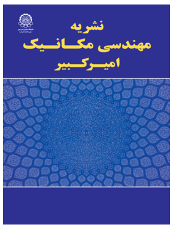

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Crystal Plasticity Finite Element Study of Necking Behavior of Aluminum Alloy Sheet Subject to Thickness-Stress

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ABSTRACT: This paper investigates the effect of thickness stress on the formability of aluminum alloy metal sheets using crystal plasticity finite element analysis. A self-hardening behavior is considered for the slip systems. Further, for the prediction of necking initiation and growth, the maximum shear strain criterion is used for damage initiation and evolution. In order to implement the model in Abaqus finite element package, a VUMAT was developed based on the discretized equations and forward Euler integration scheme. After verification of the developed code, the parameters of the model were calibrated against the tensile test results. For simulating tensile test of 1 mm thick sheet, a representative volume of 3×1.5×0.5 mm3‹was partitioned into 14790 grains through a python code in ABAQUS/CAE environment and then discretized using 50 µm tetrahedral linear elements. Using the experimental data available in the literature and considering appropriate texture for the simulation domain, the crystal orientations were assigned through Euler angles. Then, tensile tests were performed on the sample in the presence of the thickness pressure stress. The results show that application of the through thickness stress increases the strain corresponding to the necking initiation and thus postpones necking. Correspondingly, a decrease in tensile load is observed in this case.

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1. INTRODUCTION

Sheet metal formability is usually studied through a plane strain analysis. However, in forming processes like hydroforming, electromagnetic forming, and explosive forming, through thickness stress cannot be neglected. Therefore, in recent researches, the effect of thickness stress is considered [1, 2]. In addition, the Crystal Plasticity Finite Element Method (CPFEM) has been used for the analysis of the necking behavior of metal sheets [3]. In this paper, the effect of through thickness stress on the necking behavior of aluminum alloy sheet metal is studied based on 3D CPFEM analyses.

2. CONSTITUTIVE EQUATIONS AND FINITE ELEMENT MODEL

Elastic and plastic deformations of crystalline materials may be described through multiplicative decomposition of deformation gradient **F**, which leads to additive decomposition of the velocity gradient **L**. Plastic velocity gradient $\mathbf{L}^p$ associated with the plastic slip rate $\dot{\gamma}$ is described as

$$\mathbf{L}^{\mathrm{p}} = \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \mathbf{s}^{\alpha} \mathbf{m}^{\alpha} \tag{1}$$

where, $\mathbf{s}^{\alpha}$ and $\mathbf{m}^{\alpha}$ are the slip and normal directions of the slip system α, respectively. The symmetric and skew-symmetric parts of $\mathbf{L}^p$ are described as

$$\mathbf{D}^{\mathrm{p}} = \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \mathrm{symm}[\mathbf{s}^{\alpha} \mathbf{m}^{\alpha}] = \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \mathbf{P}_{\alpha} \tag{2}$$

$$\mathbf{W}^{\mathrm{p}} = \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \mathrm{skew}[\mathbf{s}^{\alpha} \mathbf{m}^{\alpha}] = \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \mathbf{W}_{\alpha} \tag{3}$$

A damage model based on the maximum shear strain γ_{m} γ_{m} is employed according to Eq. (4)

$$D = \begin{cases} 0 & (\gamma_{\mathrm{m}} \le \gamma_{\mathrm{m,ini}}) \\ D_{\max} \left(\dfrac{\gamma_{\mathrm{m}} - \gamma_{\mathrm{m,ini}}}{\gamma_{\mathrm{m,max}} - \gamma_{\mathrm{m,ini}}} \right)^{M} & (\gamma_{\mathrm{m,ini}} < \gamma_{\mathrm{m}} < \gamma_{\mathrm{m,max}}) \\ D_{\max} & (\gamma_{\mathrm{m,ini}} \le \gamma_{\mathrm{m}}) \end{cases} \tag{4}$$

in which, $\gamma_{\mathrm{m,ini}} = 0.4$, $\gamma_{\mathrm{m,max}} = 0.4376$ and $M = 2$. The equivalent stress in the damaged $\bar{\sigma}_D$ and undamaged $\bar{\sigma}$ states are related through

$$\bar{\sigma}_D(\bar{\varepsilon}, D) = (1 - D)\bar{\sigma}(\bar{\varepsilon}) \tag{5}$$

In each increment, the trial resolved shear stress $\tau^{\mathrm{T}\alpha}$ for slip system α is calculated from

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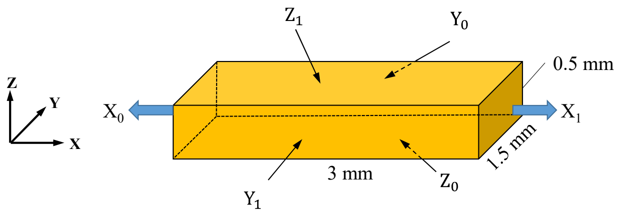

Fig. 1. Representative volume element of the sheet metal subject to uniaxial load

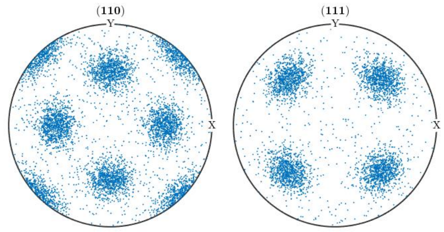

Fig. 2. Pole figures of (1 1 0) and (1 1 1) planes used in the calculation domain

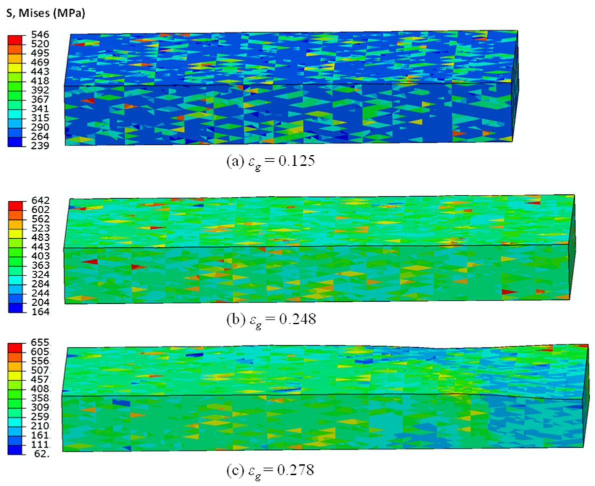

Fig. 3. Equivalent Mises stress distribution in the course of uniaxial tensile loading

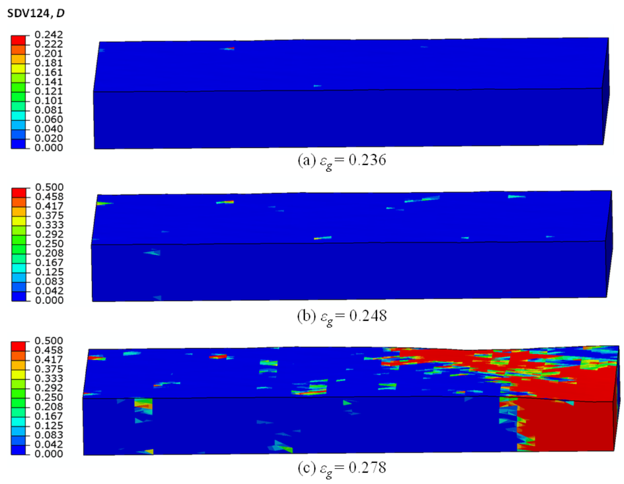

Fig. 4. Damage variable *D* distribution during uniaxial tensile loading

$$\tau_{n+1}^{\mathrm{T}\alpha} = \tau_n^\alpha + \Delta t \dot{\tau}_\alpha = \tau_n^\alpha + \Delta t \mathbf{R}_\alpha : \mathbf{D} \tag{6}$$

In Eq. (6), $\mathbf{R}_\alpha$ is a rotation tensor which depends on $\mathbf{s}^\alpha$, $\mathbf{m}^\alpha$, stress, and elastic moduli [3].

In addition, a rate dependent behavior is considered for the calculation of the resolved shear stress according to

$$\tau_{n+1}^\alpha = g^0 \left(\frac{|\dot{\gamma}^\alpha|}{\dot{\gamma}_0} \right)^m \mathrm{sign}(\dot{\gamma}^\alpha) \tag{7}$$

where, m and $\dot{\gamma}_0$ are constants taken as 0.001 and g^0 is the strength of slip system which evolves according to $g^0 = 151.5(0.001+\Gamma)^{0.24}$. Γ is the accumulated slip on all systems. Assuming a constant damage variable D within the current increment, solving the following equation, the stresses can be calculated.

$$\tau_{n+1}^{\mathrm{T}\alpha} - \Delta t \sum_{\alpha=1}^{N} \dot{\gamma}^\beta \mathbf{R}_\alpha : \mathbf{P}_\alpha - (1-D_n)\tau^\alpha = 0 \tag{8}$$

Finally, damage variable D and subsequently, the resolved shear stresses are updated.

$$D_{n+1} = D_n + \Delta D_{n+1} \tag{9}$$

$$\tau_{n+1}^\alpha = (1-\Delta D_{n+1})(\tau_{n+1}^{\mathrm{T}\alpha} - \Delta t \sum_{\alpha=1}^{N} \dot{\gamma}^\beta \mathbf{R}_\alpha : \mathbf{P}_\alpha) = 0 \tag{10}$$

Fig. 1 depicts the representative volume element selected at the center of a 1 mm thick sheet metal specimen. To reduce the calculation cost, half of the sheet thickness considered is in the computation domain. The boundary conditions applied are given in the figure. The domain is partitioned into 14790 diamond shape grains and then discretized using tetrahedral elements with an average size of 50 μm. According to the texture of the sheet metal [4], the orientation of grains is randomly selected from 1000 orientations generated using MTEX in Matlab software (Fig. 2).

The incremental constitutive equations are coded in a VUMAT subroutine and implemented in Abaqus/Explicit dynamics solver. The parameters of the model are calibrated against the experimental results of [3].

3. RESULTS AND DISCUSSION

Fig. 3 shows snapshots of the distribution of Mises stress during tensile loading. Due to a mismatch in the orientation of grains, stress concentration is observed at the grain boundaries. With an increase in the gage length strain ε_g deformation damage evolves and is accumulated (Fig. 4).

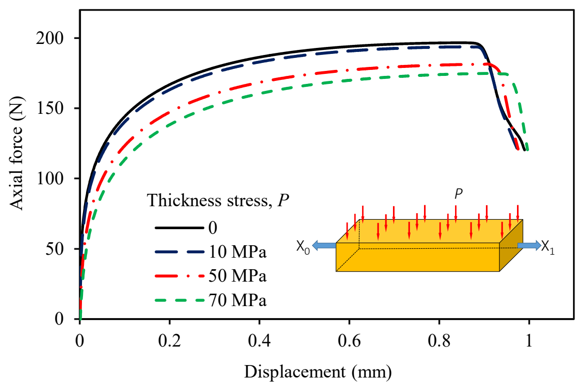

Fig. 5. Comparison of the force-displacement curves obtained under various through thickness pressures

Consequently, deformation is concentrated and a neck is formed at an angle to the loading direction. In this region, Mises stress is reduced significantly.

The effect of through thickness stress on the force-displacement curve is shown in Fig. 5. It is observed that with an increase in the pressure applied in the thickness direction, the tensile load decreases, while the strain corresponding to necking increases. These results are in line with those reported in [1] for aluminum alloy AA6011 obtained through M-K analysis.

4. CONCLUSIONS

In this paper, based on the 3D finite element crystal plasticity method, the effect of through thickness stress on the necking behavior of the aluminum alloy sheet metal is investigated. The constitutive model incorporates a rate dependent crystal behavior and a damage model based on maximum shear strain. Simulation of the sheet metal tensile loading subjected to through thickness stress was performed. The results revealed that the application of the thickness stress reduces the tensile force while increasing the necking strain.

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