High accuracy springback simulation by using material model considering the SD effect

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Abstract. In order to enhance the accuracy of springback simulation, the strength differential (SD) effect, i.e., the difference in flow stress between tension and compression, of a high strength cold-rolled steel sheet with a tensile strength of 980 MPa is measured by means of in-plane tension-compression test apparatus. Bi-axial stress tests are also performed to measure the contour of plastic work of the test material. From those experimental results, the material model which can consider the SD effect is determined. Furthermore, this material model is implemented into commercial FEM code by using user-subroutine function. To check the validity of this model and established FEM analysis system, curvature-hat crush forming experiment is performed. By comparing the experimental result and forming simulation result, the accuracy of the material model which can consider the SD effect is validated. Consequently it is concluded that the use of material model which is capable of reproducing the SD effect is a must to enhance the accuracy of springback simulation.

1. Introduction

Advanced high-strength steel (AHSS) is increasingly used in the automotive body industry for manufacture of environmental-friendly and collision-safe car. However, AHSSs are difficult materials to use in sheet metal forming process, as they cause large springback. Because of difficulty in control of springback, high accurate springback simulation is a key technology to reduce die manufacturing lead time. In order to predict springback accurately, the material model which is capable of accurately reproducing the work hardening behavior is important [1]. In particular, highly accurate modeling of the strength differential (SD) effect, which is a difference in flow stress between tension and compression, is of crucial importance for accurate springback simulation [2], [3].

Some authors proposed asymmetric yield function to reproduce the SD effect [4], [5]. However those models are not used in press forming simulation practically.

In this study, the SD effect of 980 MPa grade dual phase steel sheet was precisely measured using in-plane tension-compression test apparatus. Additionally bi-axial tension tests were performed to
measure the contour of plastic work of the test material. Using the measured those results, a material model taking into account the SD effect was developed and implemented into Commercial dynamic explicit FEM code LS-DYNA using user-subroutine function. Furthermore, to validate the material model, press forming experiment and simulation were performed.

2. Material modeling

2.1. Test material
The test material used in this study is 1.2 mm thick cold-rolled dual phase AHSS with a tensile strength of 980 MPa. The mechanical properties obtained from uniaxial tensile tests in the 0°, 45° and 90° directions to the rolling direction of the materials are listed in Table 1.

| Tensile direction (°) | $\sigma_{0.2}$ (MPa) | $c^a$ (MPa) | $n^a$ | $\alpha^a$ | r-value$^b$ |
|----------------------|---------------------|-------------|-------|------------|------------|
| 0 (RD)               | 685                 | 1482        | 0.11  | -0.0013    | 0.69       |
| 45                   | 677                 | 1464        | 0.11  | -0.0013    | 1.05       |
| 90 (TD)              | 706                 | 1525        | 0.11  | -0.0014    | 0.96       |

$^a$ Approximated using $\sigma = c\left(\alpha + \varepsilon^p\right)^n$ at $\varepsilon^p=0.002$–0.08

$^b$ Measured at an uniaxial nominal strain $\varepsilon_N = 0.1$

2.2. Experimental results
In-plane tension-compression test results are shown in figure 1. Refer literature [2] for the details of the testing procedures. Left figure shows the results in RD and right one shows the results in TD. In RD, the compressive yield stress is slightly smaller than the tensile yield stress. It is possibly caused by the Bauschinger effect due to the rolling tensile pre-strain in the x-direction.

Figure 2 shows the contours of plastic work measured using the biaxial tensile tests and in-plane compression tests. In order to evaluate the shape change of the work contours, all the stress points were normalized by the uniaxial tensile flow stress, $\sigma_0$, in the rolling direction. For all stress paths, the stress points fall on a single point, therefore this material shows isotropic work hardening.

In this study, three theoretical yield functions (von Mises, r-Hill [6], and Varma [5]) were determined. Verma’s yield function is defined as;

$$a\left(\sigma_x^2 - A\sigma_x\sigma_y + B\sigma_y^2 + C\tau_{xy}^2\right)^{1/2} + \left(k_1\sigma_x + k_2\sigma_y\right) = \sigma_0$$  (1)

**Figure 1.** Comparison of the stress-strain curves between tension and compression.
Anisotropic parameters of this function can be explicitly determined using the uniaxial tensile test data in 3 directions, compression test data in 2 directions and bi-axial tensile test data. Parameter identification method is shown in literature [5]. Using Verma’s model, the SD effect was successfully reproduced.

3. Curvature-hat press forming experiment

Figure 3 shows the schematic illustration of curvature-hat press formed part. The part was formed using a crash forming, in which a punch and a die were closed together without a blank holding force. Tensile and compressive stress states are intermixed in the inside and outside of the neutral surface. Furthermore, stretch flanging (uniaxial tensile stress state) and shrink flanging (uniaxial compression stress state) are also intermixed. So this part is suitable for validation of the SD effect. The shape of press formed part after springback was precisely measured using 3D scanner ATOS (GOM GmbH).

4. Curvature-hat press forming simulation

4.1. Simulation conditions

A Commercial dynamic explicit FEM code LS-DYNA Ver.971 R7.1.2 was used. Verma’s yield function was implemented into LS-DYNA using user-subroutine function UMAT. Bauschinger effect was neglected because the stress reversal was negligibly small in this forming process. On the other hand, the apparent Young’s modulus variation was measured and incorporated into the simulation [7].

The mesh size used for the blank was 1.2 × 1.2 mm². Full integration shell element ELFOAM=16 with 7 integration points through thickness were used. The friction coefficient between the tools and the blank was assumed to be 0.15.

4.2. Simulation results and discussions

Figure 4 compares the cross-sectional shape of the formed part at the centre (x=0) with that at the point shifted 110mm in longitudinal direction (x=110mm). At the centre, springback mode is only a wall opening. On the other hand, at the x=110mm, twist additionally occurred due to the difference of the stresses in the stretch and shrink flanging areas.

Figure 4 also compares the experimental and calculated results. Enlarged profiles of the right side of the cross-sectional shape are also shown. The black lines are experimental part shapes, and the red and blue lines are the cross-sectional shapes calculated using r-Hill and Verma’s models, respectively. At the centre of the part, the accuracy of wall opening prediction was improved by considering the SD effect. Considering the SD effect, the reproducibility of plane strain tension and compression stresses were improved, so that the calculation accuracy of bending stress was enhanced.

![Figure 2. Measured stress points forming contours of plastic work, compared with the theoretical yield loci based on selected yield functions.](image-url)
At $x=110\text{mm}$, the calculated result obtained from Verma’s model had closer agreement with the experiment than that based on r-Hill. This means that the twist prediction accuracy was also improved by considering the SD effect. Consequently, we can conclude that consideration of the SD effect is crucial in order to enhance the accuracy of springback simulation of AHSS.

5. Conclusions
- The contour of plastic work up to $\varepsilon_p^c = 0.012$ was successfully measured and Verma’s yield function was determined to reproduce the SD effect.
- Verma’s model was implemented into a commercial FEM code.
- The accuracy of springback prediction is improved by considering the SD effect.

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