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Prediction of Anisotropy and Yield Surface of Aluminum Sheet by Polycrystal Plasticity Theory

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Formability of sheet metals is strongly influenced by their mechanical properties in terms of planar anisotropy (*r*-values), bi-axial flow stresses (yield surface), the Bauschinger effect and cyclic hardening characteristics. In order to develop high formability sheet metals, it is of vital importance to know the correlation of micro structures of metals with these macroscopic mechanical properties. In the present paper, macroscopic mechanical stress-strain responses of type A5052-O aluminum alloy sheet are calculated by the polycrystal plasticity theory (extended Taylor model) using EBSD crystallographic orientation distribution data. The calculated results of stress-strain responses under uniaxial tension and in-plane cyclic tension-compression, as well as the yield surfaces, agree well with the corresponding experimental results. Furthermore, the model well predicts the planar anisotropy (*r*-values in three directions) of the sheet.

Keywords: *Crystal plasticity, Plastic anisotropy, Virtual material test*

1. Introduction

In recent years, numerical simulations of sheet metal forming are widely used in many industrial fields. For the accurate forming simulation, it is of vital importance to employ an appropriate constitutive model which well describes the elasto-plasticity behavior of sheet metals. Especially, mechanical properties in terms of planer anisotropy (*r*-value), bi-axial flow stresses (yield surface), the Bauschinger effect and cyclic hardening characteristics should be properly taken into account in the model, since they are directly related to the sheet flow and springback behavior in metal forming. In the last few decades, much effort have been made for macro-material modeling for anisotropic sheet metals based on the continuum mechanics, and as a result, nowadays we have some sophisticated models which can well predict the anisotropic yielding (e.g.,[1]-[4]) and the Bauschinger effect (e.g., [5]).

Our next target in material modeling is to understand deeply how such macroscopic material properties are correlated with materials' micro structures. It is well-known that anisotropy of sheets is closely related to their crystallographic textures, and many works have been done to predict planer anisotropies (*r*-values) of sheet metals using ploycrystal plasticity theory [6]-[8]. The stress anisotropies, which are represented by the flow stress directionalities and the anisotropic yield surfaces, have also been investigated by several crystal plasticity models [8]-[11]. However, there are still very few works that discuss the Bauschinger effect together with the deformation and stress anisotropies of sheets based on the polycrystal plasticity. One of the reasons for it is that the macro-material tests to observe the Bauschinger effect and the biaxial yield surfaces for sheet metals are not so popular, and consequently, the macro experimental data to be compared to the theoretical predictions are entirely lacking.

In the present work, *r*-values, the flow stress directionalities, the bi-axial yield surface, the Bauschinger effect and cyclic hardening charcteristics, on type A5052-O aluminum sheet, are predicted by the extended Taylor model of ploycrystal plasticity using EBSD crystallographic texture data. The calculated results are compared to the corresponding experimental data of the macro behaviors.

2. Polycrystal plasticity model

We used the extended Taylor model of polycrystal plasticity which assumes that every crystal with equal volume has the same deformation gradient. The constitutive equation of this model is given by

$$\dot{\boldsymbol{\sigma}} = \mathbf{C} : \mathbf{D} - \sum_{\alpha=1}^{slip} \dot{\gamma}^{(\alpha)} \mathbf{C} : \mathbf{p}^{(\alpha)} \tag{1}$$

where $\mathbf{C}$ is the elasticity tensor, $\mathbf{D}$ is stretching tensor, and $\mathbf{p}^{(\alpha)} = sym\left(\mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)}\right)$ is so-called Schmid tensor where **s** is the slip direction unit vector and **m** is the outward normal to the slip plane.

The rate of plastic shear strain $\dot{\gamma}^{(\alpha)}$, is expressed by the following equation:

$$\dot{\gamma}^{(\alpha)} = \dot{\gamma}_0 \operatorname{sgn}\left(\tau^{(\alpha)} - a^{(\alpha)}\right) \left| \frac{\tau^{(\alpha)} - a^{(\alpha)}}{g^{(\alpha)}} \right|^{\frac{1}{m}} \tag{2}$$

where $\dot{\gamma}_0$ is reference slip rate, $\tau^{(\alpha)}$ is resolved shear stress, $a^{(\alpha)}$ the back stress, $g^{(\alpha)}$ the critical resolved shear stress (CRSS), and m is the rate sensitivity exponent. The superscript α means the α-slip system. The evolution equations for CRSS $g^{(\alpha)}$ is given by the equation:

$$\dot{g}^{(\alpha)} = \mathbf{n}_{\alpha\beta} \sum_{\beta}^{slip} \left(Q - g^{(\beta)}\right) \left|\dot{\gamma}^{(\beta)}\right|, \quad \mathbf{n}_{\alpha\beta} = \begin{cases} n & (\alpha = \beta) \\ qn & (\alpha \neq \beta) \end{cases} \tag{3}$$

where Q is the saturation value of CRSS, n denotes the saturation rate, q is the level of latent hardening, and c is the kinematic self-hardening rate. The linear back stress evolution law:

$$\dot{a}^{(\alpha)} = c\dot{\gamma}^{(\alpha)} \tag{4}$$

is also included in the present calculation for the accurate prediction of the Bauschinger effect. The macroscopic stress of the polycrystal is calculated based on the Taylor assumption by the following simple average of the stress of overall crystals:

$$\boldsymbol{\sigma} = \frac{1}{N_{crystal}} \sum_{i=1}^{N_{crystal}} \boldsymbol{\sigma}^{(i)} \tag{5}$$

where $N_{crystal}$ is total number of crystals, and $\boldsymbol{\sigma}^{(i)}$ is number i crystal's stress.

3. Experiment

3.1 Material

The material used in this investigation was type A5052-O aluminum sheet of 1.0 mm thick. The orientation imaging microscopy was carried out in an JEOL JSM-7001F scanning electron microscope integrated with computer-aided EDAX TSL electron back scattered diffraction (EBSD) system. The EBSD data were obtained by measuring 94395 points in 1042 crystals. Fig.1 shows the measured EBSD crystallographic orientation distribution data. Fig.2 is the pole figures obtained from the EBSD measurement.

3.1 Uniaxial tension test

The uniaxial tension tests were conducted for the specimens cut from the sheet in three directions of 0^{o} (rolling direction: R.D.), 45^{o} and 90^{o} (transverse direction: T.D.). From these, Yong's modulus, stress-strain curves and *r*-values were obtained.

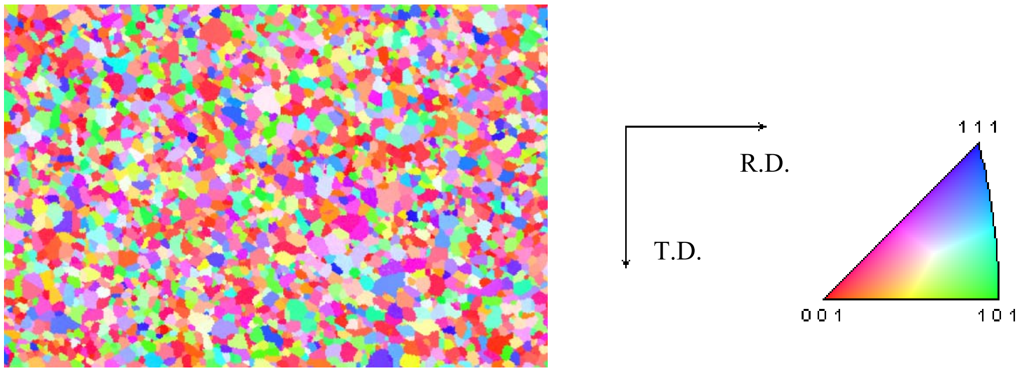


Fig.1 EBSD image of A5052-O in a region of 1 mm (in R.D.) ×0.7 mm (in T.D.)

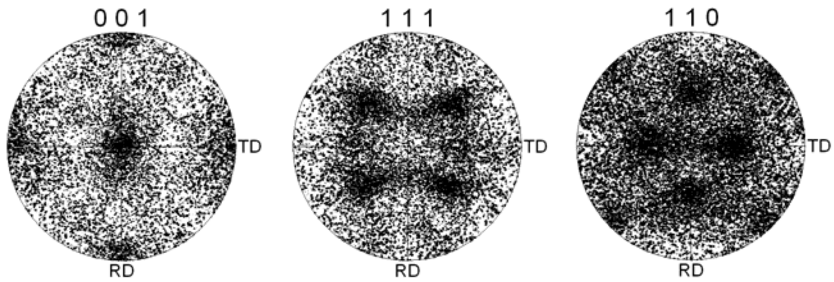


Fig.2 Pole figures obtained from EBSD measurement

3.2 Biaxial stretching experiment

To obtain the yield surface of the sheet the bi-axial stretching experiments were performed. Fig.3 shows the shape of the cruciform specimen for the experiment prepared by laser cutting. The size of gage section in this test piece is 50 mm x 50 mm, where the uniformity of stress distribution was guaranteed by FE calculation. The specimen has two slits in each arm, which is designed to release the deformation constraint on the gage section. The load capacity and the maximum stroke of each ram of the testing machine are 200 kN and 200 mm, respectively. Tensile loads were measured by load cells and biaxial strains were measured with strain gauges bonded on the surfaces of the cruciform test piece.

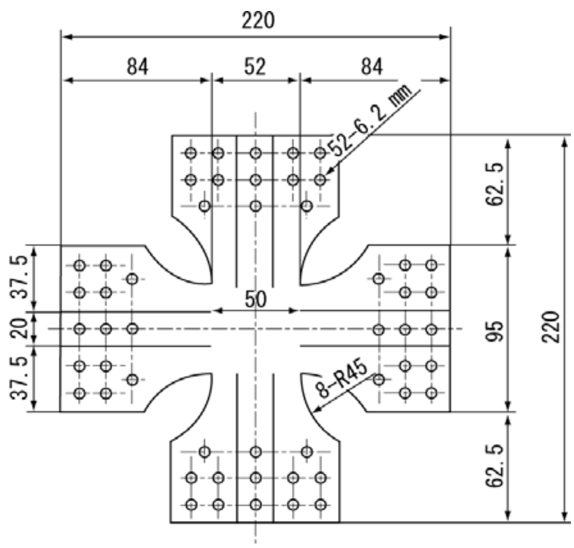


Fig.3 Shape of cruciform specimen for bi-axial stretching experiment (in mm)

3.3 In-plane cyclic tension-compression experiment

In-plane cyclic tension-compression test were carried out to observe the Bauschinger effect and cyclic hardening characteristics. The shape of the specimen for the cyclic tension-compression experiment is illustrated in Fig.4. In order to prevent the buckling of the specimen during compression deformation, four pieces of sheets were adhesively bonded together before machining so that the thickness of the specimen is 4.0 mm.

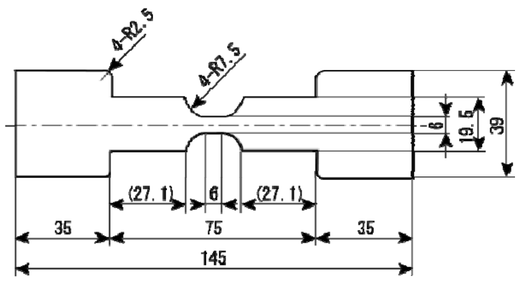


Fig.4 Shape of the specimen for in-plane cyclic tension-compression experiment (in mm)

4. Results and discussion

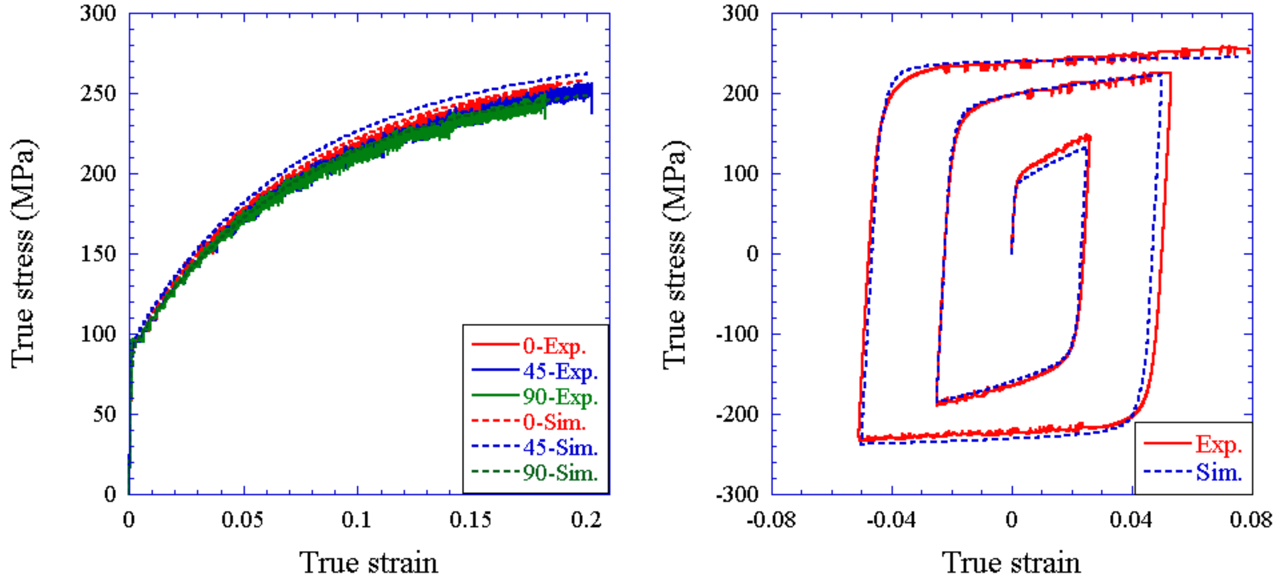
The material parameters in the polycrystal plasticity model for the aluminum sheet, which were identified from the R.D. uniaxial tension test, are listed in Table 1. Fig.5 (a) shows the comparison of simulated stress-strain curves of uniaxial tension in three directions of 0^o (R.D.), 45^o and 90^o (T.D.) with the corresponding experimental results. For both the results of simulation and experiment, weak flow stress directionality is found and the calculated results are in good agreement with the experimental ones.

Table 1 Material parameters

Crystalline structure		FCC
Calculate point number		92892
g_{ini}	{111}	34 (MPa)
Elastic tensor	C_{11}	106.0 (GPa)
	C_{12}	64.0 (GPa)
	C_{44}	28.0 (GPa)
Reference slip rate	γ_0	0.001
Rate sensitivity rate	m	0.05
Implicit parameter	θ	0.5
Level of latent	q	1.2
Isotropic hardening	n	4.2
Isotropic saturation	Q	93 (MPa)
Kinematic hardening	C	10 (MPa)

Table 2 *r*-values at 10% plastic strain

Tensile angle	Experiment	Simulation
0°	0.72	0.89
45°	0.51	0.44
90°	0.60	0.64



(a) (b)

Fig.5 Comparisons of experimental results of stress-strain responses of type A5052-O sheet with the calculated results by the polycrystal plasticity model: (a) uniaxial tension tests in three directions (0°, 45° and 90° with respect to the R.D.) of the sheet; and (b) in-plane cyclic tension-compression experiment.

The r-values at 10% plastic strain, both the results of polycrystal plasticity calculation and the experiment, are listed in Table 2. This sheet has the largest r-value at 0° and the smallest at 45°. The model captures this planar anisotropy, and the difference in r-values between the predictions and the experimental data are not so large.

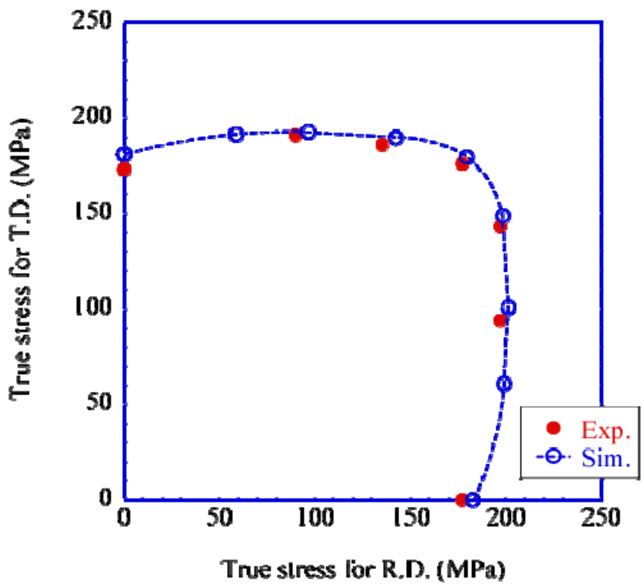


Fig.6 Comparison of the experimental data plots of equi-plastic work at 5% plastic strain with the prediction by the polycrystal plasticity model.

Fig.5 (b) shows the in-plane cyclic stress-strain response in the R.D. together with the corresponding experimental data. The calculated result shows the excellent agreement with the experimental one. Although this model assumes the linear backstress evolution (see Eq. (4)), highly nonlinear stress-strain responses in each reverse deformation (so-called '*transient Bauschinger effect*') is reproduced very well. From this result, it is concluded that the main source of the Bauschinger effect of this material is the heterogeneous stress distributions induced during plastic deformation in each grain of a polycrystal, and furthermore, *the intrinsic Bauschinger effect* (represented by Eq. (4)), which a single crystal has, also contributes to it.

Fig.6 shows the experimental data plots of equi-plastic work at 5% plastic strain, and the corresponding calculations by the polycrystal plasticity model. The calculated equi-plastic work surface (we may call it 'yield surface' when assuming the *isotropic hardening*) agrees well with the experimental results.

5 Conclusion

In the present paper, macroscopic mechanical stress-strain responses of type A5052-O aluminum alloy sheet were calculated by the polycrystal plasticity theory (extended Taylor model) using EBSD crystallographic orientation distribution data. Several types of macro material tests were also conducted to examine the accuracy of the model predictions. The highlights of the present findings are summarized as follows:

1. For stress-strain responses under uniaxial tension and in-plane cyclic tension-compression, the yield surfaces, as well as the planar anisotropy (r-values in three directions) of the sheet, the calculated results agree well with the corresponding experimental ones.
2. A special emphasize is placed on the excellent description by the model for the Bauschinger effect and cyclic hardening characteristics. It would be concluded that the main source of the Bauschinger effect of this material is the heterogeneous stress distributions, induced during plastic deformation, in each grain of a polycrystal, and furthermore, *the intrinsic Bauschinger effect* also contributes to it.

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