Influences of Materials’ Workhardening and Stretching Force on Onset of Necking under In-plane Stretch-Bending

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ABSTRACT

The necking limit of a sheet metal under stretch bending is much larger than that in uniaxial tension because of the existence of a strain gradient. This paper discusses the influences of materials’ workhardening and stretching force on the onset of necking under in-plane stretch-bending of sheet metals based on the experiment and its corresponding finite element (FE) simulation. To represent the workhardening of the material in the simulation, a combined Swift-Voce hardening model with a weighting coefficient µ was used. The anisotropy of sheets was considered using a sixth-order polynomial yield function. The results of experiment and simulation on three types of high-strength steel sheets are presented. From these results, it was found that the necking is more likely to occur for low workhardening materials under large stretching force, although the stretching can prevent the buckling of the sheet.

INTRODUCTION

In sheet metal forming operations such as deep drawing and bending, a sheet metal is subjected to a large strain beyond the uniform elongation limit of the material. Traditionally, the stress-strain curve is determined from the uniaxial tensile experiment, but a limitation of this type of test is that the necking of a specimen appears at a low strain level. To determine the large-strain stress-strain curves of sheet metals from the uniaxial tension experiment, some researchers tried to use the post-necking behavior [1-3], however, it is highly strain-rate sensitive, and it is affected by the stress triaxiality [4].

Instead of the uniaxial tension experiment, other types of experiments, such as bulge experiment [5, 6] and the simple shear experiment [7, 8] were proposed. However, the stress states (σ_ξ = σ_ψ = σ_b in the bulge and τ_{xy} in the simple shear) in these experiments are not equal to that in uniaxial tension (σ_x = σ_0). Alternatively, the present authors [9] proposed to use in-plane stretch-bending...
experiment, where the bent-surface strain is purely under uniaxial stress state, and furthermore, the limit strain is much larger than the uniform elongation limit under uniaxial tension. Thus the in-plane stretch-bending experiment possesses a high potential for the determination of large-strain stress-strain curves of sheet metals.

In the present work on the in-plane stretch bending, the influences of materials’ workhardening and the stretching force on the onset of necking were investigated based on the experiment on three levels of high-strength steel sheets (dual-phase type 590Y, 780Y and 980Y) and the corresponding FE simulation. Specifically for the discussion of materials’ workhardening characteristics, the combined Voce and Swift hardening model was used in the FE simulation.

**Combined Swift-Voce Hardening Equation.**

The Swift and Voce models expressed in Eq. (1) and (2) have been extensively used due to their simplicity and good description of the uniaxial stress-strain curves up to the uniform elongation, but when these models are extrapolated to a large strain condition, a clear difference in the workhardening is observed as is illustrated in Fig.1. To describe large-strain workhardening characteristic, a combined equation of the Swift and Voce models with a weighting coefficient \( \mu \) is used (see Eq. (3)).

\[
\sigma_S = K(\varepsilon_0 + \varepsilon_p)^n. \tag{1}
\]

\[
\sigma_V = \sigma_Y + A(1 - \exp(-b\varepsilon_p)). \tag{2}
\]

\[
\sigma_{S-V} = \mu\sigma_S + (1 - \mu)\sigma_V. \tag{3}
\]

Here, \( \mu \) is a weighting coefficient \((0 \leq \mu \leq 1)\). When \( \mu = 1 \), Eq. (3) is identical to the Swift model and to the Voce model for \( \mu = 0 \). The Swift and Voce parameters determined from the uniaxial tensile test are listed on Table 1.

**TABLE 1. HARDENING PARAMETERS OF THE SWIFT AND VOCE MODELS.**

<table>
<thead>
<tr>
<th>UNIAXIAL TEST PARAMETERS</th>
<th>Swift</th>
<th>Voce</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K )</td>
<td>( 395 )</td>
<td>39</td>
</tr>
<tr>
<td>( \varepsilon_0 )</td>
<td>( .00 )</td>
<td>33</td>
</tr>
<tr>
<td>( n )</td>
<td>( .15 )</td>
<td>1</td>
</tr>
<tr>
<td>( \sigma_Y )</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>( A )</td>
<td>5</td>
<td>49</td>
</tr>
<tr>
<td>( b )</td>
<td>5</td>
<td>44</td>
</tr>
</tbody>
</table>

**Figure 1.** Extrapolated uniaxial stress-strain curves using Swift-Voce models for 590Y, 780Y and 980Y sheets.
In-plane stretch-bending Process

Experimental procedures. In the in-plane stretch-bending test, the sheet was stretched by a constant stretching force $T$ and simultaneously a bending force $F$ was imposed by a circular punch by using a stretch-bending device adapted on a biaxial machine, as illustrated in Fig. 2a). A pair of specimens was tested at the time under the same a load condition. To prevent the buckling, the specimens were clamped by two steel plates. Teflon films with Vaseline were coated in both sides of the specimens to reduce the friction. The maximum bending strain was calculated using a scribed 18 grids with 1-mm pitch on the outer surface of the sheet where large bending strain is expected to appear (see Fig 2b)). The nodal points in an initial and deformed stage were measured with an optical measurement system.

![Figure 2](image)

(a) Schematic illustration of the stretch-bending experiment, (b) general configuration of the in-plane stretch-bending specimen and measurement area.

Finite element simulation. The finite element model was built in LS-DYNA using shell elements. The gripping jaws, punch and anti-buckling plates were idealized as a rigid bodies. The friction coefficient between the blank and punch was set as 0.1 and 0.05 between the blank and the anti-buckling plates. The bending strain was measured using the average value of the 18 elements located in the tensile area at the outer surface, outlined in the Fig. 2(b). The planar anisotropy of the material was considered by using a 6th order polynomial yield function [10]. The simulations were performed for a maximum punch stroke of 40 mm, which is the limit of the machine in the experiment.

RESULTS AND DISCUSSIONS

Effect of the stretching force on the onset of necking. To investigate the effect of the stretching force on the necking limit, the stretch-bending process were simulated for three stretching-force levels, i.e., $T=0.1$, 0.25 and 0.5$\sigma_Y$ ($\sigma_Y$ = yield strength). Fig. 3 shows the calculated results in terms of the punch stroke vs. bending strain for the 590Y sheet. It can be observed that, when the stretching force is very large, i.e., $T=0.5\sigma_Y$, necking occurs at very early stage of punch stroke in the Voce model, but not in the Swift model. However, if the stretching force is small, i.e., $T=0.1\sigma_Y$ the bending strain is small (e.g., at a punch stroke of 40 mm =
machine limit, it is 0.35 (Voce) and 0.3 (Swift)) and necking is not found for both the Swift and the Voce models. In contrast, when a moderate stretching force is used, $T=0.25\sigma_Y$, large strains over 0.4 appears. From these results it is clear that the forming limit (onset of necking) of the material on the in-plane stretch-bending process is sensitive to the stretching force level and to the type of hardening model. Similar behavior was obtained on the calculation for the 780Y and 980Y sheets, where onset of necking clearly takes place when a large stretching force, i.e., $T=0.5\sigma_Y$, was used.

Figs. 4 (a) and (b) illustrate the in-plane stretch bending calculation results using the Voce model for two different stretching forces, $T=0.25\sigma_Y$ and $T=0.5\sigma_Y$, respectively, at a punch stroke of 30mm. In Fig. 4(a), under $T=0.25\sigma_Y$, a large strain appears at the outer surface of the specimen without of necking or buckling. In contrast, in Fig. 4(b), under $T=0.5\sigma_Y$ at the same punch stroke, the necking appears. From these results it would be concluded that the stretch-bending limit can be controlled by the stretching force level.

![Figure 3](image_url)

**Figure 3.** Simulation results showing the effect of the stretching force on the stretch-bending process.
In order to obtain a large strain state without necking, a stretching force $T=0.25\sigma_Y$ was used for the experiments. Fig. 5 shows the experimental result of punch stroke vs. bending strain of 590Y under $T=0.25\sigma_Y$, and the corresponding FE simulation results by using three types of material models, i.e., the Voce model, the Swift model and the combined Swift-Voce model of $\mu = 0.5$. From this result, it was found that the workhardening of 590Y is lower than that predicted by the Swift model, but higher than that given by the Voce model, and it is represented by the combined Swift-Voce model very well. In Fig. 6, the deformation of 590Y specimen calculated by the combined Swift-Voce model (left half of the specimen) is compared with the experimental result (right half of the figure). From this figure, the FE simulation result agrees well with the experimental result.

For 590Y, a maximum bending strain of 0.41 was obtained at a punch stroke of 38 mm in the stretch-bending experiment while in the uniaxial test the uniform elongation was 0.159. In the case of the 780Y and 980Y sheets a bending strain of 0.368 and 0.268 were obtained, respectively.
CONCLUSIONS

From the FE simulation of the in plane stretch-bending process it was found that the forming limit of the sheet is strongly influenced by the stretching force and the type of hardening model. The combined Swift-Voce model is suitable for the prediction of the experimental results in terms of the punch stroke vs. bending strain.

Large strains of 0.410, 0.368 and 0.268, for 590Y, 780Y and 980Y sheets, respectively, were obtained without necking of the sheets under purely uniaxial stress states.

In-plane stretch-bending experiment possesses a potential to apply for the research on the forming limit and damage of sheet metals.

REFERENCES