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Experimental Investigation and Theoretical Prediction of Forming Limit Diagram of DP600 Steel Sheets

Qiuli ZHENG[a,1], Jiaming YAN[a], Xiujuan AN[a], Jieqing LI[a] and Haoyang LIU[a]
[a] *Norinco Group' Air Ammunition Research Institute CO., LTD., Harbin, 150030, China*

Abstract. This work established strain-based forming limit diagrams (FLDs) for DP600 steel sheets by means of experimental investigation and theoretical prediction. The results showed that compared to the theoretical forming limit curve (FLC), predicted by Keeler equation, the theoretical FLCs predicted by the Hill'79 yield criterion, or the Logan-Hosford yield criterion, were more suitable for predicting the forming limit of DP600 steel sheets. Solutions from the analytical methods were compared to experimental FLD, established based on combining uniaxial tensile tests and hydraulic bulging tests, only with an error of 3 %, proving the rationality and accuracy of the theoretical prediction.

Keywords: Experimental investigation, theoretical prediction, forming limit.

1. Introduction

The forming limit diagram (FLD) is an effective experimental method that can be used to evaluate the formability of sheet metals [1-2].

Theoretical investigation on FLDs can be summarized into the following two categories: the first one is the classical bifurcation theory, namely, the diffuse instability theory proposed by Swift [3] and the localized instability theory proposed by Hill [4] and then the Swift model was further revised by Hora and Hora and Tong et al. [5-6]; the second one is based on the assumption that local initial inhomogeneity of sheet metal is the cause of necking, such as the M-K theory [7]. Further, combining plastic instability theory with the yield criterion, the limit combined strain data of metal sheet in plastic forming process can be predicted and the FLC can be obtained. Besides, Keeler and Brazier [8] and Raghavan et al. [9] proposed a simpler empirical formula to predict the FLC of metal materials. Besides, a new method proposed by prof. Mykola Chausov allows to determine not only the margin of plasticity, but also the fracture toughness of the material, which also has outstanding advantages [10].

In this work, the theoretical limit strain data of DP600 steel sheets was obtained by combining the Hill-Swift plastic instability theory with Hill'79 yield criterion and Logan-Hosford yield criterion. Meanwhile, as another analytical method, the theoretical FLC was also predicted by using the Keeler equation. Then, the theoretical FLCs have been

[1]Corresponding Author: Qiuli ZHENG, Norinco Group' Air Ammunition Research Institute CO., LTD., Harbin, 150030, China. E-mail: qiulizheng0210@163.com

compared and validated with the experimental FLC.

2. Mechanical Properties of DP600

The material tested in this work is commercially available DP600 steel sheets of a thickness of 1.2 mm. The anisotropy coefficient r_θ of sheet metal can be expressed by Eq. (1), which can be obtained by the uniaxial tensile tests:

$$r_\theta = \frac{\varepsilon_w}{\varepsilon_t} \tag{1}$$

where ε_w and ε_t refer to the strain in the direction of width and thickness, respectively, and θ is the tensile angle relative to the rolling direction. Before deformation, circular array grids of a diameter of $\emptyset 1$ mm were electrochemically etched on the surface of rectangular area of a length of 40 mm and a width of 15 mm in the central region of the tested specimens, as shown in Figure 1. After deformation, the strains in the direction of length (ε_l) and width (ε_w) of these deformed grids can be obtained by strain instrument. The tensile tests were carried out on an Instron-5569 electronic tensile testing machine with a speed of 2 mm/min. Then, the ε_t can be calculated based on the assumption of constant volume.

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \tag{2}$$

Generally, the r-value is measured before the necking of deformed specimens. For the three specimens with $\theta = 0°, 45°, 90°$ from the rolling direction, three repetitive tests were carried out to calculate the average values of r_0, r_{45} and r_{90}. Then the r-value can be calculated by:

$$r = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{3}$$

After deformation, it was obtained that $r_0 = 0.94$, $r_{45} = 1.12$, $r_{90} = 1.14$ and $r = 1.08$.

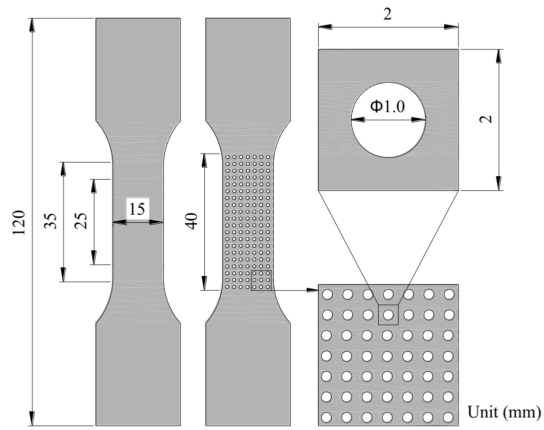

Figure 1. Grid shape and reference point marking for measurement of displacement.

Under quasi-static conditions with a strain rate of 0.001/s, the stress-strain curves of DP600 steel sheets in three directions are shown in Figure 2. It can be seen that the curve along 0 ° is 3 % lower than that along 45 ° or 90 °, while the difference between 45° and 90° can be neglected. Therefore, the DP600 steel tested in this work is not an ideal isotropic material, which exhibits slight anisotropy in the direction of 0°. Overall, the yield strength, tensile strength and total elongation are 306 MPa, 830 MPa and 28 %, respectively.

Assuming that the strain hardening law of DP600 steel sheets under the quasi-static uniaxial tensile condition is:

$$\sigma = K\varepsilon^{n} \tag{4}$$

where K is the hardening coefficient, n is the strain hardening exponent. By fitting of plastic stress-strain data, it was found that $K = 1101.57$ and $n = 0.189$.

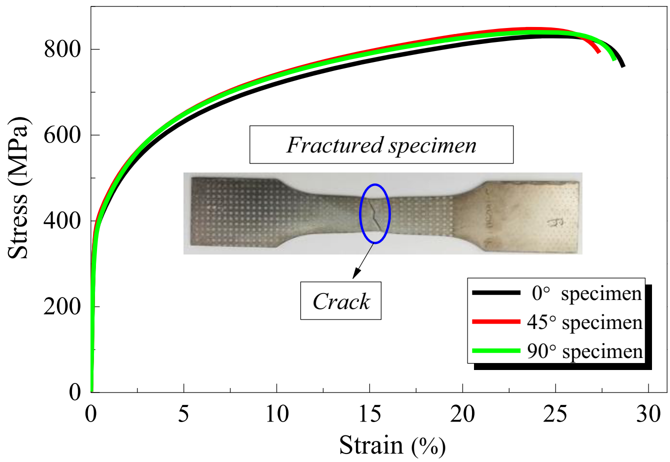

Figure 2. The fracture specimen and stress-strain curves of DP600 steel sheets.

3. Experimental Investigation

To reduce the friction between the conventional rigid punch and tested specimens, the forming limit tests of DP600 steel sheets were carried out by combining the uniaxial tensile tests and hydraulic bulging tests. The initial specimen geometries and fractured specimens under different strain paths are shown in Figure 3.

Figure 4 presents the combined strains and FLD of DP600 steel sheets under quasi-static forming conditions. Overall, 43 % major strain in equi-biaxial stretching strain path was observed at 43 % minor strain, 41 % major strain in uniaxial stretching strain path was observed at -20 % minor strain, and 18 % major strain in plane strain was observed.

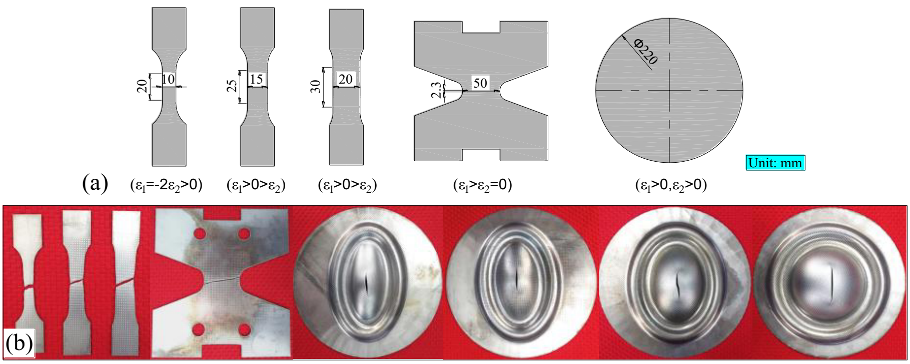

Figure 3. Initial specimen geometries (a) and fractured specimens (b) under different strain paths.

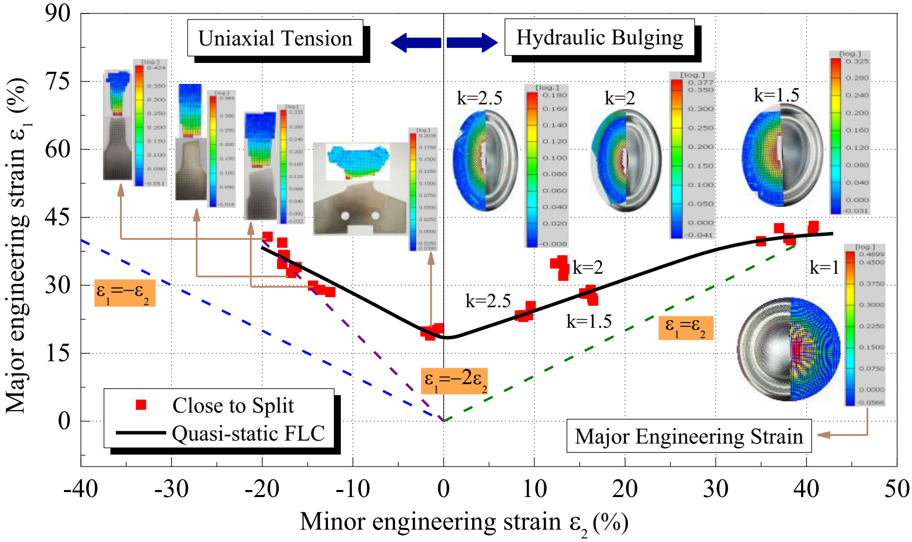

Figure 4. Experimental FLD of DP600 steel sheets.

4. Theoretical Prediction

The anisotropy of sheet metal was considered for the first time in the Hill48 yield criterion, where the anisotropy coefficient r was introduced [11]. However, it was found that the Hill48 yield criterion was not applicable for metal sheets with anisotropy coefficient less than 1, through a large number of experimental studies. Therefore, Hill proposed a second anisotropic yield criterion with universal significance on this basis in 1979. In terms of principal stresses σ_1, σ_2 and σ_3, the Hill79 yield criterion is defined as:

$$f|\sigma_2-\sigma_3|^M+g|\sigma_3-\sigma_1|^M+h|\sigma_1-\sigma_2|^M+a|2\sigma_1-\sigma_2-\sigma_3|^M+b|2\sigma_2-\sigma_3-\sigma_1|^M$$

$$+c|2\sigma_3-\sigma_2-\sigma_1|^M=\bar{\sigma}^M \tag{5}$$

where f, g, h, a, b and c are parameters related to the anisotropy coefficient r, and M is the material sensitivity index that can be obtained by the hydraulic bulging tests. According to the principle of plastic work, when a=b=f=g=0 and the anisotropic principal axis of the material coincides with the stress principal axis, the Eq. (5) will be applicable to metal materials with any r-value. Then the Eq. (5) can be simplified as:

$$|\sigma_1 + \sigma_2|^M + (1 + 2r)|\sigma_1 - \sigma_2|^M = 2(1 + r)\bar{\sigma}^M. \tag{6}$$

In addition, under the conditions of the plane stress state, Logan-Hosford [12] also proposed a yield criterion, considering the anisotropy of metal materials in the form:

$$|\sigma_1|^m + |\sigma_2|^m + r|\sigma_1 - \sigma_2|^m = (1 + r)\bar{\sigma}^m \tag{7}$$

where m is the parameter representing the shape of the yield surface. Mostly m = 6 is suitable for the body-centered cubic metals and m = 8 is suitable for the face-centered cubic metals.

There is a more convenient method that can be used as a reference for forming limit prediction, namely Keeler FLD. A certain correlation between the FLC and the thickness t and n-value of sheet metal was first found by Keeler and Brazier [13]. Then Raghavan et al. [14] and Green and Black [15] conducted a more in-depth research on FLDs.

The expression of Keeler equation is as follow:

$$\begin{cases} FLD_0 = \frac{n(23.3+14.134t)}{21} & (0 < t < 2.54\ mm) \\ FLD_0 = \frac{n(20+(20.669-1.938t)t)}{21} & (2.54 \le t \le 5.33\ mm) \\ FLD_0 = \frac{75.125n}{21} & (t \ge 5.33\ mm) \end{cases} \tag{8}$$

and the shape of FLD can be determined by the Eq. (9):

$$\begin{cases} \varepsilon_{maj} = FLD_0 + \varepsilon_{min}(0.027254\varepsilon_{min} - 1.1965) & \varepsilon_{min} < 0 \\ \varepsilon_{maj} = FLD_0 + \varepsilon_{min}(-0.008565\varepsilon_{min} + 0.784854) & \varepsilon_{min} > 0 \end{cases} \tag{9}$$

5. Analysis and Discussion

It can be seen from Figure 5 (a) that the FLCs, obtained by combining the Hill-Swift plastic instability theory with the Hill'79 yield criterion or the Logan-Hosford yield criterion, are very consistent in terms of contours. For the regions -20 % < ε_2 < 10% of FLC, these two theoretical FLCs are almost identical with the experimental fit, with an error of 3 %. While for the regions 10% < ε_2 < 20%, there is an error of about 10 % between these two theoretical FLCs and the distribution of strain data of FLC predicted by Hill'79 yield criterion is more uniform than that predicted by Logan-Hosford yield criterion. In addition, an error of about 20 % between the theoretical FLCs and experimental fit is observed when ε_2 > 20%, and the theoretical data falls within the safety zone below the experimental curve, which may lead to a slightly lower predicted safety line. From Figure 5 (b), it can be seen that the theoretical FLC predicted by the Keeler equation is similar to the experimental fit in terms of contours, but is 50 % higher overall;

and the theoretical data falls within the fracture zone above the experimental curve, which may lead to a significantly higher and inaccurate predicted safety line. Therefore, it can be concluded that compared to the theoretical FLC, predicted by Keeler equation, the theoretical FLCs predicted by the Hill'79 yield criterion or the Logan-Hosford yield criterion are more suitable for predicting the forming limit of DP600 steel sheets.

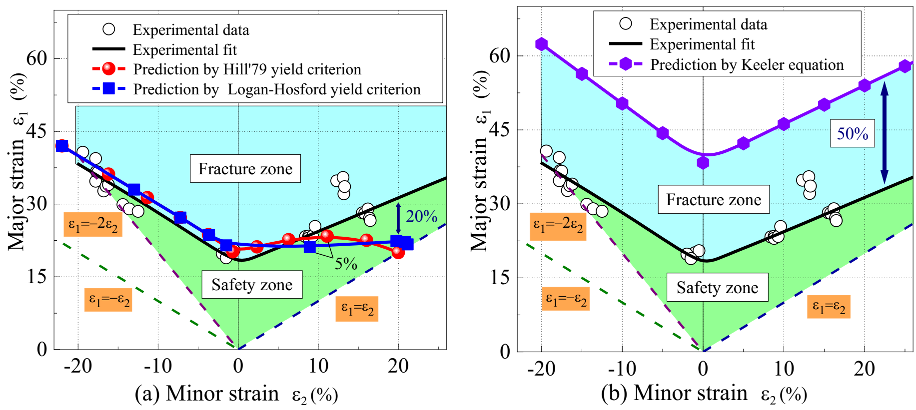

Figure 5. Comparison of experimental data to theoretical FLCs: (a) various yield criteria, (b) Keeler equation.

The FLCs predicted by Hill'79 yield criterion and Logan-Hosford yield criterion are shown in Figure 6 and Figure 7, respectively. It can be seen from Figure 6 (a) that changing the n-value does not shift the loading-path of the FLCs, indicating that the slope of the FLC predicted by Hill'79 yield criterion is independent of n-value. However, increasing the n-value remarkably raises the FLC, which results in a higher ε_1 for a given ε_2. Therefore, increasing the n-value can significantly improve the formability of DP600 steel sheets. As the strain path for uniaxial tensile test is a straight line with the slope of $-(1 + r)/r$ in the ε_1-ε_2 plane, increasing the r-value can shift the loading-path to the left, as shown in Figure 6 (b). The higher r-value has a favorable effect on the formability of DP600 material for the region of $\varepsilon_2 > 0$. On the other hand, the formability of DP600 material decreases gradually with the increase of r-value for the region of $\varepsilon_2 < 0$, and are independent of the r-value at plane strain conditions ($\varepsilon_2 = 0$), as shown in the partial enlargement on the top side of Figure 6 (b).

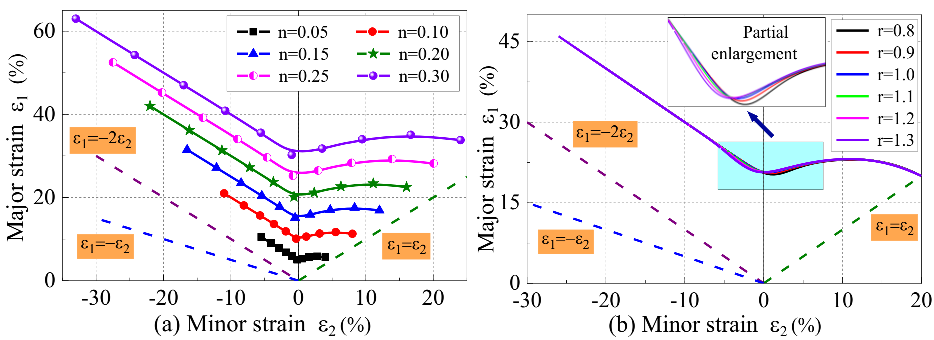

Figure 6. Theoretical prediction by Hill'79 yield criterion with various (a) n-value and (b) r-value.

Similar influence rules of r-value or n-value on the FLCs predicted by Logan-Hosford yield criterion have been observed, as shown in Figure 7. Figure 7 (a) shows that increasing the n-value can remarkably raise the FLC, meaning that the higher n-value is beneficial to improvement of formability of DP600 steel sheets. By comparing Figure 6 (a) and Figure 7 (a), it can be found that the effect of n-value on the FLCs predicted by Hill'79 yield criterion is almost exactly the same as that on the FLCs predicted by Logan-Hosford yield criterion. However, increasing the r-value has no effect on the regions $\varepsilon_2 > 0$ or $\varepsilon_2 < 0$ of FLCs predicted by Logan-Hosford yield criterion, but improves the contours near the plane strain loading-path, as shown in Figure 7 (b).

Therefore, it can be concluded that for materials with different n-values, the effects of the FLCs predicted by these two yield criterions are consistent; while for the materials with different r-values, the FLCs predicted by these two yield criterions are different, so the adopted yield criterion should be reasonably chosen according to the specific sheet conditions.

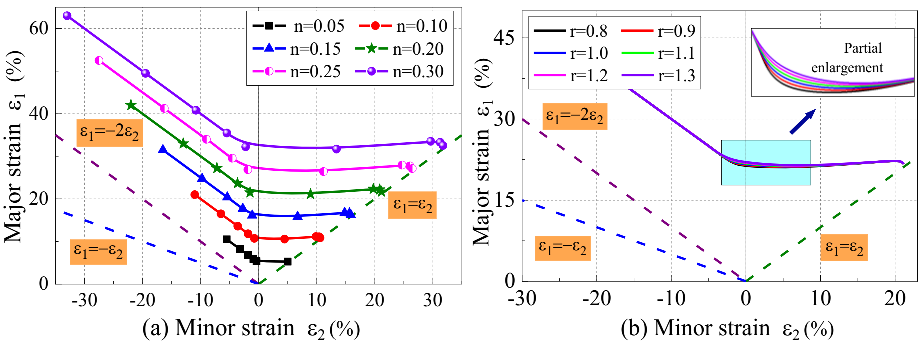

Figure 7. Theoretical prediction by Logan-Hosford yield criterion with various (a) n-value and (b) r-value.

6. Conclusions

(1) The experimental results showed that the limit major strain of DP600 material is 41 % under uniaxial tensile strain path, 43 % under biaxial tensile strain path and 18% under plane strain path.

(2) Applying the Hill'79 yield criterion and Logan-Hosford yield criterion to the forming limit models by Swift and Hill, analytical limit strains are obtained. The analytical FLCs are almost identical with the experimental fit, with an error of 3 %; while the theoretical FLC predicted by the Keeler equation is similar to the experimental fit in terms of contours, but is 50 % higher overall.

(3) The higher n-value is beneficial to improvement of overall FLCs predicted by Hill'79 yield criterion or Logan-Hosford yield criterion; while the higher r-value has a favorable effect on the FLCs predicted by Hill'79 yield criterion for $\varepsilon_2 > 0$ and on that predicted by Logan-Hosford yield criterion for $\varepsilon_2 = 0$.

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