3. Data collection

Experimental data for the subsequent analysis are collected from published literatures [12,18–26] for wide range of steel grades. The details of steels, tensile properties, sheet thickness and FLC_0 are tabulated in Appendix A (Table A1). FLC_0 is the forming limit for plane strain condition ($\alpha = 0$) and FLC_b represents extreme right of the FLC (normally $\alpha = 1$). The position of FLC_0 and FLC_b are shown in Fig. 1 schematically. The collected tensile properties are yield stress (σ_{YS}), ultimate tensile stress (σ_{UTS}), coefficient of normal anisotropy (r), total tensile strain (ε_t), uniform tensile strain (ε_{UE}) and strain hardening exponent (n). The sheet thickness is denoted as t and measured in millimetres. The collected steel sheet grades include: interstitial-free (IF), deep drawn (DD), bake hardened (BH), micro alloy (MA), dual phase (DP), transformation induced plasticity (TRIP), and twin induced plasticity (TWIP) steels. The details about experimental FLC_b for various steel grades are collected form published journal papers [19–26] and tabulated in Appendix A (Table A2). These experimental data will be used to establish correlations and validate models.

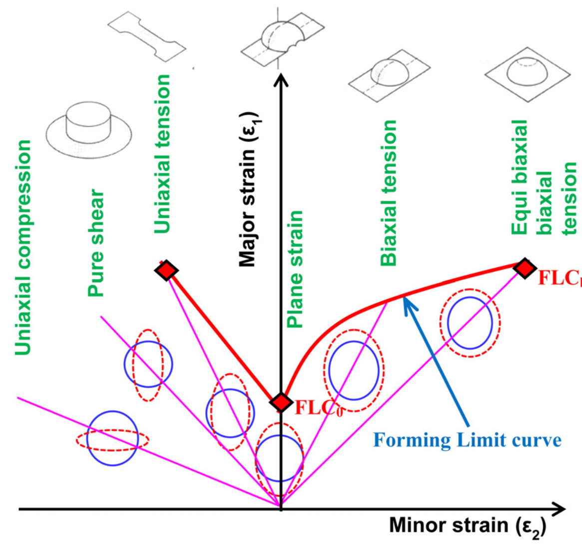

Fig. 1. Schematic diagram of forming limit diagram (FLD) indicating nature of deformation.

4. Nonlinear regression equation to predict FLC_0

Many researchers are tried to establish correlations between tensile properties and FLC_0 from beginning of the research on FLD. Keeler and Brazier [11] used a proportional relationship between FLC_0 and n. Ghazanfari and Assempour [27] also reported that increase in n results improvement in the formability of the materials. Raghavan et al. [12] used a proportional relationship FLC_0 between and ε_t. Blake et al. [19] reported a linear decay relationship between σ_{UTS} and FLC_0. It is also well established that the sheet metal formability in the drawing region (left side of the FLD) is influenced by coefficient of normal anisotropy (r) [28–35]. Coefficient of normal anisotropy (r) can be defined as the ratio of increment of width strain ($d\varepsilon_2$) and thickness strain ($d\varepsilon_3$) for uniaxial tensile loading.

$$r = \frac{d\varepsilon_2}{d\varepsilon_3} \quad (3)$$

However, accurate determination of increment of thickness strain is extremely difficult. By applying volume consistency condition ($d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 = 0$), Eq. (3) can be rewritten as

$$r = \frac{d\varepsilon_2}{-(d\varepsilon_1 + d\varepsilon_2)} \quad (4)$$

By rearranging Eq. (4), correlation between strain ratio (β) and r for uniaxial tension can be represented by Eq. (5).

$$\beta = \frac{-r}{1 + r} \quad (5)$$

As r is the measure of resistance to thickness strain, therefore it has a significant contribution in necking and hence sheet metal forming limits. Levy and Van Tyne [36] described that the slope of uniaxial tensile strain path in forming limit diagram depends upon the r. High r results higher slope of uniaxial tensile strain path in the forming limit diagram. Ghazanfari and Assempour [27] also