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Effects of grain-scale heterogeneity on surface roughness and sheet metal necking

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ABSTRACT

Strain localization of sheet metals subjected to plane-strain stretching was simulated by finite-element analysis based on a crystal plasticity model. The ratio of specimen thickness to grain size, denoted by N_g, is varied from 1 to 70, and its influence on the evolution of surface roughness and the occurrence of sheet necking is investigated. Roughening of the free surface of the specimen is induced by the grain-scale strain heterogeneity associated with local grain misorientation. The magnitude of surface roughness depends mainly on the grain size and is less sensitive to N_g. As N_g decreases while maintaining the thickness, the magnitude of surface roughness becomes large with respect to the thickness. As a result, large geometrical imperfection is generated. Therefore, the formability of sheet metal is reduced as N_g decreases. Such an effect is found to be particularly considerable when N_g is less than 30. It is also found that the localization mode shifts from a sharp shear banding mode to a localized thinning mode as N_g increases.

1. Introduction

Limit strains at the onset of sheet necking in polycrystalline metals are known to be dependent on their thickness. This feature was observed experimentally in several investigations. For instance, Miyano [1] polished a 2-mm-thick aluminum alloy sheet to produce four specimens with different thicknesses of 0.46–1.99 mm. Then, uniaxial tension tests were conducted. The limit strain of the thinnest specimen was found to be lower by about 40% than that of the thickest specimen. Similar experimental findings were reported for other metals and for other deformation modes [2,3]. In most investigations dealing with the thickness dependence of formability, the specimen thickness was varied, but other parameters such as width and length remained constant. Hence, not only the effect of thickness, but also the effect of specimen geometry was included in the experiments.

The influences of the specimen geometry on bifurcation analysis of strain localization were investigated for a cylinder under uniaxial tension [4] and for a plate under biaxial stretching [5,6]. The bifurcation from the uniform deformation delays with increasing ratio of thickness to length. The thinner specimen yields lower limit strains, provided that the specimen length is constant. Tvergaard [7] analyzed the uniaxial tensile tests of plates by a three-dimensional finite-element method and revealed that the tensile load dropped abruptly after the formation of a neck for a thin sheet. However it decreased gradually for thicker specimens showing greater ductility. According to these results, the aspect ratio of the specimen can be a source of the thickness dependence of limit strain.

In the theoretical and numerical investigations just described, the metallic specimen was assumed to be homogeneous. An actual metal is, however, not homogeneous: grains are generally anisotropic, slip occurs on particular slip systems, and the local grain orientation differs from those of neighboring grains. Such heterogeneity makes the grain-scale strain field inhomogeneous from the beginning of deformation, and its evolution naturally results in strain localization. The strain inhomogeneity also leads to different movements of grains in the direction normal to the surface so that surface roughness is generated. The roughening is a kind of thickness imperfection that is closely related to the formation of necking. The degrees of strain heterogeneity are expected to be appreciable when the grain size becomes large with respect to the thickness. Therefore, the ratio of thickness to grain size could be a parameter affecting the thickness dependence of the limit strains.

The effects of the ratio of thickness to grain size (the number of grains across thickness) N_g on the limit strain and surface roughness were investigated experimentally and numerically. Yamaguchi et al. [2] conducted uniaxial tensile tests for aluminum alloy, copper, and steel specimens with different thicknesses. Results showed that the limit strains depend on the thickness and that this dependence is particularly strong for N_g less than 30. The same trend was observed also for the equi-biaxial tension state by

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Wilson et al. [3], who carried out the hydraulic bulge test for copper, brass, and steel. The development of surface roughness was found experimentally to depend linearly on both the equivalent plastic strain and the grain size [3,8–10]. The same features were reconfirmed in recent investigations [11,12]. Becker [13] analyzed the evolution of surface roughness using finite-element simulation in conjunction with a crystal plasticity model, and the same trend that had been found in the experiment was reproduced. Grain-scale surface roughing of polycrystalline sheets were experimentally investigated by Baczynski et al. [14] and Raabe et al. [15], and the correlation among the crystallographic orientation of a grain and/or clustering of crystal orientations and surface morphology was examined. Spatial distributions of Goss, cube, and rotated Goss oriented grains, which are typical recrystallization textures of aluminum alloy, are mainly responsible for the surface roughness induced by plastic deformation. The investigation was extended by Guillontin et al. [16] who considered the through-thickness grain orientation distributions. It was concluded that the first three or four grain layers are important to the surface property.

For the last decade, the demand for metal forming technology for small parts with the dimensions of hundreds of micrometers to a few millimeters has increased continuously [17,18]. The sheet metal thickness has decreased accordingly. Therefore, the number of grains across thickness N_g generally becomes less, except for some special ultra fine-grain sheets. The influences of grain-scale strain inhomogeneity on the limit strains and surface roughness become significant in the forming processes of these miniature products, and a deeper understanding on these effects is necessary. As described, in the previous investigations, the thickness was varied and the length was kept constant. As a result, the experimental and numerical results include the influences of both the aspect ratio of the specimen and N_g. In the present investigation, the effect of the number of grains across thickness N_g is pursued only by maintaining a constant aspect ratio of the specimen. Finite-element analysis based on a crystal plasticity model is performed to incorporate heterogeneity due to the variation of grain orientation and to examine its evolution.

2. Theoretical framework

2.1. Crystal plasticity model

The rate-dependent crystal plasticity model used in the present investigation follows the formulation presented by Peirce et al. [19] and by Asaro and Needleman [20]. The velocity gradient $\mathbf{L}$ is decomposed additively into the elastic part $\mathbf{L}^*$ and the plastic part $\mathbf{L}^p$, i.e., $\mathbf{L}=\mathbf{L}^*+\mathbf{L}^p$. Plastic deformation is regarded as arising solely from slip on slip systems, and $\mathbf{L}^p$ is written as

$$\mathbf{L}^p = \sum_\alpha \dot{\gamma}^{(\alpha)} \mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)}, \tag{1}$$

where $\dot{\gamma}^{(\alpha)}$ is the slip rate and $\mathbf{s}^{(\alpha)}$ and $\mathbf{m}^{(\alpha)}$ respectively represent the slip direction and the slip plane normal for the αth slip system. The plastic part of the rate of deformation $\mathbf{D}^p$ and plastic spin $\mathbf{W}^p$, which are, respectively, the symmetric and antisymmetric parts of $\mathbf{L}^p$, are given as

$$\mathbf{D}^p = \sum_\alpha \dot{\gamma}^{(\alpha)} \mathbf{p}^{(\alpha)}, \text{ with } \mathbf{p}^{(\alpha)} = \frac{1}{2}\left(\mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)} + \mathbf{m}^{(\alpha)} \otimes \mathbf{s}^{(\alpha)}\right) \text{ and} \tag{2}$$

$$\mathbf{W}^p = \sum_\alpha \dot{\gamma}^{(\alpha)} \mathbf{w}^{(\alpha)}, \text{ with } \mathbf{w}^{(\alpha)} = \frac{1}{2}\left(\mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)} - \mathbf{m}^{(\alpha)} \otimes \mathbf{s}^{(\alpha)}\right). \tag{3}$$

The symmetric and antisymmetric parts of $\mathbf{L}^*$ respectively correspond to the elastic lattice stretching $\mathbf{D}^*$ $(=\mathbf{D}-\mathbf{D}^p)$ and the lattice spin $\mathbf{W}^*$ $(=\mathbf{W}-\mathbf{W}^p)$. The corotational rate of the Cauchy stress with respect to the lattice spin, denoted by $\overset{\circ}{\boldsymbol{\sigma}}{}^*$, is given as

$$\overset{\circ}{\boldsymbol{\sigma}}{}^* = \dot{\boldsymbol{\sigma}} - \mathbf{W}^* \cdot \boldsymbol{\sigma} + \boldsymbol{\sigma} \cdot \mathbf{W}^*, \tag{4}$$

where $(\,\dot{}\,)$ stands for the material time derivative. The elastic response is assumed to be unaffected by slip and the hypoelastic law is adopted. Then, the lattice corotational rate of the Cauchy stress $\overset{\circ}{\boldsymbol{\sigma}}{}^*$ is related to the lattice stretching $\mathbf{D}^*$ by the fourth-order elastic tensor $\mathbf{C}^e$

$$\overset{\circ}{\boldsymbol{\sigma}}{}^* = \mathbf{C}^e : \mathbf{D}^* = \mathbf{C}^e : \mathbf{D} - \sum_\alpha \dot{\gamma}^{(\alpha)} \mathbf{C}^e : \mathbf{p}^{(\alpha)} \tag{5}$$

$\overset{\circ}{\boldsymbol{\sigma}}{}^*$ is related to the Jaumann rate of the Cauchy stress $\overset{\circ}{\boldsymbol{\sigma}}$ $(=\dot{\boldsymbol{\sigma}} - \mathbf{W} \cdot \boldsymbol{\sigma} + \boldsymbol{\sigma} \cdot \mathbf{W})$ via

$$\overset{\circ}{\boldsymbol{\sigma}} = \overset{\circ}{\boldsymbol{\sigma}}{}^* - \mathbf{W}^p \cdot \boldsymbol{\sigma} + \boldsymbol{\sigma} \cdot \mathbf{W}^p \tag{6}$$

Eqs. (5) and (6) lead to the rate-form constitutive relation in the form of

$$\overset{\circ}{\boldsymbol{\sigma}} = \mathbf{C}^e : \mathbf{D} - \sum_\alpha \dot{\gamma}^{(\alpha)} \left(\mathbf{C}^e : \mathbf{p}^{(\alpha)} + \mathbf{w}^{(\alpha)} \cdot \boldsymbol{\sigma} - \boldsymbol{\sigma} \cdot \mathbf{w}^{(\alpha)}\right) \tag{7}$$

To complete the rate-form constitutive relation, slip rates $\dot{\gamma}^{(\alpha)}$ must be specified. The slip rate is assumed to be related to the resolved shear stress $\tau^{(\alpha)}$ $(=\mathbf{s}^{(\alpha)} \cdot \boldsymbol{\sigma} \cdot \mathbf{m}^{(\alpha)})$ through the power-law relation

$$\dot{\gamma}^{(\alpha)} = \dot{\gamma}_0 \,\mathrm{sgn}(\tau^{(\alpha)}) \left| \frac{\tau^{(\alpha)}}{g^{(\alpha)}} \right|^{1/m}, \tag{8}$$

where $\dot{\gamma}_0$ is the reference slip rate, m is the strain-rate sensitivity exponent, and $g^{(\alpha)}$ is the resistance to slip.

The rate of increase of the slip resistance $g^{(\alpha)}$ is

$$\dot{g}^{(\alpha)} = \sum_\beta h^{\alpha\beta} |\dot{\gamma}^{(\beta)}|, \tag{9}$$

where $h^{\alpha\beta}$ is the hardening modulus describing both the self-hardening and latent hardening of slip systems. The hardening moduli $h^{\alpha\beta}$ are specified simply as

$$h^{\alpha\beta} = h = h_0 \left(1 + \frac{h_0 \gamma_A}{\tau_0 n}\right)^{n-1}, \quad \gamma_A = \int_0^t \sum_\alpha |\dot{\gamma}^{(\alpha)}| dt, \tag{10}$$

where n, h_0, and τ_0 respectively denote the power-law hardening exponent, the initial hardening rate, and the initial slip resistance. t stands for time.

The orientation of a slip system evolves as

$$\dot{\mathbf{s}}^{(\alpha)} = \mathbf{W}^* \cdot \mathbf{s}^{(\alpha)}, \ \dot{\mathbf{m}}^{(\alpha)} = \mathbf{W}^* \cdot \mathbf{m}^{(\alpha)}. \tag{11}$$

In the actual computations presented in subsequent sections, the rate tangent modulus method formulated by Peirce et al. [19] is applied for numerical integration of the constitutive relations.

Throughout this paper, face-centered cubic crystals with 12 slip systems of the $\{111\}\langle 110 \rangle$ type are considered. The material parameters are set as $\tau_0 = 40$ MPa, $h_0/\tau_0 = 25$, $n = 0.2$, $m = 0.002$, $\dot{\gamma}_0 = 0.002$, $C^e_{1111} = 107$ GPa, $C^e_{1122} = 61$ GPa, and $C^e_{1212} = 28$ GPa [21]. The elastic tensor is written as $\mathbf{C}^e = C^e_{ijkl} \hat{\mathbf{e}}_i \otimes \hat{\mathbf{e}}_j \otimes \hat{\mathbf{e}}_k \otimes \hat{\mathbf{e}}_l$, where $\hat{\mathbf{e}}_i$ is an orthonormal base vector representing the [100], [010], or [001] direction of the cubic crystal lattice.

2.2. Formulation of finite-element simulation

An updated-Lagrangian finite-element formulation is used. The rate form of the static force equilibrium at time t is expressed on the basis of the principle of virtual work (e.g., [22]) neglecting the body force effect

$$\int_{V_t} \dot{\boldsymbol{\Pi}}^{\mathrm{T}} : (\delta \dot{\mathbf{u}} \otimes \nabla_{\mathbf{x}})\, dV = \int_{S_t} \dot{\mathbf{t}} \cdot \delta \dot{\mathbf{u}}\, dS, \tag{12}$$

where V and S respectively denote the volume and surface at time t, and $\nabla_{\mathbf{x}}$ represents the spatial derivative $\partial(\ )/\partial \mathbf{x}$ with $\mathbf{x}$ denoting