Aluminum sheet metals have been widely utilized for a light weight construction of automobile. However, these metals still remain one of the difficult materials to predict the accurate final shapes after press forming processes, because of several mechanical features such as plastic anisotropy of yield stress and small Lankford value. In order to solve the problems, the present author has developed a new constitutive model. The model can describe accurate non-proportional hardening behaviors of aluminum sheet metals. In the present research, some experimental procedures were carried out to reveal the mechanical properties of an aluminum sheet under proportional and non-proportional deformations. The comparisons between experimental data and the corresponding calculated results by the proposed constitutive model confirm the advantages of our model.

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1. Introduction

With tremendous advances of the computational technologies, finite element calculations of sheet metal stamping, using some commercial finite element codes, have been widely popular among various fields of metal forming industries, especially press-forming industries. However, still now the accuracy of numerical simulation is...
not always guaranteed, especially in springback analysis. In most of cases of stamping simulations, the criterion combined von Mises yield criterion with an isotropic hardening model is utilized by default, however, it causes the serious errors of stress analysis due to the lack of description of the plastic anisotropy and the Bauschinger effect of sheet metals. An appropriate choice of the combination is very important for an accurate sheet-metal stamping simulation.

For that purpose, Yoshida and Uemori (2003, 2010, 2011) have proposed “Yoshida-Uemori model” and its high capability in simulating cyclic behavior. The model has been already verified by comparing the numerical simulations with several evidences (e.g., Uemori, 2010; Tamura, 2010). The verification of this model is not guaranteed for especially the non-proportional deformation behaviors of low yield point materials. In order to solve the problem, the present author has proposed a new constitutive model (“modified Yoshida-Uemori model”) which can describe non-proportional deformation. The verification of the proposed model for an aluminum sheet metal was examined in the present research.

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( Y \) | initial yield stress |
| \( \phi \) | yield function |
| \( D_p \) | plastic strain rate tensor |
| \( \dot{\rho} \) | equivalent plastic strain rate |
| \( \sigma \) | Cauchy stress tensor |
| \( \alpha \) | back stress tensor of yield surface |
| \( \alpha' \) | back stress tensor rate of yield surface |
| \( \alpha_r \) | relative back stress tensor |
| \( \alpha_{rel} \) | equivalent Relative back stress tensor |
| \( \beta \) | back stress tensor of bounding surface |
| \( \beta' \) | back stress tensor rate of bounding surface |
| \( q \) | back stress tensor of non-isotropic hardening region |
| \( q' \) | back stress tensor rate of non-isotropic hardening region |
| \( a \) | material parameter of Yoshida-Uemori & Modified Yoshida-Uemori model |
| \( B \) | initial radius of bounding surface |
| \( C \) | hardening rate of back stress for yield surface |
| \( m \) | hardening rate of back stress for bounding surface |
| \( R_{sat} \) | saturated value of isotropic hardening for bounding surface |
| \( R \) | isotropic hardening stress of bounding surface |
| \( \dot{p} \) | equivalent plastic strain rate |
| \( h \) | material parameter for workhardening stagnation |
| \( \Gamma \) | radius of non-hardening religion |
| \( T \) | temporary hardening/softening of bounding surface |
| \( C_{Th} \) | temporary hardening rate of kinematic hardening during non-proportional deformation |
| \( C_{Ts} \) | temporary softening rate of kinematic hardening during non-proportional deformation |
| \( C_o \) | initial hardening rate of back stress for yield surface |
| \( C_C \) | relative hardening rate of back stress for yield surface during non-proportional deformation |

2. Experimental procedures

In the present research, In order to obtain the material properties of an aluminum sheet metal (A1050-O), the following several kinds of material tests were conducted.
2.1. Uniaxial tension tests

Uniaxial tension tests were carried out for specimens (JIS type 13, thickness 1.0mm) cut from an aluminum sheets of A1050-O in five directions of 0° (rolling direction), 22.5°, 45°, 67.5° and 90°. The initial yield stress for each direction and the Lankford values for the sheet are listed in Table 1. This table shows that the anisotropy of this sheet is rather weak.

| Tensile direction /deg | 0°  | 22.5° | 45°  | 67.5° | 90°  |
|------------------------|-----|-------|------|-------|------|
| Initial yield stress /MPa | 22  | 21    | 20   | 22    | 22   |
| Lankford value         | 0.72| 0.77  | 0.83 | 0.66  | 0.58 |
| Young’s modulus /GPa   | 70  | 70    | 72   | 72    | 70   |

2.2. Pre-straining tests

In order to obtain the pre-strained A1050-O sheet metal, pre-tensile tests were conducted by using large size specimen, see Fig.1. After pre-straining, several specimens with an arbitrary large strain for tension-compression tests were cut from this large size test piece. For the strain measurements, the strain gauges were set on the center of the test piece. FE simulation (MSC.Marc2013.0.0) confirmed that the parallel parts of the foregoing large size specimen deform uniformly at large strain ranges.

Fig. 1. Schematic illustrations of pre-straining test: (a) After pre-straining procedures, several specimen cut from the large size specimen, (b)Shape of specimens for pre-straining test (unit: mm)

2.3. Bi-axial tension test

We conducted bi-axial tension test to evaluate the type of the yield function of the present material. Tensile loads are measured by load cells (capacity of 400 kN), and displacements are measured by displacement transducers set in each axis. Fig. 2 shows a cruciform specimen for bi-axial stretching tests. The size of gage section is 50 mm × 50 mm. For strain measurement, strain gauges were used. Fig. 3 shows the initial yield loci
calculated by the above mentioned several types of yield functions, together with the corresponding experimental data. The yield functions calculated results by Hill 1948 yield function agrees well with the experimental data.

Fig.2 Cruciform specimen for biaxial tension experiments (in mm).  
Fig.3 Yield loci calculated by the three types of yield functions.

2.4. In-plane cyclic tension-compression tests

In order to reveal the cyclic stress-strain responses for the aluminium sheet metal with non-proportional deformation histories, six pre-strained aluminium sheets were utilized to produce one test piece for non-proportional cyclic test. The size of test piece is shown in Fig. 4. The six sheets were laminated and adhesively bonded together in order to prevent buckling under compression loading. Constant cyclic straining range (strain history: $0 \rightarrow +5\% \rightarrow -5\%$, $\cdots$) was imposed on the test pieces. Tests were carried out until the rupture or buckling occurs. The thickness of each adhesive layer was as thin as 0.01mm, so that the effect of the adhesive layer on the stress strain response was negligibly small (Yoshida and Uemori, 2002).

Fig. 4. Shapes for specimen for non-proportional cyclic tension-compression test (unit: mm)

3. Constitutive modeling

3.1. Modified Yoshida-Uemori model

Yoshida-Uemori model has been widely used as one of the most accurate constitutive model which can describe the Bauschinger effect very precisely. However, the model has some problems to describe stress-strain responses with non-proportional deformation histories. In order to describe the complicated stress-strain response properly, a new constitutive model has been developed for materials with low initial yield stresses. The details of our new constitutive model is described as follows. For yield function $\phi$, we may choose one among existing anisotropic yield functions (e.g., Hill, 1948; Gotoh, 1977; Logan-Hosford, 1980; Barlat, 2003). The criterion for the subsequent yield is written by
\[ f = \phi(\sigma, \alpha) - (Y + T) = 0, \] (1)

where \( \sigma \) and \( \alpha \) denote the Cauchy stress and the back stress, respectively. \( Y \) is the initial yield stress and \( T \) is the temporary expansion of yield surface during stress-reversal. The evolution of the temporary hardening/softening \( T \) in the above mentioned equation is defined as the following equation.

\[ dT = \left[ C_{th} \left( 1 - \frac{(\sigma - \alpha) : \alpha}{\|\sigma - \alpha\|\alpha} \right) a - C_{T_s} T \right] \dot{p}, \quad \dot{p} = \sqrt{\frac{2}{3} \sigma : \sigma}, \] (2)

where \( C_{th}, C_{T_s} \) and \( a \) are material constants. The plastic strain rate \( \sigma^p \) is determined by the associated flow rule:

\[ \sigma^p = \frac{\partial \phi}{\partial \sigma}. \] (3)

The relative kinematic motion of the yield surface with respect to the bounding surface is expressed by

\[ \alpha = \alpha - \beta, \] (4)

\[ \alpha^* = C \left[ \left( \frac{a}{Y} \right) (\sigma - \alpha) - \frac{a}{\sqrt{\alpha}} \right] \dot{p}, \quad \alpha^* = \phi(\alpha^*), \quad C = C_0 + C_C \left( 1 - \frac{\sigma : \beta}{\|\sigma\|\beta} \right), \] (5)

\[ \beta^* = m \left[ \left( \frac{b}{Y} \right) (\sigma - \alpha) - \beta \right] \dot{p}. \] (6)

where \( m, b, C_0 \) and \( C_C \) are material constants. To describe workhardening stagnation, the evolution equations of the non-isotropic hardening surface is written by

If \( g_\sigma = 0 \) and \( (\beta - q) : \beta > 0 \) then,

\[ \dot{R} = m(R_{\text{sat}} - R) \dot{p}, \quad q^* = (1 - h) R, (\beta - q) \] (7)

Otherwise,

\[ \dot{R} = m(R_{\text{sat}} - R) \left( 1 - \frac{\beta : \beta}{\|\beta\|\beta} \right) \dot{p}, \quad q^* = 0. \] (8)

where \( R \) is the isotropic hardening stress, and \( R_{\text{sat}} \) is its saturated value at infinitely large plastic strain. \( q \) is the back stress of non-isotropic hardening surface. \( h \) is a material constant.
4. Results and discussion

The compressive stress-strain responses of prestrained aluminum sheet in the 45° and 90° angle with respect to the R.D. are shown in the Fig. 5, respectively. These stress-strain curves are obtained by using the specimens after 5% and 10% plastic straining in the R.D. These results show completely different stress-strain curves from the response of the uniaxial compression in the rolling direction. From these results, it is founded that stress-strain responses (the Bauschinger effect) are dependent on both the plastic deformation histories and pre-strained directions. The experimental stress-strain responses in each directions have common features: (a) The stress-strain responses with non-proportional deformation history show yield plateau during re-yielding, (b) With the increases of plastic deformations, the stress level is getting to be equal to the one of compression deformation in the R.D.

The stress-strain responses calculated by Yoshida-Uemori model and the modified Yoshida-Uemori model are also shown in Fig.5. The material parameters of the above mentioned models are determined by the experimental tension-compression stress-strain response of R.D. Yoshida-Uemori model cannot describe the non-proportional stress strain responses, on the other hand, the calculated stress-strain responses by the Modified Yoshida-Uemori model show good agreements with the corresponding experimental data. It is found the temporary expansion of yield surface, one of special features of the modified Yoshida-Uemori model, make a great important role in describing the Bauschinger effect during non-proportional deformations.

Fig. 5. Compressive stress-strain responses of A1050-O aluminum sheet after 5% and 10% prestraining in the rolling direction and the corresponding calculations by Yoshida-Uemori model and the Modified Yoshida Uemori model: (a) compressive stress strain curves in the diagonal direction, (b) compressive stress strain curves in the transversal direction

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