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# Prediction of spring-back behavior in high strength low carbon steel sheets

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**Abstract**

The spring-back of polycrystalline materials has been predicted numerically using the elastic and visco-plastic crystal plasticity models. The anisotropic plane strain moduli for texture components typical in high strength steel sheets and low carbon high strength steel sheets were calculated with the upper–lower bounds and elastic self-consistent model. The yield stresses of polycrystalline materials were calculated with the visco-plastic self-consistent polycrystal model. The influence of texture components on the spring-back was analyzed in detail. The elastic and visco-plastic self-consistent models were also used to evaluate magnitude and directionality of the spring-back angle of high strength low carbon steel sheets subjected to plane strain bending.


*Keywords:* Spring-back; Elastic modulus; High strength steel; Self-consistent model

## 1. Introduction

The application of high strength interstitial free (IF) or low carbon steel sheets for automotive use requires the control of spring-back because of their higher yield strength to elastic modulus ratio. After the press forming operations, the forming parts change their shapes to achieve the equilibrium with no external force. Spring-back is thus an elastically driven process that adjusts internal stresses to attain zero moment and force at each sheet location [1]. It is known that the spring-back is affected by several material parameters and process variables. The prediction of spring-back for polycrystalline materials has been conducted using the finite element methods [2–4]. For an accurate simulation, it is required that the anisotropic behaviors of elastic and plastic properties of polycrystalline materials should be considered in the constitutive equation. Most of these studies has been used the isotropic elastic stiffness tensor and simple yield function in the formulation. Geng and co-workers [2,3] predicted spring-back behavior more accurately by introducing rigorous yield function and kinematic hardening law. Polycrystalline material consists of many single crystals exhibiting strong anisotropic elastic and plastic properties. Renavikar et al. [5] investigated the effect of crystallographic orientation of single crystal steel on the spring-back behavior in plane strain bending application. Chan and Wang [6] predicted the spring-back behavior of polycrystalline leadframe materials by a plane stress model taking into account crystallographic textures and grain shape. However, they did not evaluate the effect of crystallographic texture components on the spring-back behavior.

In the present work, first of all, the elastic stiffness tensors and anisotropic plane strain elastic modulus for the crystallographic texture components typical in high strength steel sheets were evaluated by using the upper–lower bounds [7,8] and elastic self-consistent method [9]. The visco-plastic self-consistent model [10] was used to predict yield stress directionality for the crystallographic texture components typical in the high strength steel sheets. The effect of the crystallographic texture components on the spring-back behavior was theoretically investigated for the high strength steel sheets subjected to the plane strain bending. Moreover, the spring-back behavior for low carbon high strength steel sheets was measured and compared with predicted results.

## 2. Calculation procedure

For the sheet metals having very large width-to-thickness ratio, bending of the sheet metals approaches a plane strain operation. The phenomenon of spring-back in the plane strain bending is schematically described in Fig. 1. If we assume that sheet metals exhibit elastically isotropic and an elastic–ideally

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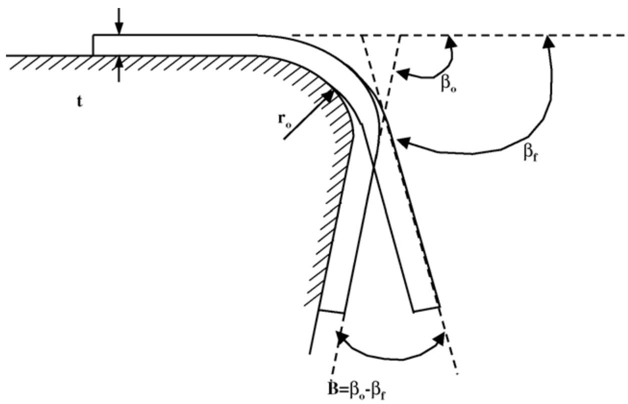


Fig. 1. Schematic diagram of spring-back in plane strain bending.

plastic (i.e. non-strain hardening) behavior, the amount of relative spring-back of sheet metals having a thickness, $t$ can be calculated from the following equation [1]:

$$\frac{1}{r_{\rm o}} - \frac{1}{r_{\rm f}} = \frac{3\sigma_{\rm o}}{tE(1-\nu^2)} = \frac{1}{E'}\frac{3\sigma_{\rm o}}{t} \tag{1}$$

where $r_{\rm o}$ and $r_{\rm f}$ are radii of curvature before and after spring-back, respectively. And $\sigma_{\rm o}$ and $E'$ are flow stress in plane strain and plane strain elastic modulus at the length direction, respectively. The isotropic plane strain elastic modulus $E'$ can be calculated from the Young's modulus, $E$ and Poisson's ratio, $\nu$.

If the sheet metals exhibit elastically anisotropic behavior and isotropic strain hardening during plane strain bending, Eq. (1) cannot be used to calculate the amount of relative spring-back of sheet metals. From the generalized form of Hook's law [11] and boundary conditions and the Ludwik relation ($\sigma \cong \sigma_{\rm o} + K\varepsilon^n$), the amount of relative spring-back of sheet metals can be calculated from the following equation:

$$\frac{1}{r_{\rm o}} - \frac{1}{r_{\rm f}} = \left(S^{\theta}_{1111} - \frac{S^{\theta}_{2211}S^{\theta}_{1122}}{S^{\theta}_{2222}}\right)\frac{3\sigma_{\rm o}(\theta)}{t} + \left(\frac{6}{n+2}\right) \times \left(S^{\theta}_{1111} - \frac{S^{\theta}_{2211}S^{\theta}_{1122}}{S^{\theta}_{2222}}\right)K\left(\frac{t}{2r_{\rm o}}\right)^n\left(\frac{1}{t}\right) = \frac{1}{E'(\theta)}\frac{3\sigma_{\rm o}(\theta)}{t} + \left(\frac{6}{n+2}\right)\left(\frac{K}{E'(\theta)}\right)\left(\frac{t}{2r_{\rm o}}\right)^n\left(\frac{1}{t}\right) \tag{2}$$

where $S^{\theta}_{ijkl}$ is the overall elastic compliance tensor expressed in the sample coordinate, $n$ the strain hardening exponent and $K$ is the strength coefficient. And $\sigma_{\rm o}(\theta)$ and $E'(\theta)$ are yield stress in plane strain and anisotropic plane strain elastic modulus at an angle $\theta$ from the rolling direction (RD), respectively. The anisotropic plane strain elastic modulus $E'(\theta)$ can be calculated from overall elastic compliance tensor, $S_{ijkl}$ expressed in the sample coordinate as follows [9,12]:

$$S^{\theta}_{ijkl} = r^{\theta}_{im}r^{\theta}_{jn}r^{\theta}_{ko}r^{\theta}_{lp}S_{mnop} \tag{3}$$

where $\mathbf{r}$ is the rotation matrix that rotates around the normal direction (ND) by an angle $\theta$.

Assuming the stress neutral plane and strain neutral plane are consistent, spring-back angle, $B(\theta)$ can be expressed as a function of relative spring-back as follows [13]:

$$B(\theta) = \beta_{\rm o} - \beta_{\rm f} = \beta_{\rm o}r_{\rm o}\left(\frac{1}{r_{\rm o}} - \frac{1}{r_{\rm f}}\right) = \beta_{\rm o}r_{\rm o}\left(\frac{1}{E'(\theta)}\frac{3\sigma_{\rm o}(\theta)}{t} + \left(\frac{6}{n+2}\right) \times \left(\frac{K}{E'(\theta)}\right)\left(\frac{t}{2r_{\rm o}}\right)^n\left(\frac{1}{t}\right)\right) \tag{4}$$

where $\beta_{\rm o}$ and $\beta_{\rm f}$ are bending angle before and after spring-back, respectively.

For a given bending angle and radius of curvature before spring-back, the spring-back angle is a function of anisotropic plane strain elastic modulus and yield stress in plane strain, at a specific direction from the RD. To minimize the spring-back angle, a polycrystalline sheet exhibiting a low yield stress in plane strain and a high plane strain elastic modulus at an angle $\theta$ from the RD is preferable. To minimize the variation of spring-back angle, a polycrystalline sheet exhibiting uniform elastic and plastic properties in the plane of the sheet is preferable. To predict the elastic compliance tensor of polycrystalline aggregates, the upper bound (Voigt average) and lower bound (Reuss average) [7,8] were used. The Voigt and Reuss averages of elastic modulus provide upper and lower bounds on the elastic modulus of polycrystal aggregates. The Voigt average assumes a uniform strain throughout polycrystal and the Reuss average assumes a uniform stress. The Voigt and Reuss polycrystal averages can be expressed as follows:

$$C^{\rm V}_{ijkl} = \langle g^{\rm T}_{ii'}g^{\rm T}_{jj'}g^{\rm T}_{kk'}g^{\rm T}_{ll'}C_{i'j'k'l'}\rangle, \quad S^{\rm R}_{ijkl} = \langle g^{\rm T}_{ii'}g^{\rm T}_{jj'}g^{\rm T}_{kk'}g^{\rm T}_{ll'}S_{i'j'k'l'}\rangle \tag{5}$$

where $C_{i'j'k'l'}$ and $S_{i'j'k'l'}$ are the elements of the elastic stiffness and compliance tensors for the single crystal. $\mathbf{g}^{\rm T}$ represents transpose of an orientation matrix and $\langle\,\rangle$ means the arithmetic volume average over polycrystal aggregates. It should be noted that the elastic tensors could also be represented as matrices [13]. This allows a corresponding compliance tensor to be calculated for the Voigt stiffness tensor through matrix inversion. The elastic self-consistent model [9] assumes that grains embedded in a homogeneous equivalent medium (HEM) having the average elastic properties of the aggregate. The embedding assumption in the self-consistent procedure is that the response in the vicinity of the grain is adequately described by the average modulus of the HEM, independently of the actual neighborhood of the grain. For spherical or ellipsoidal grains, stress and strain are uniform within the domain of the grain, and they are linearly related to the stress and strain at the boundary through the interaction equation as follows:

$$\tilde{\sigma} = -\mathbf{C}^{\rm S} : \mathbf{R} : \tilde{\varepsilon} \tag{6}$$

$$\mathbf{R} = (\mathbf{I} - \mathbf{E}) : \mathbf{E}^{-1} \tag{7}$$

where $\tilde{\varepsilon} = \varepsilon^{\rm c} - \varepsilon$, $\tilde{\sigma} = \sigma^{\rm c} - \sigma$ defines the deviations in strain and stress with respect to the average magnitudes. $\mathbf{I}$ is the fourth