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Improvement of springback prediction accuracy using material model considering elastoplastic anisotropy and Bauschinger effect

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ABSTRACT

Springback prediction is necessary when applying high-strength steel sheets to automotive parts. The accuracy of springback prediction depends on the material model, which describes the deformation behavior of steel sheets. In this research, a material model which considers important material behaviors (Bauschinger effect, average Young's modulus, elastic anisotropy and plastic anisotropy) was developed and implemented in FEM software. Springback analyses were performed for curved hat-shaped parts made of high-strength steel sheets. As a result, the effects of each material behavior on springback were clarified. It was found that not only the Bauschinger effect and average Young's modulus but also elastic anisotropy and plastic anisotropy influenced the results of springback predictions, particularly in the case of anisotropic material. Springback analysis considering all four material behaviors yielded better springback prediction accuracy than those of conventional analyses.

1. Introduction

High strength steel sheets have played a key role in weight reduction and improved crashworthiness of automotive bodies in recent years. Since the amount of springback tends to increase with material strength, springback is among the most important issues in sheet metal forming processes. Analysis by the finite element method (FEM) in the design stage of automotive parts is an effective approach for reducing the number of tool adjustments in the forming process, especially when using high strength steel sheets.

High strength steels show a significant Bauschinger effect, i.e., a softening phenomenon after stress reversal, compared with mild steels (Han et al., 2005). In order to consider the Bauschinger effect, Yoshida and Uemori (2002) proposed a two-surface isotropic-kinematic hardening material model (Yoshida–Uemori model). Eggertsen and Mattiasson (2009) determined kinematic hardening parameters by inverse modeling of a three-point bending test and suggested that the Yoshida–Uemori model improved springback prediction accuracy in U-bend forming.

In addition to the Bauschinger effect, the elastic stress–strain relationship is also an important material behavior, especially given that springback is an elastic recovery phenomenon. Cleveland and Ghosh (2002) investigated the non-linearity of the stress–strain curves of steels during unloading and reloading. To consider that elastic behavior, Yoshida et al. (2002) proposed the concept of the average Young's modulus, which is a linearly-approximated stress–strain gradient during unloading, and demonstrated that the average Young's modulus decreases gradually with plastic deformation.

It is well known that the accuracy of springback prediction depends strongly on consideration of the Bauschinger effect and the average Young's modulus, as reported by Zang et al. (2007). However, some steel sheets display elastic anisotropy and plastic anisotropy. Kuwabara et al. (2002) investigated the plastic anisotropy of various types of steel sheets under a biaxial stress condition and evaluated the accuracy of the yield functions for yield loci. Hu (1980) evaluated the elastic anisotropy of steel sheets by measuring their elastic properties in various in-plane directions and compared those experimental elastic properties with the calculated results predicted by averaging schemes. Those studies suggested that elastic and plastic anisotropy also influence the results of springback analysis in varying degrees.

For accurate springback prediction, it is essential to choose a material model that takes all these major material behaviors into account. However, as the relative influences of each material behavior on springback prediction have not been clarified, users of FEM may not understand which material behaviors have the most dominant impacts. This situation can result in unnecessary computational time due to consideration of irrelevant material behaviors in springback analysis.

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Moreover, there has been no study in which all four material behavior parameters, that is, the Bauschinger effect, average Young's modulus, elastic anisotropy and plastic anisotropy, were considered simultaneously in springback analysis. This means that a springback prediction may not be accurate if a high strength steel with elasto-plastic anisotropy is used in press forming.

The objectives of this study are to clarify the influence of each material behavior on springback analysis and to improve springback prediction accuracy by choosing a proper material model considering the material behaviors which have relatively large influences on springback. A material model considering the Bauschinger effect, average Young's modulus, elastic anisotropy and plastic anisotropy was developed and implemented in FEM software, and springback analyses were carried for curved hat-shape parts of two high strength steels in order to clarify the influences of each material behavior on springback and verify the springback prediction accuracy of the proposed model.

2. Material behaviors and modeling

2.1. Materials

HSLA590 steel and DP980 steel (hereinafter, 590R and 980Y, respectively) with the thickness of 1.2 mm were used in this study. The mechanical properties of the steels in three directions are shown in Table 1. Yield strength YS, tensile strength TS and *r*-value *r* are obtained by uniaxial tensile tests in the directions of 0°, 45°, and 90° with respect to rolling direction (R.D.). The Young's modulus *E* and the shear modulus *G* are obtained by the resonance method (ASTM Standard, 2001) in each direction. 590R displays plastic anisotropy and elastic anisotropy in its mechanical properties, which vary depending on the tensile direction. The mechanical properties of 980Y are approximately uniform, independent of the tensile direction. That is, the anisotropy of 980Y is weaker than that of 590R.

2.2. Plastic anisotropy

To consider the biaxial anisotropy influences on the result of sheet metal forming analysis strongly, as reported by Paraianu et al. (2012). Therefore, in order to investigate the plastic anisotropy of the steel sheets in more detail, the equi-plastic work loci were obtained by biaxial tension tests. The strains were measured with strain gauges arranged at right angles to each other at the center of the specimen. In the biaxial tension tests, the loads in two directions were controlled to three predefined stress ratios, 1:1 (equi-biaxial), 2:1 and 1:2 (plane strain).

For description of anisotropic behavior, a lot of anisotropic yield functions have been developed, as reviewed by Banabic (2010). In order to clarify the impact of plastic anisotropy on springback predictions, Hill's 48 yield function (Hill, 1948) and Yld2000-2d yield function (Barlat et al., 2003) were used as the contrasting anisotropic yield functions which are simple one and complicated one. Hill'48 yield function is most conventional criteria and was used in commercial FEM software widely. Yld2000-2d yield function is also available in commercial FEM software and is considered as an accurate criterion for description of anisotropy (Kuwabara et al., 2011).

Table 1
Mechanical properties.

Steel	Direction	YS (MPa)	TS (MPa)	*r*	*E* (GPa)	*G* (GPa)
590R	0°	446	622	0.50	213	77
	45°	447	596	1.33	203	86
	90°	492	635	0.77	227	77
980Y	0°	702	986	0.82	202	82
	45°	691	998	0.87	211	79
	90°	685	1007	0.98	210	82

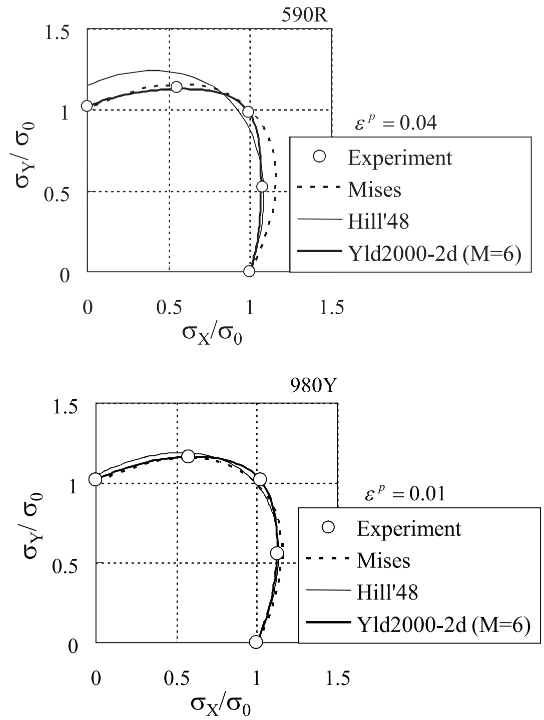

Fig. 1. Comparison of experimental results of biaxial tension test with results by various yield functions.

The experimental normalized yield loci are shown in Fig. 1 compared with those calculated by von Mises, Hill'48, Yld2000-2d yield function. The anisotropic coefficients of Hill's 48 yield function were determined from *r*-values of three uniaxial directions (r_0, r_{45} and r_{90}). The anisotropic coefficients of Yld2000-2d yield function were determined by least squares method using the uniaxial tensile stresses at 4% plastic strain in three direction (σ_0, σ_{45} and σ_{90}), the equi-biaxial stress (σ_b), the plane strain stresses (σ_{px}, σ_{py}) and the *r*-values of three uniaxial directions (r_0, r_{45} and r_{90}).

In Fig. 1, the stresses in the 0° direction σ_x and in the 90° direction σ_y are normalized by the stresses in the 0° direction σ_0.

In the experimental yield locus of 590R, the stress of plane strain in the 90° direction is higher than that in the 0° direction. This means that 590R steel is anisotropic under a biaxial stress condition. Yld2000-2d yield function provides a better approximation of the yield locus than von Mises and Hill's 48 yield functions.

The experimental yield locus of 980Y is nearly symmetrical when the stresses of plane strain in the 0° direction and 90° direction are compared. The results show that 980Y is substantially isotropic under biaxial stress conditions. The yield loci calculated not only by Yld2000-2d yield function but also by von Mises and Hill's 48 yield functions are in fairly good agreement with the experimental result.

2.3. Bauschinger effect

In this paper, Isotropic hardening model and Yoshida–Uemori model were used to evaluate the effect of Bauschinger effect. Yoshida–Uemori model is two-surface isotropic-kinematic hardening material model, wherein the yield surface moves within the bounding surface. The criterion for the subsequent yield surface *f* is given by

$$f = \phi(\sigma - \alpha) - Y = 0 \quad (1)$$