Experimental Observation of Elasto-Plasticity Behavior of Type 5000 and 6000 Aluminum Alloy Sheets*1

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Elasto-plasticity behavior of type A5052-O and AA6016-T4 aluminum alloy sheets was examined by performing several experiments of uniaxial tension, biaxial stretching and in-plane cyclic tension-compression. Both sheets exhibit apparent r-value planar anisotropy, especially for AA6016-T4 it is extremely strong, while their flow stress directionality under uniaxial tension is not so significant. Both the sheets show strong cyclic hardening with weak Bauschinger effect. Such material behavior is well described by Yoshida-Uemori kinematic hardening model combined with an appropriate choice of anisotropic yield function. [doi:10.2320/matertrans.L-MZ201101]

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1. Introduction

Aluminum alloy sheets are attractive lightweight materials, however their formability is not so good as mild steel sheets because strain localization is more likely to occur, and furthermore, they have large springback due to their low elastic rigidity (their Young’s modulus is about 1/3 of steel). They often show significant planar anisotropies both in r-values and flow stresses,1–3) strongly influence the sheet metal flow in press forming. To describe such a crystallographic texture-induced anisotropy, several anisotropic yield functions have been proposed in the past (e.g., Hill’48,4) Hill’90,5) and Fusahito Yoshida10)). The Bauschinger effect, which is a typical deformation-induced anisotropy, extremely affects springback behavior of sheet metals, since in many cases of sheet metal forming a sheet is subjected to bending-unbending, which is a process of cyclic plasticity deformation.10) A reverse deformation at a large strain is characterized by early re-yielding, transient Bauschinger effect and permanent stress-offset (softening), and furthermore, workhardening stagnation appearing in a certain range of reverse deformation (see Hu et al.,11) Takahashi et al.,12) Yoshida et al.10)). To describe all of these reverse deformation characteristics, two of the present authors (Yoshida & Uemori13,14) proposed a large-strain cyclic plasticity model, which are widely accepted for its high accuracy and flexibility in describing several types of materials (e.g., see Eggertsen & Mattiason15)). Although this model provides a framework that can incorporate any types of anisotropic yield function, there are still very few papers on material modeling, for aluminum sheets, which take into account both the planar anisotropy and the Bauschinger effect based on experimental observations (c.f., Barlat et al.7–9) and Kuwabara8) intensively investigated the anisotropic yield loci of aluminum sheets in the framework of the isotropic hardening model, but not the kinematic hardening model).

In the first part of this paper, the elasto-plasticity deformation characteristics of two types of aluminum sheets (A5052-O and AA6016-T4) are summarized from newly obtained experimental results of uniaxial tension, biaxial stretching and in-plane cyclic tension-compression. In the second part, material modeling for the planar anisotropy, as well as the Bauschinger effect and cyclic hardening characteristics, is discussed in the framework of an advanced kinematic hardening model (Yoshida-Uemori model,13,14) hereafter, we call it ‘Y-U model’) incorporating with an appropriate choice of anisotropic yield function. For such a material model, we discuss whether it is possible to identify two sets of material parameters, one for the anisotropic yield function and the other for the kinematic hardening law, separately, by using experimental data for the yield locus and the data of cyclic plasticity, respectively.

2. Experimental Procedures

Test materials used in this study were type A5052-O of 1.2-mm thick and AA6016-T4 of 1.0-mm thick. Uniaxial tension tests were carried out using Autograph AG-IS (SHIMADZU, load capacity is 50kN). JIS 13A-type specimen (parallel portion is 20-mm wide and 120-mm long) was used in the uniaxial tension test. Stress-strain curves and r-values were determined by uniaxial tension experiments in five directions (0°, 22.5°, 45°, 67.5° and 90° from the rolling direction).

Biaxial stretching tests were carried out using the cruciform specimen (see Fig. 1). The specimen has two slits in each arm, which is designed so as to release the deformation constraint on the gauge section. The strains, εx and εy, were measured by strain gauge bonded on the surface of the specimen. Initial yield locus and the subsequent equi-plastic work loci, and furthermore, the direction of plastic strain increment were obtained. The stresses σx and σy were

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calculated by the following equations based on St Venant’s principle:

$$\sigma_x = \left(\frac{P_x}{A_0}\right) \exp(\epsilon_x), \quad \sigma_y = \left(\frac{P_y}{A_0}\right) \exp(\epsilon_y),$$  \hspace{1cm} (1)

where $P_x$ and $P_y$ are the applied loads, $A_0$ is the initial cross-sectional area of the square portion ($52 \text{ mm} \times 52 \text{ mm}$) of the specimen, and $\epsilon_x$ and $\epsilon_y$ are the true strains measured by strain gauge (YEFCA-2, Tokyo Sokki Kenkyujo Co. Ltd.). From FE simulation of biaxial stretching, it was confirmed that the errors of thus determined stresses are within $\pm 3.1\%$ for stress ratios of $0.5 \leq \sigma_y/\sigma_x \leq 2.0$. Here, FE simulation assumed the isotropic hardening with von Mises yield criterion. Figures 2(a) and (b) show the contours of the equivalent stresses in a specimen under biaxial loadings of $P_x : P_y = 1 : 1$ and $P_x : P_y = 2 : 1$, respectively. It is seen from these figures that the equivalent stresses homogeneously distribute in enough wide area near the center of the specimen. Note that in such a testing, the homogeneity of stresses in whole the square region of the specimen is not necessary. If the stress at the strain gauge area (near the center) is determined by eq. (1) within an acceptable small error, it is enough for stress determination. For example, Figs. 3(a) and (b) show FE simulation results of two stress-strain curves, one uses stresses determined by eq. (1) (solid line) and the other is the case of stresses at the center of the specimen (dotted line), for $P_x : P_y = 1 : 1$ and $P_x : P_y = 2 : 1$, respectively. The two stress-strain curves are so close to each other. Such an experiment of biaxial stretching using cruciform specimens was first performed by Shiratori and Ikegami,\textsuperscript{16}) and several data on yield loci obtained from the similar experiments have also been reported by some other researchers in the last few decades (e.g., Green \textit{et al.},\textsuperscript{17}) Kuwabara\textsuperscript{18}).

3. Framework of Material Modeling

When the yield function at the initial state, $f_0$, has a general form:

$$f_0 = \phi(\sigma) - Y = 0,$$  \hspace{1cm} (2)

where $\phi$ denotes a function of the Cauchy stress $\sigma$, and $Y$ is the initial yield strength. For function $\phi$, we may choose an appropriate one among existing anisotropic yield functions. Assuming the kinematic hardening of the yield locus, the subsequent yield criterion is generally written by

$$f = \phi(\sigma - \alpha) - Y = 0,$$  \hspace{1cm} (3)

where $\alpha$ stands for the backstress. The associated flow rule is written as

$$D^p = \frac{\partial f}{\partial \sigma} \dot{\lambda} = \frac{\partial \phi}{\partial \sigma} \dot{\lambda},$$  \hspace{1cm} (4)
where $\mathbf{D}^p$ denotes the plastic part of the rate of deformation. Thus the constitutive equation of plasticity is derived by determining the evolution law of the backstress $\mathbf{C}_{11}$, together with an appropriate choice of an anisotropic yield function $\mathbf{C}_{30}$.

As for the kinematic hardening law, here we use Y-U model.\textsuperscript{13,14} This model is constructed in the framework of two-surface modeling, wherein the yield surface moves kinematically within the bounding surface, as schematically illustrated in Fig. 5. The bounding surface $\mathbf{F}$ is expressed by the equation

$$
\mathbf{F} = \mathbf{C}_{30}(\mathbf{C}_{27}; \mathbf{C}_{12}) = 0, \quad (5)
$$

where $\mathbf{C}_{12}$ denotes the center of the bounding surface, and $B$ and $R$ are its initial size and isotropic hardening (IH) component. One of the strong originalities of this model is a proposition of a kinematic hardening law that accurately expresses the Bauschinger effect of materials. The relative kinematic motion of the yield surface with respect to the bounding surface is expressed by

$$
\alpha^* = \alpha - \beta. \quad (6)
$$

For the evolution of $\alpha^*$, the following equation is assumed:

$$
\dot{\alpha}^* = C \left[ \left( \frac{a}{Y} \right) (\alpha - \alpha^*) - \sqrt{\alpha^*} \right] \dot{\mathbf{p}}, \quad (7)
$$

$$
\dot{\mathbf{p}} = \sqrt{\frac{2}{3}} \mathbf{D}^p : \mathbf{D}^p, \quad \alpha^* = \phi(\alpha^*), \quad a = B + R - Y. \quad (8)
$$

where $\dot{\mathbf{p}}$ is the equivalent plastic strain rate, defined as the second invariant of $\mathbf{D}^p$, and $C$ and $a$ are material parameters that control the rate of the kinematic hardening. For the isotropic hardening of the bounding surface, the following evolution equation is assumed:

$$
\dot{\mathbf{R}} = m(\mathbf{R}_{sat} - \mathbf{R})\dot{\mathbf{p}}, \quad (9)
$$

where $\mathbf{R}_{sat}$ is the saturated value of the isotropic hardening stress $\mathbf{R}$ at infinitely large strain, and $m$ is a material parameter that controls the rate of isotropic hardening. For the kinematic hardening of the bounding surface, the following evolution equation is assumed:

$$
\dot{\beta} = m \left( \frac{b}{Y} \right) (\sigma - \alpha) - \beta \dot{\mathbf{p}}, \quad (10)
$$

where $b$ denotes a material parameter. Here, parameter $m$ is assumed to be the same as in the evolution equation of the isotropic hardening stress. To describe the phenomenon of workhardening stagnation appearing in a reverse deformation, the model of non-IH hardening surface is introduced (refer to Yoshida & Uemori\textsuperscript{13,14}).

Besides the kinematic hardening model, the following model of plastic-strain dependent Young’s modulus (Yoshida et al.\textsuperscript{10}) was used in the calculation:

$$
E = E_0 - (E_0 - E_\infty)(1 - \exp(-\xi \hat{\epsilon})), \quad (11)
$$

where $E_0$ and $E_\infty$ stands for Young’s modulus for virgin and infinitely large pre-strained materials, respectively, and $\xi$ is a material constant.

As for anisotropic yield functions, here we examine the followings:
4. Experimental Results and Discussion

4.1 Deformation behavior under uniaxial tension

Stress-strain curves of A5052-O and AA6016-T4 under uniaxial tension are illustrated in Figs. 6(a) and (b), respectively, for the specimens cut from the sheets in three directions of 0°, 45° and 90° with respect to their rolling direction. Type A5052-O sheet exhibits apparent yield plateau and serrations in the stress-strain curves, which is caused by well-known Portevin-Le Chatelier (PLC) effect. From these figures it is found that the flow stress directionality is not very significant for both sheets. The mechanical properties of the sheets in terms of yield strengths, $\sigma_y$, (defined as stresses at 3% or 4% plastic strain), and r-values, $r_a$ at $\alpha = 0°, 22.5°, 45°, 67.5°$ and 90°, are summarized in Table 1. In addition, biaxial yield strength, $\sigma_{bi}$, determined from biaxial stretching experiment is also indicated. These sheets exhibit apparent r-value planar anisotropy, especially for AA6016-T4 it is extremely strong. In Figs. 7(a) and (b), the calculated results of flow stress directionality (flow stress $\sigma_y$ normalized by $\sigma_0$), for A5052-O and AA6016-T4, respectively, by several yield functions are compared with the corresponding experimental data. Here, for Hill’48’s yield criterion, completely different two sets of anisotropic parameters can be determined depending on the selection of mechanical properties used for parameter identification, where r-values $(r_{0}, r_{45}$ and $r_{90})$ are used for Hill’48-r and yield stresses $(\sigma_0, \sigma_{45}$ and $\sigma_{90})$ for Hill’48-σ. For Yld2000-2d’s yield function, exponent of $a = 6$ was used in the simulation. Among these, Yld2000-2d $(a = 6)$ gives the best fit to the experimental results, and the results by Gotoh’s yield function are also reasonably well. The Gotoh’s calculation of $\sigma_y$ at $\alpha = 67.5°$ on AA6016-T4 shows a bit large error, since in this material parameter identification $\sigma_0$, $\sigma_{22.5}, \sigma_{45}, \sigma_{90}, \sigma_{bi}$ and $r_0, r_{22.5}, r_{45}, r_{90}$ are solely employed as Gotoh proposed in his paper, but not $r_{77.5}$ and $\sigma_{90}$. Instead of using $r_{22.5}$, if we used $\sigma_0$, $\sigma_{22.5}, \sigma_{45}, \sigma_{90}, \sigma_{bi}$ as Hu proposed, the results would become better. Hill’48-σ model predicts the flow stress directionalities on both the sheets, since it employs $\sigma_0$, $\sigma_{bi}$ for material parameter identification. In contrast, the predictions by Hill’48-r model are very poor.

In Figs. 8(a) and (b), the calculated results of r-value planar anisotropies, for A5052-O and AA6016-T4, respectively, by several yield functions are compared with the

Fig. 6 Stress-strain curves under uniaxial tension of aluminum sheets in three directions of 0°, 45° and 90° with respect to their rolling direction. (a) A5052-O; (b) AA6016-T4.

Table 1 Mechanical properties for A5052-O and AA6016-T4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle from rolling direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>Stress/MPa</td>
<td></td>
</tr>
<tr>
<td>A5052-O$^{(1)}$</td>
<td>166</td>
</tr>
<tr>
<td>A5052-O$^{(2)}$</td>
<td>195</td>
</tr>
<tr>
<td>A6016-T4$^{(1)}$</td>
<td>166</td>
</tr>
<tr>
<td>A6016-T4$^{(2)}$</td>
<td>195</td>
</tr>
<tr>
<td>r-value</td>
<td></td>
</tr>
<tr>
<td>A5052-O$^{(3)}$</td>
<td>0.72</td>
</tr>
<tr>
<td>A6016-T4$^{(3)}$</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Superscripts s1, s2 and s3 indicate plastic strains of 0.04, 0.03 and 0.1, respectively, where stresses and/or r-values were obtained.

- Hill’48 quadratic function:

$$ f = \frac{1}{2} \left[ F\sigma_{xy} + G\sigma_{xx} - (\sigma_{xx} - \sigma_{yy})^2 + 2N\sigma_{xy}^2 \right] - G + H \sigma^2 = 0, $$

(12)

where $F$, $G$, $H$ and $N$ are anisotropic material parameters. For Gotoh’s bi-quadratic function:

$$ f = A_1\sigma_{xx}^2 + A_2\sigma_{xx}\sigma_{yy} + A_3\sigma_{xx}^2 + A_4\sigma_{yy}^3 $$

$$ + A_5\sigma_{xx} + (A_6\sigma_{xx}^2 + A_7\sigma_{xx}\sigma_{yy} + A_8\sigma_{yy}^2)\tau_{xy}^2 $$

$$ + A_9\tau_{xy}^4 - A_1\sigma^3 = 0, $$

(13)

where $A_1$ to $A_9$ are anisotropic material parameters.

- Barlat Yld2000-2d model:

$$ \phi = \phi' + \phi'' = 2\tilde{\sigma}^a, \quad \phi' = |X'_1 - X'_2|^a, $$

$$ \phi'' = |2X''_2 + X''_1|^a + |2X''_1 + X''_2|^a, $$

(14)

where $X'_1$, $X'_2$, $X''_1$ and $X''_2$ denote principal values of $X' = L' : \sigma$ and $X'' = L'' : \sigma$, respectively. $L'$ and $L''$ are transformation matrix that contain eight anisotropic material parameters. The exponent $a$ is usually chosen as either 6 or 8.

Most of previous papers on material modeling for aluminum sheets focus either on the description of the Bauschinger effect (e.g., Boger et al.) or on the anisotropic yield function (e.g., Barlat et al.; Kuwabara et al.; Naka et al.), in contrast, the present paper discusses both the material characteristics in the framework of cyclic plasticity modeling with the anisotropic yield function.
corresponding experimental data. The predictions by Yld2000-2d \((a = 6)\), Gotoh and Hill’48-r are in good agreement with the experimental results, since all these models employ at least three \(r\)-values \((r_{0}, r_{45}, r_{90})\) for material parameter identification. In contrast, Hill’48-\(\sigma\) model fails in the prediction.

In order to investigate the dependency of plastic strain of Young’s modulus, incremental tension-unloading experiments were performed, and Young’s moduli of pre-strained sheets were obtained from unloading stress-strain slopes. Figure 9 shows the relationship between Young’s modulus and accumulated plastic strain on A5052-O and AA6016-T4. The result of A5052-O showed that Young’s modulus is almost kept constant independently on the plastic strain, while that for AA6016-T4 decreases slightly with increasing plastic strain, which can be expressed by eq. (10).

### 4.2 Equi-plastic work loci under biaxial stretching

Figures 10(a) and (b) show the comparison of normalized equi-plastic work loci (defined as stresses at 3% or 4% plastic strain) with the corresponding predictions by several yield functions. Note that the equi-plastic work loci are identical with the yield loci only when the isotropic hardening of the yield loci is assumed.

From the experimental results, it is found that the shape of equi-plastic work locus of A5052-O is almost symmetric with respect to equi-biaxial stress axis \((\sigma_{x} = \sigma_{y})\). Contrary to this, the yield locus of AA6016-T4 is not symmetry, and it expands toward plane strain side \((\sigma_{x} : \sigma_{y} = 2 : 1)\). The yield loci calculated by Gotoh’s function agrees well with the experimental results of both A5052-O and AA6016-T4. The predictions of the loci by Yld2000-2d are mostly in good agreement with the experimental results of both sheets, while a certain discrepancy is found in the yield stress of AA6016-T4 at \(\sigma_{x} : \sigma_{y} = 2 : 1\). Since von Mises’s yield function
assumes isotropy of materials, the discrepancies between experimental results and the predictions of \( r \)-values and yield stresses are very large especially for AA6016-T4. As already mentioned, Hill’48-\( \sigma \) hardly predicts \( r \)-values for both sheets (see Table 1) although the calculated results of the equi-plastic work loci agree fairly well with the experimental results. On the other hand, Hill’48-\( r \) completely fails in simulating the loci.

Furthermore, the validation of normality rule was also carried out. Figures 11(a) and (b) show the comparison of direction of plastic strain incremental vectors between experimental results and the corresponding calculated ones using various yield functions. In the experiments, the directions of plastic strain rate were kept constant during plastic deformation. Gotoh’s and Yld2000-2d’s yield functions predict well both equi-plastic work loci and plastic strain vector.

4.3 Cyclic tension-compression

Figures 12(a) and (b) show the stress-strain curves obtained from in-plane cyclic tension-compression test and uniaxial tension test. In these figures, the calculated results by the IH (isotropic hardening) model and Y-U model are illustrated. From these, significant cyclic workhardening and weak Bauschinger effect (compared to high strength steel sheets\(^{10} \)) are found for both materials. Y-U model successfully describes such characteristics of cyclic stress-strain responses. Note that works on cyclic plasticity modeling for aluminum sheets based on the experimental data, which are of importance for numerical simulation of multi-stage sheet metal forming, are still very limited, although there are some discussions on the Bauschinger effect in reverse deformations (e.g., Lee et al.\(^{23} \)).

5. On Modeling of Cyclic Plasticity for Anisotropic Materials

Figures 13(a) and (b) show the comparisons of the calculated results by two models of the IH and Y-U, for equi-plastic work loci and the directions of plastic strain increments, respectively, under proportional (radial) loadings on A5052-O. Here Gotoh’s yield function is used in both models. From these, it is found that the calculated results by IH and Y-U models are almost the same. Note that it does not mean that IH model is sufficient for the description of cyclic plasticity behavior (see Fig. 12: cyclic stress-strain response calculated by IH model). For accurate simulation of the Bauschinger effect and cyclic hardening characteristics, the use of a non-linear kinematic hardening model is essential. An important conclusion
derived from the results shown in Figs. 13(a) and (b) is that we can identify two sets of material parameters, one for the anisotropic yield function and the other for the kinematic hardening law, separately, by using experimental data for the yield locus and the data of stress-strain responses of uniaxial cyclic plasticity, respectively.

6. Conclusions

Elasto-plasticity behavior of type A5052-O and AA6016-T4 aluminum alloy sheets was examined by various experiments. From the comparison of the experimental observations of the stress-strain responses with the corresponding simulations using several models of anisotropic plasticity, appropriate material modeling was discussed. The highlights of the present findings are summarized as follows:

1. Both sheets exhibit apparent r-value planar anisotropy, especially for AA6016-T4 it is extremely strong, while their flow stress directionality under uniaxial tension is not so significant.
2. Both the sheets show strong cyclic hardening with comparatively weak Bauschinger effect.
3. Such material behavior is described accurately by Y-U kinematic hardening model with an appropriate choice of anisotropic yield function. As for anisotropic yield functions, either Gotoh’s bi-quadratic function or Barlat’s Yld2000-2d is a good choice for these aluminum sheets.

4. One of the advantages of the present framework of material modeling is that two sets of material parameters, one for the anisotropic yield function and the other for the kinematic hardening law can be identified separately. For the yield function parameters we solely use experimental data of the yield loci (or equi-plastic work loci) under proportional (radial) loadings, and for the parameters of kinematic hardening law only data of stress-strain responses of uniaxial cyclic plasticity are necessary.

REFERENCES


