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Prediction of FLD of Sheet Metals based on Crystal Plasticity Model

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Abstract. In some advanced sheet metal forming processes such as the incremental forming process, a local fracture strain after necking is very important. In order to accurately predict necking and fracture phenomena, a crystal plasticity model is introduced in the finite element analysis of tensile tests. A tensile specimen is modeled by many grains that have their own crystalline orientation. And each of the grains is discretized by many elements. Using this analysis, necking behavior of a tensile specimen can be predicted without any initial imperfections. A damage model is also implemented to predict sudden drops of load carrying capacity after necking and to reflect the void nucleation and growth of the severely deformed region. From an analysis of the tensile test, the necking behavior is well predicted. Finally, analyses are carried out for various strain paths, and FLDs up to necking and fracture are predicted.

Keywords: Crystal Plasticity, Grain, Forming Limit Diagram (FLD).
PACS: 81.20.Hy

INTRODUCTION

A forming limit diagram (FLD) [1-3] is a well-known measure for necking and fracture prediction in the ordinary stamping process. Stoughton and Yoon [3] proposed a stress-based FLD and showed that the stress-based FLD is not dependent on pre-strain. In the ordinary stamping process, the necking strain and the fracture strain are almost identical because deformation after necking takes place in very local regions and averaged strain in a grid is measured. FLD, which is obtained by averaged strain in a grid, therefore, can be used in the prediction of fractures in general sheet metal forming processes such as stamping and deep drawing In specific sheet metal forming processes such as the incremental forming process, however, local fracture strain is important because the deformation takes place in very local regions. This local deformation is considered to be the main reason for the formability improvement in incremental sheet metal forming.

In this study, localized necking behavior of aluminum 6022-T4 is analyzed using the crystal plasticity finite element method and FLDs up to necking and fracture are predicted. By using the crystal plasticity finite element method, the localized necking can be predicted without any initial imperfection. In the crystal plasticity finite element method, stress concentration in the grain boundaries can cause initial voids and can initiate localized deformation. The authors [4] predicted the necking behavior using crystal plasticity finite element method. In this study, the basic methodology is the same as that employed in previous work except for the damage evolution model. A damage evolution model based on the maximum shear strain is used in this study, and FLDs for necking and fracture are predicted by several analyses for different strain paths. Without the evolution of damage or material softening due to damage, no sudden drop of load carrying capacity can be described [5]. Void nucleation, growth and coalescence are modeled by mathematical equations and many coefficients have to be decided in order to use the experimental data. To obtain FLD, analyses were carried out in several strain paths and the results were compared with the experimental results.

DAMAGE MODELS

The crystal plasticity model accounts for the deformation of a material by crystallographic slip and for the reorientation of the crystal lattice. In this work, a rate-dependent TBH model, which was well described by Dao and Asaro [6], was employed. The detailed implementation procedures were described in the work of Yoon et al. [7]. Wierzbicki et al. [8] intensively reviewed the prediction capability of various damage models. Cockcroft and Latham [9] proposed a damage model as a function of principal stress and effective strain. The authors [4] used a

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modified Cockcroft Latham damage model in the analysis of necking. In this study, it is assumed that damage is related to the shear strain, because the deformation mechanism in crystal plasticity is based on slip along slip planes. Therefore, a new model is proposed as follows.

$$dD = \begin{cases} \dfrac{\gamma d\bar{\varepsilon}}{\gamma_{cr} \cdot \Delta\bar{\varepsilon}_{cr}} & for \quad \gamma \geq \gamma_{cr} \;\; and \quad d\varepsilon_1 \geq 0, \\ 0 & for \quad \gamma < \gamma_{cr} \;\; or \quad d\varepsilon_1 < 0 \end{cases} \tag{1}$$

$$D = \int dD \tag{2}$$

In Equation (1), γ_{cr} is the critical shear strain over which damage starts to accumulate and $\Delta\bar{\varepsilon}_{cr}$ is the plastic strain amount from damage initiation to fracture. If the shear strain is less than the critical value, or if the deformation is compressive, the damage increment is zero. γ_{cr} and $\Delta\bar{\varepsilon}_{cr}$ are parameters that need to be determined. The values of γ_{cr} and $\Delta\bar{\varepsilon}_{cr}$ are determined as 0.233 and 0.08, respectively, by several trial analyses.

ANALYSIS MODEL

The crystal plasticity model is implemented into the commercial software ABAQUS/Explicit [10] via a user-defined material subroutine (VUMAT). For computational effectiveness, analysis of the tensile test is carried out for only a part of a tensile specimen as shown in FIGURE 1. Only a small region of a tensile specimen (6.0 mm in length, 2.0 mm in width, and 0.5 mm in thickness) is subjected to analysis. Considering the plane symmetry, the front and bottom surfaces ('S_F' and 'S_B' in Figure 1) of the analysis domain are treated as a symmetric boundary. Tensile displacement boundary conditions, U_X and $-U_X$, were imposed on the right and left surfaces. The tensile displacement boundary condition of U_Y is imposed on the backside surface and the value of U_Y is changed for different strain paths. For the uniaxial tension test, all nodes on the backside surface are coupled in the Y direction in order to consider the continuing domain next to the surface.

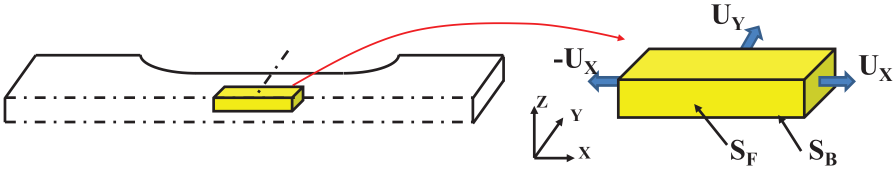


FIGURE 1. Definition of analysis domain and boundary conditions for FLD test.

FIGURE 2 shows the analysis model and grain shape. Grain shape is assumed to be a regular octahedron as shown in FIGURE 2(c). Considering the shape change during the rolling process, grain size is assumed to be about 0.2, 0.1, and 0.05 mm the in x, y, and z directions, respectively. Each grain is discretized by many elements and the same orientation angles are allocated to all elements in each grain as shown in FIGURE 3(a). The elements in each grain are sorted in one group and the same orientations are allocated. FIGURE 3(a) shows the contour of '-cosϕ', where ϕ is the second Euler angle. It can be seen that the same orientation angles are allocated to all elements in each grain. FIGURE 3(b) shows the (111) pole figure of the materials.

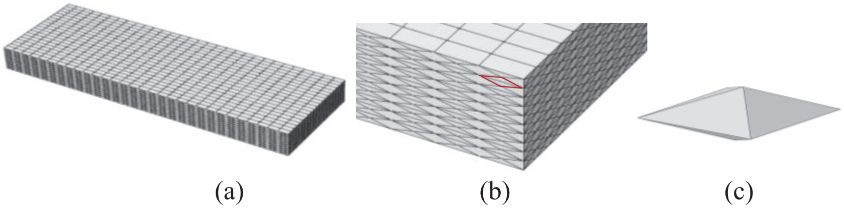
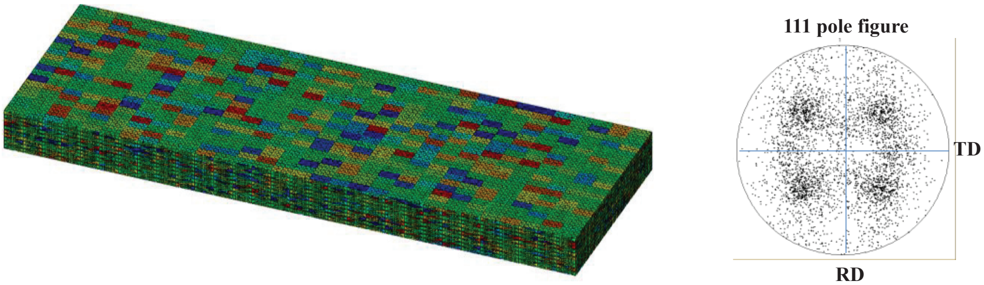

(a) (b) (c)

FIGURE 2. Division of specimen by octahedron grains: (a) full model, (b) magnified view and (c) octahedron shape of grain.

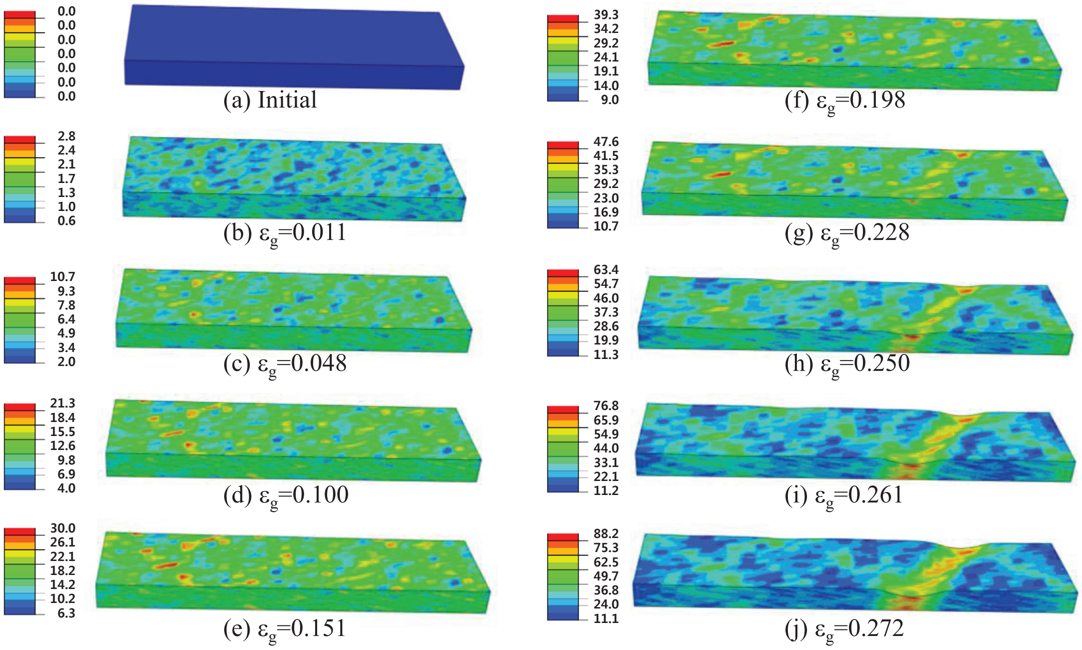


(a) (b)

FIGURE 3. (a) Contour of '-cosϕ' showing the correct allocation of orientation angles and (b) (111) pole figure for 6022-T4 aluminum sheet sample.

RESULTS AND DISCUSSIONS

FIGURE 4 shows the major strain distributions at several time stages for uniaxial tension. In FIGURE 4, ε_g is the gage strain calculated from the initial length and tensile displacement. As expected, it can be seen that the strain distribution is not even. This means that stress concentration takes place at many points. This stress concentration is considered to be caused by orientation mismatches on the grain boundaries. As tensile strain increases, the stress concentration becomes bigger. If shear strain becomes greater than the critical value, damage starts to accumulate. FIGURE 4 clearly shows the void initiation, void growth, and void coalescence procedures.



(a) Initial
(b) ε_g=0.011
(c) ε_g=0.048
(d) ε_g=0.100
(e) ε_g=0.151
(f) ε_g=0.198
(g) ε_g=0.228
(h) ε_g=0.250
(i) ε_g=0.261
(j) ε_g=0.272

FIGURE 4. Major strain distributions in uniaxial tension (unit: %).

Analyses were carried out for various values of 'U_Y' (see FIGURE 1) to change the strain path, and FLDs up to necking and fracture were obtained. The FLD up to necking was obtained from the major and minor strains just before necking. The FLD up to fracture was obtained from the major and minor strains at fracture. From the comparison with the experiment, fracture is considered to take place when the minimum thickness on the necking region reaches 0.6 times the thickness of the uniformly deformed region. FIGURE 5 shows the predicted FLDs and the comparison with the experimental results. The predicted FLD up to necking is in good agreement with the experimental results when the minor strain is less than zero. When the minor strain is greater than zero, however, the predicted FLD shows deviation from the experimental value. In the experiment, the major necking strain increases as the strain path becomes closer to the biaxial strain path. In the predicted FLD, however, the major necking strain continues to become smaller. The shape of the FLD up to fracture is similar to that determined in the experiment. However, the major fracture strain is very high compared to that of the necking. This result can be effectively used in the design of an incremental sheet metal forming process, because deformation takes place in very local regions in increment sheet forming.

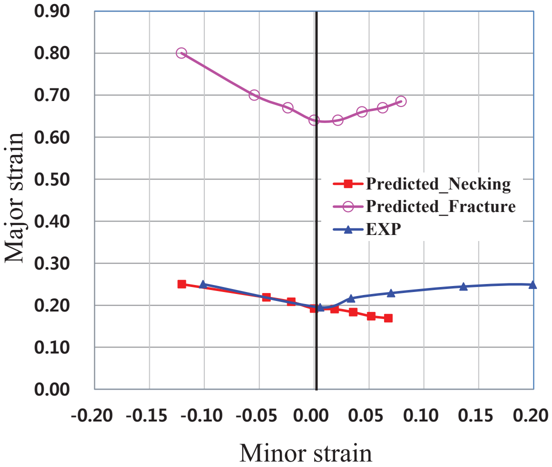


FIGURE 5. Predicted FLDs for necking and fracture.

CONCLUSIONS

The necking behaviors of aluminum 6022-T4 are analyzed based on a crystal plasticity model. A test specimen is divided into octahedral grains and each grain is discretized by many elements. Stress concentration is observed at many points due to the orientation mismatch of the grain boundaries; this stress concentration causes damage initiation. The void nucleation, growth and coalescence phenomena are well described. Analyses are carried out for various strain paths and FLDs up to necking and fracture are obtained. The predicted FLD up to necking shows some deviation from the experimental values in the biaxial strain region. The shape of the FLD up to fracture is similar to that of the experiment. However, the major fracture strain is very high compared to that of the necking.

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