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Distinguishing micro-scale from macro-scale tensile flow stress of sheet metals in microforming

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ABSTRACT

This study describes the effect of grain size on the flow stress of sheet metal under simple tension in microforming. A simple model of the tensile flow stress of sheet metal is firstly developed based on the Hall–Petch equation. Experimental results verify the accuracy of the developed model, which is a function of T/D (sheet thickness/grain size). A critical condition $(T/D)c$ that distinguishes micro-scale from macro-scale tensile flow stress is subsequently proposed based on Li's theory of dislocation with density type. The trend of the predicted $(T/D)c$ with varying grain size is similar to the experimental finding that the $(T/D)c$ decreases as the grain size increases. Therefore, the developed model can elucidate to understand the tensile flow stress of sheet metal in microforming.

1. Introduction

The microforming process is essential in industry because it enables the mass-fabrication of the micro parts. The size of micro parts makes their forming process significantly different from that of regularly sized parts. Microstructures of a material become increasingly important as the size of the material is reduced to the micro scale. When sheet metal is only a few grains thick, its mechanical properties may differ from those of the bulk metal with regular scale. This effect is the so-called "size effect". Therefore, various mechanical properties of a deformed sheet metal must be reassessed on the micro scale and new concepts must be applied to extend forming techniques to micro specimens. The flow stress in a miniature specimen under simple tension must be obtained as it is fundamental to the study of the size effect.

The size effect that is associated with miniaturization has been examined extensively. Geiger et al. [1] revealed the effects of specimen size and the microstructure of sheet metal on the manufacturing of micro parts. Raulea et al. [2] revealed that grain and specimen sizes affect the forming characteristics of metal sheets. Engel et al. [3] examined how free surface grains affect the forming technique that is used to fabricate micro parts. Engel and Eckstein [4] elucidated the effects of free surface grains on microforming. Kals and Eckstein [5] and Geiger et al. [6] comprehensively described size effects in microforming by performing various tests. Ahn et al. [7] developed a nanoindentation technique to determine the tensile flow properties of thin films. A few researches have elucidated the strong effects of specimen size and grains on the deformation behavior of a material. Miyazaki et al. [8] showed that flow stress increases with the specimen size for various grain sizes. More recently, Peng et al. [9] proposed an elastic–plastic constitutive model of thin sheet metal under micro uniaxial tension. Kim et al. [10] presented a scaling model to examine the size effect on micro deformation behaviors. Leu [11] proposed a hyperbolic function $tanh(T/D)$ incorporated with a critical value $(T/D)c$ to describe the tensile flow stress. Chan et al. [12] investigated the effect of grain size on the micro deformation behavior of pure copper under micro compression. Deng et al. [13] reported that interfacial friction increases with the decrease of specimen size, and decreases with the increase of grain size for surface deformation. Moreover, large asperity increases the efficiency of lubricant. Chan and Fu [14] reported that the flow stress of sheet metal decreases linearly with the ratio of specimen size to grain size, and decreases with the increasing volume fraction of surface grains in microforming. Liu et al. [15] proposed a constitutive model of the surface layer to examine the size effect on spring-back in micro V-bending. Chan et al. [16] investigated the size effect on micro-scale plastic deformation and frictional phenomenon using micro-cylindrical compression test, micro-ring compression test and finite-element simulation. Chan et al. [17] proposed a material constitutive model based on micro-compression test, and reported that the flow pattern, the surface constraint and the deformation model significantly affect the material flow stress curve. Chan et al. [18] reported that grain size effect is sensitive to the friction force, and the large grain size prohibits the backward flow in micro-extrusion process. Fu and Chan [19] found that flow stress, fracture stress and strain, and the number of micro-voids on the fracture surface decrease with the decreasing ratio of specimen size to grain size in micro-scale plastic deformation. Chen and Jiang

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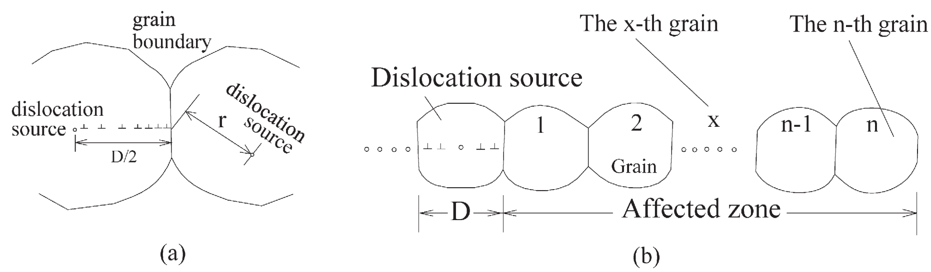

Fig. 1. (a) Pile-up of dislocations at an obstacle and (b) model of affected zone ([8] and [11]).

[20] performed a micro V-bending test to assess the punch force, spring-back, and spring-forward using the sheet thickness/grain size ratio. Nicaise et al. [21] combined the effects of grain size distributions and crystallographic textures on the tensile flow behavior, local stresses and strains, stored energy and normal plastic anisotropy for IF steels. Zhu et al. [22] developed a mechanism-based plasticity model to examine the variations in strength, ductility and work hardening rate of nanotwinned metals with the twin spacing, in which the critical twin spacing is proportional to the grain size. Zhu and Lu [23] developed a micromechanics-based model to examine the strength and ductility of the bimodal metals, furthermore, this model can be used to optimize the mechanical properties by tuning the grain size and corresponding fractions. Chang and Lin [24] developed a specialized forming test to investigate the effects of grain size and temperature on the micro upsetting of copper, and reported that the refined grain size and the increased forming temperature reduce inhomogeneous flow. Dobosz et al. [25] combined the effects of grain boundary and particles strengthening on nano-crystalline metals using FE simulations. Cordero et al. [26] investigated how grain size affects plastic strain and dislocation density tensor fields in two-dimensional polycrystals using microcurl model. Xu et al. [27] reported the clearance/grain size ratio significantly affects the micro-blanking deformation, moreover, the fracture mechanism of micro-blanking is changed with the decrease of foil thickness. Thus, a novel size effect mode is established by considering the blanking clearance and grain size. Song and Li [28] showed how grain size and temperature affect the mechanical behavior of nano-polycrystal magnesium under tensile test using molecular dynamics simulation. Li and Soh [29] developed a dislocation-density-based model, considering the factor of stress-driven grain growth and the effect of thickness fraction of the grain size gradient region, for surface-nanocrystallized materials. Ran et al. [30] developed a size-effect-based surface layer model for ductile fracture analysis, and reported that size effect significant affects the ductile fracture in microforming. Yu et al. [31] performed a tensile test to study the fracture behaviors and the shear fracture angles for both rolled and aged ultrafine grained aluminum 6061 sheets produced by asymmetric cryorolling. In addition, the results of FE simulations based on Gurson–Tvergaard–Needleman criterion are similar to the experimental results in trend. Meng et al. [32] first investigated the micromechanical damage and deformation behaviors in progressive microforming, and then developed a systematic knowledge for improving the microformed part design, process configuration and tooling design. However, the effect of grain size on micro deformation behavior has yet to be elucidated, and miniature specimens are yet to be modeled.

This work examines the effect of grain size on the tensile flow stress using a proposed simple flow stress model to elucidate deformation under simple tension, which is a function of the ratio of the sheet thickness to the grain size, T/D, which is therefore defined as a measure of the size effect. A critical value $(T/D)c$ for distinguishing the micro scale from the regular (macro) scale for flow stress under simple tension, is developed from Li's theory of dislocation with density type [33] and the Hall–Petch equation.

2. Materials and methods

The mechanical properties of a miniature specimen differ from those of a regularly sized specimen in metals. The first task of interest herein is to elucidate accurately tensile flow stress under simple tension.

2.1. A complete flow stress as a function of T/D

Based on experimental observations of the distribution of tensile flow stress σ and the ratio T/D, such as Cu, Al, Cu-13 at.% Al and Fe, Miyazaki et al. [8] expressed the flow stress σ of sheet metal on the micro scale under simple tension as,

$$\sigma(T/D) = \sigma_0 + H(T/D)(\sigma_\infty - \sigma_0) \quad (1)$$

where σ_0 and σ_∞ represent the true stresses of a single crystal and a polycrystal, respectively, and the dimensionless parameter $H(T/D)$ is a function of T/D (sheet thickness/grain size). Dividing Eq. (1) by σ_∞ yields a normalized flow stress, $S(T/D) = S_0 + H(T/D)(S_\infty - S_0)$, where $S_0 = 0.2$ is a mean value extrapolated to $T/D = 0$, as evaluated by Miyazaki et al. [8]. At $T/D = 0$ (as $D \to \infty$), $H(T/D) = H(0) = 0$ for a single crystal, and $\sigma(0) = \sigma_0$. At $T/D \to (T/D)_c$, $H(T/D) = H((T/D)_c) = 1$ specifies the critical condition that distinguishes the micro scale from the macro scale of tensile flow stress, and $\sigma[(T/D)_c] = \sigma_\infty$. The condition of $0 \le T/D \le (T/D)_c$ is defined that the flow stress is under the micro-scale and $T/D \ge (T/D)_c$ is under the macro-scale, respectively. The critical value $(T/D)c$ is important to separate macro scale from micro scale. The parameter $H(T/D)$ is important in modeling tensile flow stress. Leu [11] proposed $H(T/D)$ as a hyperbolic function, $tanh(T/D)$, based on the geometric shape of the distributions of the tensile flow stress σ and the ratio T/D.

Table 1
G, b, D, τ_i, τ_∞ and $(T/D)c$ for various materials [8].

Material	Strain	G (GPa)	b (A°)	D (μm)	τ_i (MPa)	τ_∞ (MPa)	$(T/D)c$ Cal.	$(T/D)c$ Exp.
Al	$\varepsilon = 20\%$	26	2.86	180	4.34	19.2	4.08	4.24
				90	4.34	21.0	5.49	6.40
Cu	$\varepsilon = 20\%$	39	2.56	140	10.58	56.1	3.96	5.03
				65	10.58	65.5	5.46	6.34
				22	10.58	67.5	9.67	9.13
				16	10.58	69.4	12.98	13.51
Cu-13 at.% Al	$\varepsilon = 20\%$	37	2.71	77	24.43	81.1	3.13	8.89
				40	24.43	99.2	3.99	18.26
				31	24.43	107.4	4.68	31.17
Fe	Upper Y. S.	75	2.48	60	35.16	124.1	3.43	13.19
				25	35.16	186.2	5.01	20.19
	Lower Y. S.	75	2.48	60	35.16	80.0	3.19	12.00
				25	35.16	100.0	4.39	14.84

Y. S.: yield stress; Exp.: experimental; and Cal.: calculated (Eq. (13)).
In Eq. (7): $S_0 = 0.2$ and $S_\infty = 1.0$ taken from [8]; In Eqs. (9–11): $\alpha = 0.4$ and $k_0 = 1$.