Fracture Prediction for High-strength Steel Sheet Subjected to Draw-bending Using Forming Limit Stress Criterion

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Abstract. A fracture criterion for sheet metals subjected to draw-bending is investigated using the concept of the forming limit stress criterion. The test material used is a 1.0-mm-thick high-strength steel sheet with a tensile strength of 590 MPa. The specimen undergoes bending-unbending under tension when passing over the die profile. The drawing speed was set to 5-100 mm s⁻¹. The magnitude of true stress \( \sigma_{DB} \) when a specimen fractured has been precisely determined. Moreover, multiaxial tube expansion tests of the test material are performed to measure the forming limit stress \( \sigma_{PT} \) of the test material under plane-strain tension. It is found that \( \sigma_{DB} \) is larger than \( \sigma_{PT} \) by 2.8-6.3 %. Therefore, it is concluded that the forming limit stress criterion is effective as a fracture criterion in draw-bending.

1. Introduction

Draw-bending is one of the typical deformation modes in sheet metal forming. It causes serious thickness reduction to sheet metals and very often leads to fracture. Therefore, it is crucial to establish a fracture criterion for sheet metals subjected to draw-bending. A forming limit curve (FLC) [1] is commonly used for the prediction of sheet metal fracture. However, experimental results [2] and numerical analyses [3] suggest that FLCs notably depend on the strain paths. On the other hand, a forming limit stress curve (FLSC) is reported to be independent of strain paths [4]. Yoshida and coworkers measured the forming limit strains and forming limit stresses of an extruded aluminum alloy tube [5] and a steel tube [6], using the servo-controlled, combined tension-internal pressure testing apparatus [7], [8]. They found that forming limit stresses in stress space lie on a single curve, irrespective of the loading paths, when the observed equivalent stress-equivalent plastic strain curves for given linear and combined (two-stage) stress paths are on a single curve. Saito and Kuwabara [9] compared the forming limit stress and the draw-bending fracture of a 590 MPa dual-phase steel sheet. However, the drawing speed was 1 mm/s, much slower than those in industrial press forming processes.

The objective of this study is to clarify whether the forming limit stress criterion can be applied to
the fracture prediction of the sheet metals subjected to draw-bending with industrial forming speeds. A high-speed draw-bending testing machine has been developed to measure the fracture stresses of a 590 MPa high strength steel sheet subjected to draw-bending. The draw-bending fracture stresses are compared to the forming limit stress under plane strain tension measured using the multiaxial tube expansion testing method [10].

2. Experimental method

2.1. Test material

The test material used in this study was a 1.0 mm-thick high-strength steel sheet (JSC590R) with a tensile strength of 590 MPa. The work hardening characteristics and r-values at 0 and 90° to the rolling direction (RD) of the sample are listed in Table 1. Hereafter, the RD, TD and the thickness directions of the sample are defined as the x-, y- and z-axes, respectively.

### Table 1. Material properties of the test material.

| Tensile direction [°] | \( \sigma_{0.2} \) [MPa] | \( c^a \) [MPa] | \( n^b \) | \( \alpha^b \) | r-value \(^b\) |
|----------------------|----------------|----------------|--------|--------|--------|
| 0 (RD)               | 464            | 1043           | 0.177  | 0.0089 | 0.71   |
| 90 (TD)              | 486            | 1037           | 0.169  | 0.0094 | 1.02   |

\(^a\) Approximated using \( \sigma = c(\alpha + \varepsilon^p)^p \) for \( 0.002 \leq \varepsilon^p \leq 0.093 \).

\(^b\) Measured at nominal strain \( \varepsilon_n = 0.1 \).

2.2. Draw-bending test

Draw-bending experiments were carried out to experimentally determine the forming limit stress of the sheet metal subjected to draw-bending. Figure 1(a) shows a schematic diagram of the servo-controlled high-speed draw-bending testing machine developed in this study. The hydraulic cylinder A draws the specimen while the hydraulic cylinder B applies a back tensile force, which is kept constant by a relief valve, to the specimen. Thus, the specimen is subjected to draw-bending as it passes over the die profile. The drawing speed \( V_{DB} \) was chosen to be 5, 50 and 100 mm s\(^{-1}\). The die profile radius \( R \) was 4 mm. The RD of the test sample was taken to be parallel to the drawing direction.

Figure 1(b) shows the dimensions of the specimen used in this study. A square grid of 2×2 mm\(^2\) was printed on the outer surface of the specimen for strain measurement. The specimen was first bent along a bending line and then a drawing force was applied. The cross-sectional area of the drawn section decreases with the progress of drawing as the sheet edges have an arc shape. As a result, the back-tension for making the specimen fracture at the exit of the tool profile could be easily determined.

The strain components were measured at the positions adjacent to the localized necking area, 2 mm distant from the fracture surface, as shown in figure 2(a). The width strains were measured using the deformation of the square grids. The specimens were cut along the white lines by a wire electrical discharge machine for the measurement of thickness. The draw-bending stress \( \sigma_{DB} \) at which the specimen fractured was calculated using the cross-sectional area and the drawing force \( F \) measured by a load cell. Figure 2(b) shows the division of the cross-sectional area. It was found that the specimens fractured under plane strain tension at \( S_1 \) to \( S_5 \), while they fractured under uniaxial tension at \( S_6 \) and \( S_7 \). From this observation \( \sigma_{DB} \) was determined as follows:

\[
\sigma_{DB} = F - \sigma_{0.2}(S_6 + S_7) / (S_1 + S_2 + S_3 + S_4 + S_5)
\]

2.3. Multiaxial tube expansion test

Multiaxial tube expansion tests were performed to measure the forming limit stress \( \sigma_{PT} \) for the test material under plane strain tension. The servo-controlled multiaxial tube expansion testing machine [10] was used. An axial load and internal pressure were applied to a tubular specimen by a hydraulic
cylinder and pressure booster, respectively. Tubular specimens with an inner diameter of 53.9 mm and a length of 230 mm were fabricated by bending the sheet sample into a cylindrical shape and laser-welding the sheet edges together. Linear stress paths were applied to the tubular specimens; the true stress ratio was chosen to be $\sigma_x/\sigma_y = 2:1$. The equivalent plastic strain rates were approximately constant at $4 \times 10^{-4}$ s$^{-1}$. Details of the testing apparatus and testing method are given in [10].

3. Results and discussion

Figure 3 shows the distribution of strain components in the width direction of the fractured specimens; $\varepsilon_p^x \approx -0.3$, $-0.04 \leq \varepsilon_p^y \leq -0.01$, and $0.3 \leq \varepsilon_p^z \leq 0.35$ for a range of $-15 \leq y \leq 15$ mm. The drawing speed had little effect on the strain distribution within the limit of the experimental conditions. Therefore, it was concluded that the deformation mode of the fractured specimens was close to a plane strain tension for a range of $-15 \leq y \leq 15$ mm.

Figure 4 shows the measured results of $\sigma_{DB}$ and $\sigma_{PT}$. The values of $\sigma_{DB}$ is larger than $\sigma_{PT}$ by 2.8-6.3%. Therefore, $\sigma_{PT}$ can be used effectively as a fracture criterion for draw-bending with a margin of safety. The strain rates under draw-bending with $V_{DB} = 5, 50$ and $100$ mm·s$^{-1}$ are approximately 0.2, 2.5 and 4.9 s$^{-1}$, respectively, while the average strain rate under multiaxial tube expansion test was $5 \times 10^{-4}$ s$^{-1}$. $\sigma_{PT}$ is estimated to increase to 844, 853 and 856 MPa for strain rates of 0.2, 2.5 and 4.9 s$^{-1}$, respectively, assuming the constitutive model proposed by Kuroda et al. [11], which takes into account the strain rate effect on the flow stress. Thus, the values of $\sigma_{PT}$ become much closer to the measured values of $\sigma_{DB}$. Therefore, it is concluded that the predictive accuracy of $\sigma_{DB}$ is improved by using $\sigma_{PT}$ as a fracture criterion and by taking into account the strain rate effect in evaluating $\sigma_{PT}$.

Kim et al. [12] investigated the shear fracture of high strength steel sheets under draw-bending, and concluded that deformation-induced heating has a dominant effect on the occurrence of shear failure. For the material used in this study, however, the concept of forming limit stress criterion seems to work well, even without taking account of temperature effect, as a practical method for predicting the draw-bending fracture.
4. Concluding remarks

The forming limit stress $\sigma_{PT}$ under plane strain tension can be effectively used as a forming limit stress criterion for the draw-bending of the high-strength steel sheet with a margin of safety. The predictive accuracy of $\sigma_{DB}$ is further improved by taking into account the effect of the strain rate on the magnitude of $\sigma_{PT}$.

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