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Calibration of anisotropic yield function by introducing plane strain test instead of equi-biaxial tensile test

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Abstract: The equi-biaxial tensile test is often required for parameter identification of anisotropic yield function and it demands the special testing technique or device. Instead of the equi-biaxial tensile test, the plane strain test carried out with the traditional uniaxial testing machine is suggested to provide the experimental data for calibration of anisotropic yield function. This simplified method by using plane strain test was adopted to identify the parameters of Yld2000-2d yield function for 5xxx aluminum alloy and AlMgSi alloy sheets. The predicted results of yield stresses, anisotropic coefficients and yield loci by the proposed method were very similar with the experimental data and those by the equi-biaxial tensile test. It is validated that the plane strain test is effective to provide experimental data instead of equi-biaxial tensile test for calibration of Yld2000-2d yield function.

Key words: aluminum alloy sheet; anisotropic behavior; yield function; parameter identification; plane strain test

1 Introduction

As one of the lightweight materials, aluminum alloy sheet is widely used in the astronautical, aeronautical and automobile industry and so on. Due to the polycrystal and texture structure, aluminum alloy sheet usually exhibits very strong anisotropic plastic behavior. Hence, an accurate constitutive model of aluminum alloy sheet is vitally required for finite element simulation of aluminum alloy sheet forming processes [1,2]. Up to date, many advanced anisotropic yield functions have been suggested to describe the anisotropic yield behavior of aluminum alloy sheet [3]. The advanced anisotropic yield functions usually introduce a number of parameters to guarantee the flexibility of anisotropic plasticity. The parameter identification of yield function needs the same number of experimental data as the number of parameters. Therefore, a number of mechanical tests should be employed to provide the required experimental data for calibration of yield function. BARLAT et al [4] proposed the Yld2000-2d yield function to describe the anisotropic yield behavior of aluminum alloy sheets. For the parameter identification, the equi-biaxial tensile yield stress was obtained by the bulge test and the equi-biaxial anisotropic coefficient was provided by poly-crystal model, through-thickness disk compression or calculation with Yld96 yield function. BARLAT et al [5] utilized the experimental data and several calculated data by the identified Yld2000-2d yield function to calibrate the Yld2004-18p and Yld2004-13p yield functions. BANABIC et al [6] suggested the BBC2000 yield function for orthotropic metal sheets under plane stress conditions. The biaxial tensile test of cruciform specimen was carried out to provide the yield stress and anisotropic coefficient under equi-biaxial tensile state. BANABIC et al [7] also adopted the biaxial tensile test of another cross-shaped specimen to calibrate the BBC2003 yield function. BRON and BESSON [8] presented a phenomenological yield function to represent the anisotropic plasticity of aluminum sheets. The uniaxial tests of U-notched samples with different notch radii were used to obtain the material behavior under various stress states and they were assumed to play a similar role as biaxial tests. WU et al [9] obtained the experimental yield points by biaxial tensile tests with cruciform

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specimen. It showed that the Barlat 89 and Hosford yield criteria could well describe the yield loci of aluminum alloy sheets than Hill 90，Hill 48 and Mises criteria. FLORES et al [10] improved an identification method for Hill 1948 and Hosford 1979 yield functions by introducing the uniaxial tensile tests, plane strain tests and simple shear tests along rolling direction and transverse direction of metal sheets. ARETZ et al [11] improved the calibration procedure of Yld2003 yield function on the basis of uniaxial and plane strain tensile tests. The required tests can be simplified by involving only a traditional uniaxial tensile testing machine. GÜNER et al [12] presented the inverse identification for Yld2000-2d yield function by using a uniaxial tensile testing specimen with varying cross-section. The employed specimen covered a stress state ranging from uniaxial tension to plane strain tension, and the equi-biaxial stress state obtained from layer compression tests was also utilized to define the objective function. POTTIER et al [13] developed an out-of-plane testing procedure for inverse identification of Hill 1948 yield function and Ludwick hardening law. The testing specimen was designed to contain the expansion zone, tension zone and shear zone. TEACA et al [14] determined some parameters of Ferron−Makkouk−Morreale (FMM) yield criterion by inverse analysis based on the heterogeneous biaxial tensile tests of cross-shaped specimen. One cross-shaped specimen was dedicated to cover the stress state ranging from uniaxial tensile state to equi-biaxial tensile state. ZHANG et al [15] calibrated the Bron and Besson yield criterion by either conventional mechanical tests or single biaxial test of cruciform specimen. The conventional tests included the representative stress state by the uniaxial tensile tests, simple shear tests and bulge test, while the single biaxial test covered a range of stress state by the heterogeneous deformation field in central zone of cruciform specimen. KIM et al [16] suggested a complex geometry of specimen to exhibit heterogeneous stress states in a uniaxial tensile test. Based on the heterogeneous deformation field, the Hill 1948 yield criterion and Swift hardening law were calibrated by the virtual field method.

In the case of less access to equi-biaxial tensile test or other dedicated experimental technique, the plane strain tests along the rolling and transverse directions were proposed to offer the experimental data for parameter identification of anisotropic yield function. The simplified identification procedure based on the plane strain test was presented for the Yld2000-2d yield function. The parameters of Yld2000-2d yield function were calibrated for 5xxx aluminum alloy and AlMgSi alloy sheets. The identified results were compared with the experimental data and those by the equi-biaxial tensile test to validate the proposed method.

2 Yld2000-2d yield function

The Yld2000-2d yield function (F) is presented under the plane stress condition:

$$\begin{cases} F = F' + F'' = 2\bar{\sigma}^a \\ F' = \left|X_1' - X_2'\right|^a \\ F'' = 2\left|X_1'' + X_2''\right|^a + \left|2X_1'' + X_2''\right|^a \end{cases} \tag{1}$$

where a is a coefficient determined by the crystal structure. For the BCC material, a=6, and for the FCC material, a=8. X_1 and X_2 are the principle values of $\boldsymbol{X}'$ and $\boldsymbol{X}''$ as follows:

$$\begin{cases} X_1 = \dfrac{1}{2}[X_{11} + X_{22} + \sqrt{(X_{11} - X_{22})^2 + 4X_{12}^2}\,] \\ X_2 = \dfrac{1}{2}[X_{11} + X_{22} - \sqrt{(X_{11} - X_{22})^2 + 4X_{12}^2}\,] \end{cases} \tag{2}$$

where $\boldsymbol{X}'$ and $\boldsymbol{X}''$ are deviatoric stress tensors by using two linear transformations on the Cauchy stress tensor as follows:

$$\boldsymbol{X}' = \boldsymbol{L}'\boldsymbol{\sigma},\ \boldsymbol{X}'' = \boldsymbol{L}''\boldsymbol{\sigma} \tag{3}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, and $\boldsymbol{L}'$ and $\boldsymbol{L}''$ are the coefficient matrixes given by

$$\begin{cases} \begin{bmatrix} X_{11}' \\ X_{22}' \\ X_{12}' \end{bmatrix} = \begin{bmatrix} L_{11}' & L_{12}' & 0 \\ L_{21}' & L_{22}' & 0 \\ 0 & 0 & L_{66}' \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \\ \begin{bmatrix} X_{11}'' \\ X_{22}'' \\ X_{12}'' \end{bmatrix} = \begin{bmatrix} L_{11}'' & L_{12}'' & 0 \\ L_{21}'' & L_{22}'' & 0 \\ 0 & 0 & L_{66}'' \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \end{cases} \tag{4}$$

$$\begin{cases} \begin{bmatrix} L_{11}' \\ L_{12}' \\ L_{21}' \\ L_{22}' \\ L_{66}' \end{bmatrix} = \begin{bmatrix} 2/3 & 0 & 0 \\ -1/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 2/3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_7 \end{bmatrix} \\ \begin{bmatrix} L_{11}' \\ L_{12}' \\ L_{21}' \\ L_{22}' \\ L_{66}' \end{bmatrix} = \dfrac{1}{9} \begin{bmatrix} -2 & 2 & 8 & -2 & 0 \\ 1 & -4 & -4 & 4 & 0 \\ 4 & -4 & -4 & 1 & 0 \\ -2 & 8 & 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & 9 \end{bmatrix} \begin{bmatrix} \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_8 \end{bmatrix} \end{cases} \tag{5}$$

where α_i (i=1, ⋯, 8) are the material parameters to be identified for each material. The parameter identification was presented by Newton−Raphson numerical procedure. The Jacobian matrix should be derived firstly and a reasonable initial point should be given for numerical convergence.

The Yld2000-2d yield function and its improved formulations were validated to well describe the anisotropic plasticity for aluminum alloy and steel sheets [17,18]. Meanwhile, the formulation of Yld2000-2d yield function is particularly suitable for finite element simulation and has been implemented in the commercial finite element software [19]. Therefore, the Yld2000-2d yield function can be widely adopted for the finite element simulation of sheet metal forming processes in the industry.

3 Parameter identification

3.1 Minimization of error function

To avoid the derivation of Jacobian matrix and satisfy the demand of reasonable initial point for Newton−Raphson numerical procedure, the parameter identification of anisotropic yield function can be achieved by minimization of error function. The error function is defined by the discrepancy between the predicted and experimental data. These data usually include the uniaxial yield stresses and anisotropic coefficients along different directions, equi-biaxial tensile yield stress and equi-biaxial anisotropic coefficient. Hence, the error function δ_1 is given by

$$\begin{cases} \delta_1=\delta_\sigma+\delta_r \\ \delta_\sigma=\sum_{i=1}^{3}\left(\dfrac{\sigma_{\theta_i}^{\mathrm{pre}}-\sigma_{\theta_i}^{\mathrm{exp}}}{\sigma_{\theta_i}^{\mathrm{exp}}}\right)^2+\left(\dfrac{\sigma_{\mathrm{b}}^{\mathrm{pre}}-\sigma_{\mathrm{b}}^{\mathrm{exp}}}{\sigma_{\mathrm{b}}^{\mathrm{exp}}}\right)^2 \\ \delta_r=\sum_{i=1}^{3}\left(\dfrac{r_{\theta_i}^{\mathrm{pre}}-r_{\theta_i}^{\mathrm{exp}}}{r_{\theta_i}^{\mathrm{exp}}}\right)^2+\left(\dfrac{r_{\mathrm{b}}^{\mathrm{pre}}-r_{\mathrm{b}}^{\mathrm{exp}}}{r_{\mathrm{b}}^{\mathrm{exp}}}\right)^2 \\ (\theta_1=0°,\ \theta_2=45°,\ \theta_3=90°) \end{cases} \tag{6}$$

where $\sigma_{\theta_i}^{\mathrm{pre}}$ and $r_{\theta_i}^{\mathrm{pre}}$ are respectively the predicted uniaxial yield stress and anisotropic coefficient along the angle θ with respect to the rolling direction, $\sigma_{\theta_i}^{\mathrm{exp}}$ and $r_{\theta_i}^{\mathrm{exp}}$ are respectively the experimental uniaxial yield stress and anisotropic coefficient along the angle θ with respect to the rolling direction, $\sigma_{\mathrm{b}}^{\mathrm{pre}}$ and $r_{\mathrm{b}}^{\mathrm{pre}}$ are respectively the predicted equi-biaxial yield stress and anisotropic coefficient, $\sigma_{\mathrm{b}}^{\mathrm{exp}}$ and $r_{\mathrm{b}}^{\mathrm{exp}}$ are respectively the experimental equi-biaxial yield stress and equi-biaxial anisotropic coefficient. These yield stresses and anisotropic coefficients predicted by the Yld2000-2d yield function are presented in the next section.

Considering the fact that the plane strain test is more available than equi-biaxial tensile test or other dedicated identification technique, the yield stresses along the rolling and transverse directions obtained by plane strain test are adopted instead of equi-biaxial tensile yield stress and anisotropic coefficient to define the error function as follows:

$$\begin{cases} \delta_2=\delta_\sigma+\delta_r \\ \delta_\sigma=\sum_{i=1}^{3}\left(\dfrac{\sigma_{\theta_i}^{\mathrm{pre}}-\sigma_{\theta_i}^{\mathrm{exp}}}{\sigma_{\theta_i}^{\mathrm{exp}}}\right)^2+ \\ \qquad\left(\dfrac{\sigma_{0}^{\mathrm{ps(pre)}}-\sigma_{0}^{\mathrm{ps}}}{\sigma_{0}^{\mathrm{ps}}}\right)^2+\left(\dfrac{\sigma_{90}^{\mathrm{ps(pre)}}-\sigma_{90}^{\mathrm{ps}}}{\sigma_{90}^{\mathrm{ps}}}\right)^2 \\ \delta_r=\sum_{i=1}^{3}\left(\dfrac{r_{\theta_i}^{\mathrm{pre}}-r_{\theta_i}^{\mathrm{exp}}}{r_{\theta_i}^{\mathrm{exp}}}\right)^2, \\ (\theta_1=0°,\ \theta_2=45°,\ \theta_3=90°) \end{cases} \tag{7}$$

where $\sigma_{0}^{\mathrm{ps(pre)}}$ and $\sigma_{90}^{\mathrm{ps(pre)}}$ are respectively the predicted yield stresses of plane strain test along the angles 0° and 90° with respect to the rolling direction, σ_{0}^{ps} and $\sigma_{90}^{\mathrm{ps}}$ are respectively the experimental yield stresses of plane strain test along the angles 0° and 90° from the rolling direction. The yield stresses of plane strain test along the angle 0° and 90° with respect to the rolling direction predicted by the Yld2000-2d yield function are derived in the next section.

For the minimization of error function in the modeFRONTIER® platform, the bounded Broyden−Fletcher−Goldfarb−Shanno (B-BFGS) algorithm is adopted. The B-BFGS is based on the quasi-Newton method and can achieve fast convergence. A large number of initial points can be used to cover all the parameter ranges.

3.2 Prediction of uniaxial yield stress and anisotropic coefficient

For the uniaxial yield stress σ_θ obtained by the standardized uniaxial tensile test along the angle θ with respect to the rolling direction, the components of Cauchy stress tensor can be calculated as follows:

$$\begin{cases} \sigma_{11}=\sigma_\theta\cdot\cos^2\theta \\ \sigma_{22}=\sigma_\theta\cdot\sin^2\theta \\ \sigma_{12}=\sigma_{21}=\sigma_\theta\cdot\cos\theta\cdot\sin\theta \end{cases} \tag{8}$$

Then, the predicted uniaxial yield stress can be calculated as follows:

$$\sigma_\theta^{\mathrm{pre}}=Y_{\mathrm{ref}}/\bar{\sigma}_\theta=Y_{\mathrm{ref}}/\left(\frac{1}{2}F_\theta\right)^{1/a} \tag{9}$$

where Y_{ref} is the referenced yield stress, $\bar{\sigma}_\theta$ is the uniaxial equivalent stress calculated by taking the Cauchy stress tensor of uniaxial yield stress σ_θ into the anisotropic yield function, and F_θ is the function defined by the anisotropic yield function for uniaxial tensile test along the angle θ with respect to the rolling direction.

With the hypotheses of associated flow rule, the predicted uniaxial anisotropic coefficients can be derived as follows:

$$r_\theta=-\frac{\sin^2\theta\cdot\dfrac{\partial F}{\partial\sigma_{11}}-\dfrac{1}{2}\sin 2\theta\cdot\dfrac{\partial F}{\partial\sigma_{12}}+\cos^2\theta\cdot\dfrac{\partial F}{\partial\sigma_{22}}}{\dfrac{\partial F}{\partial\sigma_{11}}+\dfrac{\partial F}{\partial\sigma_{22}}}\Bigg|_{\sigma_\theta} \tag{10}$$

where the partial differentials of equivalent stress to the Cauchy stress component for the Yld2000-2d yield function are given as follows:

$$\begin{pmatrix}\dfrac{\partial F}{\partial\sigma_{11}}\\ \dfrac{\partial F}{\partial\sigma_{22}}\\ \dfrac{\partial F}{\partial\sigma_{12}}\end{pmatrix}=\begin{pmatrix}\dfrac{\partial F'}{\partial X'}\cdot\dfrac{\partial X'}{\partial\sigma_{11}}+\dfrac{\partial F''}{\partial X''}\cdot\dfrac{\partial X''}{\partial\sigma_{11}}\\ \dfrac{\partial F'}{\partial X'}\cdot\dfrac{\partial X'}{\partial\sigma_{22}}+\dfrac{\partial F''}{\partial X''}\cdot\dfrac{\partial X''}{\partial\sigma_{22}}\\ \dfrac{\partial F'}{\partial X'}\cdot\dfrac{\partial X'}{\partial\sigma_{12}}+\dfrac{\partial F''}{\partial X''}\cdot\dfrac{\partial X''}{\partial\sigma_{12}}\end{pmatrix} \tag{11}$$

$$\begin{cases}\begin{pmatrix}\dfrac{\partial X'}{\partial\sigma_{11}}\\ \dfrac{\partial X'}{\partial\sigma_{22}}\\ \dfrac{\partial X'}{\partial\sigma_{12}}\end{pmatrix}=\begin{pmatrix}\dfrac{\partial X'}{\partial X'_{11}}\cdot L'_{11}+\dfrac{\partial X'}{\partial X'_{22}}\cdot L'_{21}\\ \dfrac{\partial X'}{\partial X'_{11}}\cdot L'_{12}+\dfrac{\partial X'}{\partial X'_{22}}\cdot L'_{22}\\ \dfrac{\partial X'}{\partial X'_{12}}\cdot L'_{66}\end{pmatrix}\\ \begin{pmatrix}\dfrac{\partial X''}{\partial\sigma_{11}}\\ \dfrac{\partial X''}{\partial\sigma_{22}}\\ \dfrac{\partial X''}{\partial\sigma_{12}}\end{pmatrix}=\begin{pmatrix}\dfrac{\partial X''}{\partial X'_{11}}\cdot L''_{11}+\dfrac{\partial X''}{\partial X'_{22}}\cdot L''_{21}\\ \dfrac{\partial X''}{\partial X'_{11}}\cdot L''_{12}+\dfrac{\partial X''}{\partial X''_{22}}\cdot L''_{22}\\ \dfrac{\partial X''}{\partial X''_{12}}\cdot L''_{66}\end{pmatrix}\end{cases} \tag{12}$$

3.3 Prediction of equi-biaxial yield stress and anisotropic coefficient

For the equi-biaxial yield stress, the components of Cauchy stress tensor are given by

$$\sigma_{11}=\sigma_{12}=\sigma_b,\ \sigma_{12}=\sigma_{21}=0 \tag{13}$$

The predicted equi-biaxial yield stress and anisotropic coefficient are given as follows:

$$\begin{cases}\sigma_b^{pre}=Y_{ref}/\bar{\sigma}_b=Y_{ref}/\left(\dfrac{1}{2}F_b\right)^{1/a}\\ r_b^{pre}=\dfrac{\partial F/\partial\sigma_{22}}{\partial F/\partial\sigma_{11}}\Bigg|_{\sigma_b}\end{cases} \tag{14}$$

where $\bar{\sigma}_b$ is the equi-biaxial equivalent stress calculated by taking the Cauchy stress tensor of equi-biaxial yield stress σ_b into the anisotropic yield function, and F_b is the function defined by the anisotropic yield function for equi-biaxial tensile test.

3.4 Prediction of plane strain yield stress

For the plane stresses σ_0^{ps} and σ_{90}^{ps} along the rolling and transverse directions, the components of Cauchy stress tensor are respectively given as follows:

For σ_0^{ps}, there exists

$$\begin{cases}\sigma_{11}=1,\ \sigma_{22}=\eta,\ \sigma_{12}=\sigma_{21}=0\\ \eta=\sigma_{22}/\sigma_{11}\end{cases} \tag{15}$$

For σ_{90}^{ps}, there exists

$$\begin{cases}\sigma_{11}=\xi,\ \sigma_{22}=1,\ \sigma_{12}=\sigma_{21}=0\\ \xi=\sigma_{11}/\sigma_{22}\end{cases} \tag{16}$$

where η and ξ are the ratios of minor and major principal stresses for plane strain test along the rolling and transverse directions, respectively. Considering the fact that the strain along the angle 90° with respect to the tensile direction equals zero for the plane strain test, the following equations of associated flow rule should be fulfilled with

$$\frac{\partial F}{\partial\sigma_{22}}\bigg|_{\sigma_0^{ps}}=0,\quad \frac{\partial F}{\partial\sigma_{11}}\bigg|_{\sigma_{90}^{ps}}=0 \tag{17}$$

So, the constants η and ξ can be determined by solving Eqs. (15) and (16) with the bisection method.

The predicted yield stress of plane strain tests is calculated as follows:

$$\sigma_{ps}^{pre}=Y_{ref}/\bar{\sigma}_{ps}=Y_{ref}/\left(\frac{1}{2}F_{ps}\right)^{1/a} \tag{18}$$

where $\bar{\sigma}_{ps}$ is the equivalent stress of plane strain tensile calculated by taking the Cauchy stress tensor of plane strain yield stress σ_{ps} into the anisotropic yield function, the F_{ps} is the function defined by the anisotropic yield function for plane strain test.

4 Results and discussion

4.1 Anisotropic model of 5xxx aluminum alloy sheet

The two proposed methods were used to calibrate the Yld2000-2d yield function for a 5xxx aluminum alloy (Al-5xxx) sheet. For the first method, the error object is defined with the experimental and predicted data of the uniaxial tensile tests and equi-biaxial tensile test, and it is denoted as EB. For the second method, the error object is defined with the experimental and predicted data of the uniaxial tensile tests and plane strain test, and it is denoted as PS. The experimental data of Al-5xxx sheet was given by VEGTER et al [20]. The difference of the results predicted by the simplified method PS from the experimental data and those predicted by the traditional method EB can be ignored for Al-5xxx sheet, as shown in Table 1. The parameters of Yld2000-2d yield function identified by the two methods for Al-5xxx sheet are similar with each other, as shown in Table 2.

Table 1 Experimental and predicted results of Al-5xxx sheet

Parameter	Exp	Pre(EB)	Pre(PS)
σ_0	0.992	0.992	0.992
σ_{45}	1.008	1.008	1.008
σ_{90}	0.992	0.992	0.991
σ_b	1.026	1.026	−
σ_0^{ps}	1.081	−	1.081
σ_{90}^{ps}	1.054	−	1.056
r_0	0.73	0.73	0.73
r_{45}	0.79	0.79	0.79
r_{90}	0.67	0.67	0.67
r_b	1.00	1.00	−

Table 2 Identified parameters of Yld2000-2d yield function for Al-5xxx sheet

Parameter	EB	PS
α_1	0.9910	0.9753
α_2	0.9532	0.9861
α_3	0.9063	1.0336
α_4	1.0071	1.0323
α_5	1.0042	1.0107
α_6	0.9190	0.9453
α_7	0.9709	0.9776
α_8	1.0463	0.9992

For the Al-5xxx alloy sheet, the trends of normalized flow stress and anisotropic coefficient under uniaxial tensile condition predicted by the two methods are compared in Figs. 1 and 2. While the predicted trends of normalized flow stress are very similar except near the angle 90° with respect to the rolling direction, and the predicted trends of uniaxial anisotropic coefficient coincide with each other in the whole range. As shown in Fig. 3, the Yld2000-2d yield loci of Al-5XXX alloy sheet obtained by the two methods are almost the same.

4.2 Anisotropic model of AlMgSi alloy sheet

The same procedures were also applied to identifying the parameter of Yld2000-2d yield function for an AlMgSi alloy sheet. The experimental data of AlMgSi alloy sheet were given by VEGTER and BOOGAARD [21]. For the AlMgSi alloy sheet, the results predicted by the simplified method PS are nearly the same as the experimental data and those predicted by the traditional method EB, as shown in Table 3. The identified parameters of Yld2000-2d yield function identified by the two methods are in relatively good agreement, as shown in Table 4.

For the AlMgSi alloy sheet, the trends of normalized flow stress predicted by the two methods are similar although there is a very small discrepancy near the angles 0° and 90°, as shown in Fig. 4, while the trends of uniaxial anisotropic coefficient predicted by the two methods are the same in the whole range, as shown in Fig. 5. The Yld2000-2d yield loci of AlMgSi alloy sheet obtained by the two methods coincide with each other, as shown in Fig. 6.

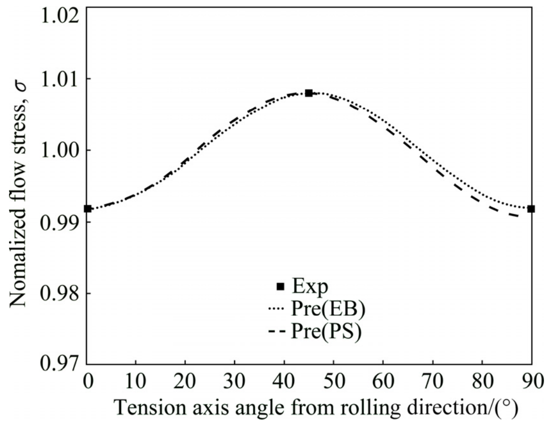

Fig. 1 Comparison of normalized flow stress for Al-5xxx alloy sheet

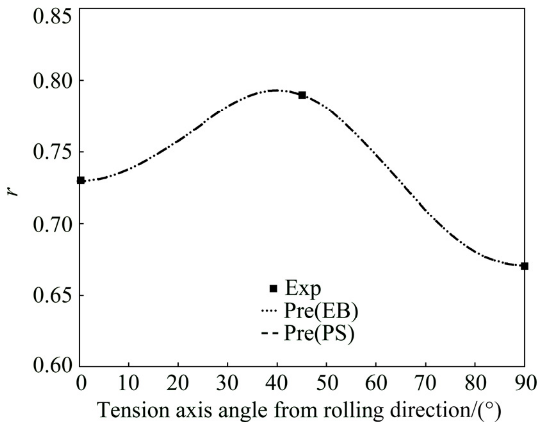

Fig. 2 Comparison of anisotropic coefficient for Al-5xxx alloy sheet

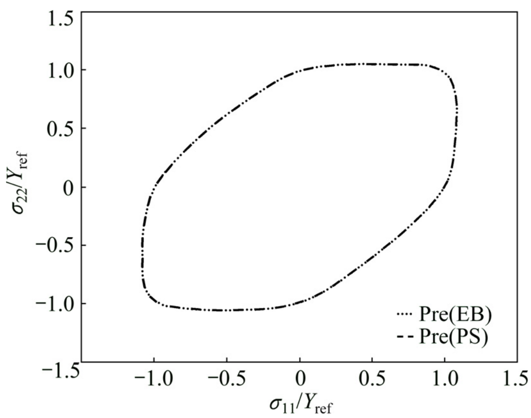

Fig. 3 Comparison of yield loci for Al-5xxx alloy sheet

Table 3 Experimental and predicted results of AlMgSi sheet

Parameter	Exp	Pre(EB)	Pre(PS)
σ_0	1.021	1.021	1.021
σ_{45}	0.987	0.987	0.987
σ_{90}	1.009	1.009	1.008
σ_b	1.004	1.004	−
σ_0^{ps}	1.061	−	1.059
σ_{90}^{ps}	1.048	−	1.049
r_0	0.64	0.64	0.64
r_{45}	0.48	0.48	0.48
r_{90}	0.76	0.76	0.76
r_b	0.889	0.889	−

Table 4 Identified parameters of Yld2000-2d yield function for AlMgSi sheet

Parameter	EB	PS
α_1	0.9188	0.9263
α_2	1.0003	1.0415
α_3	0.9651	1.3763
α_4	0.9965	1.0798
α_5	1.0059	1.0588
α_6	1.0042	1.2671
α_7	0.9425	0.9828
α_8	1.1249	0.9226

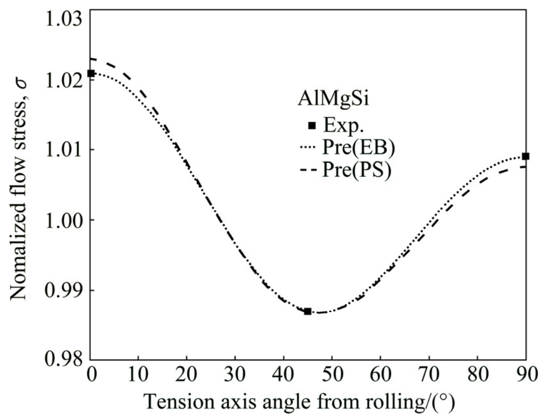

Fig. 4 Comparison of normalized flow stress for AlMgSi alloy sheet

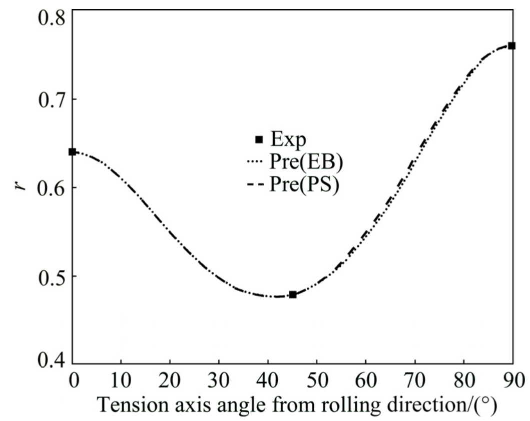

Fig. 5 Comparison of anisotropic coefficients for AlMgSi alloy sheet

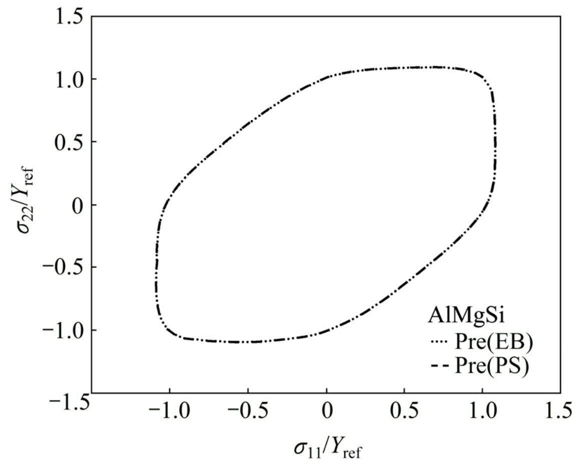

Fig. 6 Comparison of yield loci for AlMgSi alloy sheet

5 Conclusions

1) A simplified method for parameter identification of anisotropic yield function was presented by using the plane strain test instead of equi-biaxial tensile test. The simplified method and the traditional one were compared to calibrate the Yld2000-2d yield function for Al-5xxx alloy and AlMgSi alloy sheets.

2) For parameter identification of Yld2000-2d yield function by the two methods, the same anisotropic coefficients were used, so the predicted trend of anisotropic coefficient is very similar. However, when the yield stresses under plane strain state were adopted instead of those under equi-biaxial tensile state, the predicted trend of normalized flow stress shows very small discrepancy to be negligible.

3) The proposed method is validated for calibration of anisotropic yield function. It is more convenient for parameter identification to use plane strain test to provide the experimental data instead of equi-biaxial tensile test or other dedicated technique.

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采用平面应变替代等双拉实验的各向异性屈服函数识别

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摘 要：各向异性屈服函数参数识别中经常需要完成等双拉实验，但这要求专用的实验技术或设备。采用基于传统单轴拉伸实验装置的平面应变实验取代等双拉实验，以提供相关实验数据，完成各向异性屈服函数的参数识别。运用基于平面应变实验的简易方法，对 5xxx 铝合金和 AlMgSi 铝合金板材实现 Yld2000-2d 各向异性屈服函数的参数识别。结果表明，通过该方法预测的屈服应力、各向异性系数、屈服轨迹与实验值以及采用等双拉实验的预测值十分接近。因此，采用平面应变实验替代等双拉实验完成 Yld2000-2d 屈服函数参数识别的方法是有效的。

关键词：铝合金板材；各向异性行为；屈服函数；参数识别；平面应变实验

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