Numerical biaxial tensile test for sheet metal forming simulation of aluminium alloy sheets based on the homogenized crystal plasticity finite element method

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Abstract. The simulation of the stretch forming of A5182-O aluminum alloy sheet with a spherical punch is performed using the crystal plasticity (CP) finite element method based on the mathematical homogenization theory. In the simulation, the CP constitutive equations and their parameters calibrated by the numerical and experimental biaxial tensile tests with a cruciform specimen are used. The results demonstrate that the variation of the sheet thickness distribution simulated show a relatively good agreement with the experimental results.

1. Introduction

In order to improve the accuracy of finite element simulations of sheet metal forming processes, it is essential to check whether the material models and parameters used in the simulations adequately describe the plastic deformation behavior of sheet metals under a multiaxial stress state or not. Recently, the authors have developed the numerical biaxial tensile test (NBT) based on the crystal plasticity finite element (CPFE) method and the mathematical homogenization method [1]. Furthermore, NBTs of a A5182-O aluminum alloy sheet were performed. The results demonstrated that NBT enables us to calibrate the material models and parameters by comparing the contours of equal plastic work calculated by NBT with those measured by the biaxial tensile test using a cruciform specimen [2].

In this paper, the CPFE simulation of the stretch forming of the A5182-O aluminum alloy sheet with a spherical punch is presented. In the forming simulation, the data of crystallographic texture in the sheet measured experimentally and the material parameters calibrated by NBT are used. In order to verify our methodology, the results of the forming simulation are compared with the corresponding experimental results.

2. Crystal plasticity model

NBT and the stretch forming of A5182-O aluminum alloy sheet are performed using the CP constitutive equations proposed by Peirce et al. [3] and the two-scale CPFE method proposed by Nakamachi et al. [4]. In this study, the following constitutive equations are used.

$$\hat{\sigma}_{ij} = D^e_{ijkl}\dot{\epsilon}_{kl} - \sum_{\alpha} R^{(\alpha)}_{ij}\dot{\gamma}^{(\alpha)} \tag{1}$$

$$R^{(\alpha)}_{ij} = D^e_{ijkl}P^{(\alpha)}_{kl} + W^{(\alpha)}_{ik}\sigma_{kj} - \sigma_{ik}W^{(\alpha)}_{kj} \tag{2}$$

Here, $\hat{\sigma}_{ij}$ represents the objective rate of the Cauchy stress tensor, D^e_{ijkl} is the elastic modulus tensor and $\dot{\varepsilon}_{ij}$ is the strain rate tensor. $P^{(\alpha)}_{ij}$ and $W^{(\alpha)}_{ij}$ are the Schmid and the spin tensors for the αth slip system, respectively. In this study, twelve {111}<110> slip systems in a face-centered cubic crystal are taken into account. The plastic shear strain rate on each slip system is given by the following equation [5]:

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

where $\dot{\gamma}^{(\alpha)}_0$ is the reference plastic shear strain rate, $\tau^{(\alpha)}$ is the resolved shear stress for αth slip system, m is the strain rate sensitivity factor. $g^{(\alpha)}$ is the critical resolved shear stress and its evolution is described as

$$g^{(\alpha)} = \sum_{\beta} h(\gamma)\left|\gamma^{(\beta)}\right| \tag{2}$$

where $h(\gamma)$ is the hardening coefficient matrix. In this study, we use the following equation [4]:

$$h(\gamma) = h_0 nC\left\{C(\gamma_0 + \gamma)\right\}^{n-1} \tag{3}$$

where δ is the Kronecker delta. q is a parameter describing the self and latent hardenings and assumed to be $q = 1$ in this study. h_0 is the initial hardening coefficient, n is the hardening exponent and C is the hardening coefficient. γ_0 is the initial plastic shear strain. γ is the accumulated plastic shear strain. In this study, the initial resolved shear stress, τ_0, and the material parameters, h_0, n, C and γ_0, identified by NBT [2] are used.

As similar to Nakamachi et al. [4], in order to simulate the macroscopic deformation of the sheet during the forming on the basis of the data of crystallographic texture, the mathematical homogenization method proposed by Guedes et al. [6] is used. By using this homogenization method, the principals of virtual work for both macroscopic and microscopic (crystalline) scales are derived simultaneously. Furthermore, the dynamic explicit solver and a parallel computing technique are used for accelerating the simulation. The detail of the formulation can be found in the literature [4].

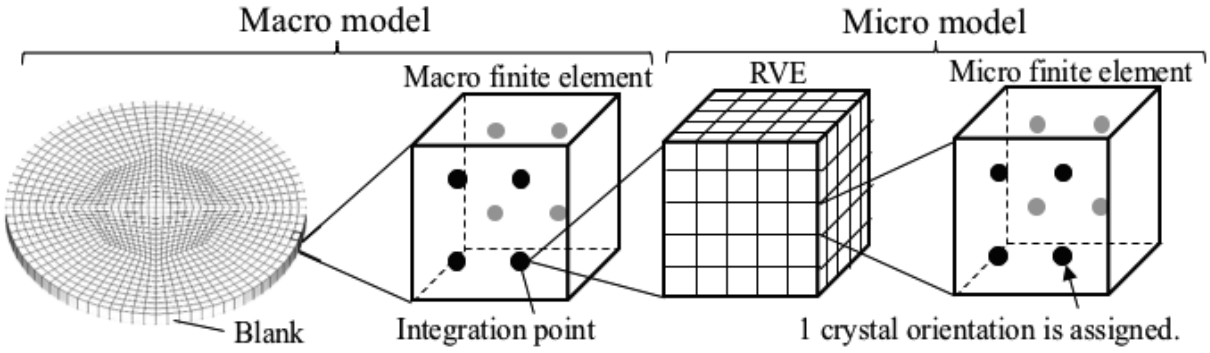


Figure 1. Finite element models used in the CPFE simulation of the stretch forming.

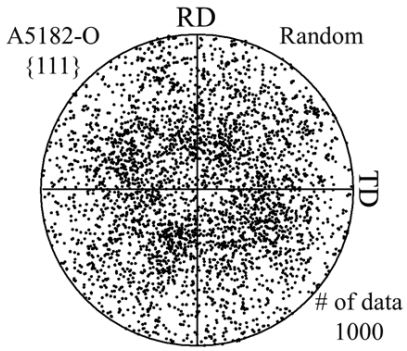


Figure 2. {111} pole figure of the initial crystal orientation [2].

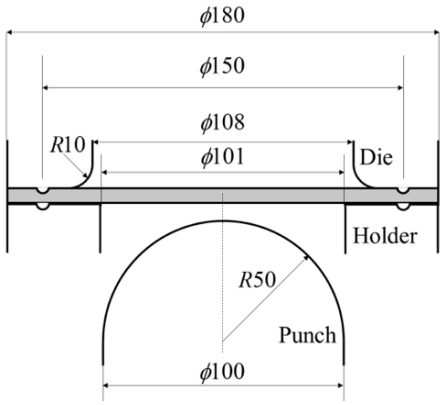


Figure 3. Dimensions of tools.

3. Simulation of stretch forming of A5182-O aluminium alloy sheet using a spherical punch

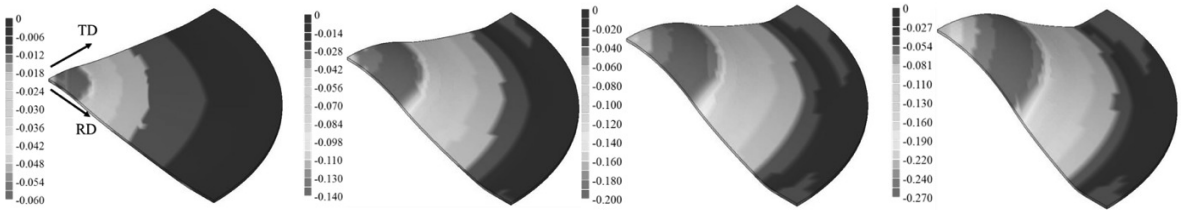
3.1. Simulation model and condition

Figure 1 shows the finite element models for the CPFE simulation of the stretch forming of A5182-O aluminum alloy sheet with a spherical punch. The macro and micro models describes a blank and a representative volume element (RVE) of polycrystalline aggregate in the sheet, respectively. The number of finite elements for the blank is 1083. One orientation data is assigned to each integration point in the RVE. The number of finite element for the RVE is 125. Therefore, 1000 initial crystal orientations are taken into account at each integration point in a finite element consisting of the macro model. The initial crystal orientations are randomly sampled from the orientation data measured by electron backscattered diffraction (EBSD). Figure 2 shows {111} pole figure of the initial crystal orientations. Note that the same initial orientations were used in NBT [2]. The initial critical resolved shear stress and the material parameters for A5182-O aluminum alloy sheet validated by NBT [2] are as follows: $\tau_0 = 43.5$ MPa, $h_0 = 120$ MPa, $n = 0.24$, $C = 17$, and $\gamma_0 = 0.1$.

Figure 3 shows the size and geometry of tools used in this study. In the experiment, the punch speed was set to be 6 mm/min. and the maximum forming height was 30 mm. In the simulation, the friction coefficient between the blank and the punch is assumed to be 0.1. Instead of modeling the bead in the simulation explicitly, the nodal displacement at 75 mm away from the center of the blank is fixed to be zero.

3.2. Simulation results

Figure 4 shows the distributions of the plastic strain along the through-thickness direction at different forming heights, h. It is seen that the strain localization occurs at the center of the blank at $h = 10$ mm. As the forming height is increased, the region where shows the maximum plastic strain moves to a little far away from the center of the blank due to the friction between the punch and the blank. Figure 5 shows the calculated and measured distributions of the sheet thickness along the rolling direction (RD) at $h = 10$, 20, 25 and 30 mm. The experimental results were reported by Kawaguchi et al. [7]. It is shown that the calculated thickness distribution at $h = 10$ mm shows very good agreement with the experimental. As shown in the experimental results, the distance between the center of the blank and the minimum thickness position is increased with increasing h. Although the present simulation can qualitatively predict this tendency, the minimum sheet thickness predicted by the CPFE simulation underestimates the experimental results. In order to improve the simulation results obtained in this study, we need to investigate the effects of initial crystal orientations and the friction coefficient.



(a) h = 10 mm (b) h = 20 mm (c) h = 25 mm (d) h = 30 mm

Figure 4. Distributions of the plastic strain along the through-thickness direction calculated by the CPFE simulation.

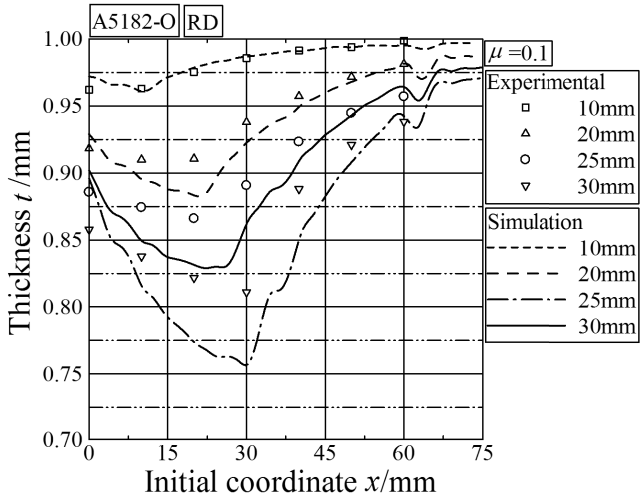


Figure 5. Calculated distributions of the sheet thickness along the RD compared with the experimental results [7].

4. Conclusion

The stretch forming of A5182-O aluminum alloy sheet with a spherical punch was simulated using the CPFE method based on the mathematical homogenization theory. In order to perform the forming simulation accurately, we used the material parameters calibrated by NBT. It was demonstrated that the simulated variation of the sheet thickness shows relatively good agreement with the experimental results.

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