A Hybrid Model for Studying the Size Effects on Flow Stress in Micro-Forming with the Consideration of Grain Hardening

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A hybrid model for studying the size effects on flow stress in Micro -forming with the consideration of grain hardening

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Abstract. Size effects extremely exist in the metal micro-forming process. When a deformation process scales down to micro scale, the appearances of geometry size and single grain size starts to play a major role in deformation. Generally, the size effects are unavoidable in the experimental work and cannot be neglect in the optimization of micro-forming processes. In this paper, size effect on flow stress is investigated in the form of the coupled effect of workpiece geometry (sample thickness) and grain size, (T/D) by the micro tensile test of pure copper foil. Following the previous approaches, a new hybrid material model is projected to describe the hardening behavior of grains in polycrystalline material. Tensile tests performed on the copper foil with constant thickness and width, while to get dissimilar grain sizes, the foil annealed for different times. The ratio of thickness to grain size (T/D) is limited to larger than 1 (T/D>1). A hybrid material model is proposed and established based on grain heterogeneity and sample thickness. The hybrid material model builds a relationship between the surface layer and sheet interior. The hybrid material model developed by the strain gradient theory in which the dislocation cell structure, cell densities (interior and wall) engaged to define the polycrystalline aggregate and calculated the dislocations in a grain (grain interior and grain wall). The results show that flow stress varies with the different values of T/D, but with an increase of the share of the grains flow stress start to decreases. After applying the hybrid material model of flow stress, the micro-tensile test of copper foil is simulated by finite element method. The simulation outcomes well matched with experimental results.

1. Introduction

Today the new inventions in micro-scale technologies have surprised the progress in the usage of different small-scale devices, for instance, mobile phone, microsurgery tools. All the compact size devices require a significant quantity of micro-scale components, e.g. miniature screws. The fabrication of these micro-level connecting elements is done by metal forming process of a thin (5μm -100 μm) sheet. The traditional micro-forming techniques are not applicable to this thickness range. Because in micro-forming the overall mechanical behaviors are changed due to the scale down the sample dimensions, results in so-called size effects. In other words, size effects are deviations from intensive or extensive values of a process, which occurs while scaling down the geometrical dimensions [11, 17].

In the last few years, scholars have established a series of standard information and models. In micro forming the material behavior is not only influenced by overall dimension but also be influenced by the microstructural topographies, notably the grain size. Mostly these both factors (dimension and grain size) consider together for deep understanding. Therefore, in this study, the size effect on the material deformation behavior of pure copper is investigated in term of T/D (thickness/grain size). In this study, the ratio of thickness to grain size is limited to larger than 1, which means that the specimen material can be observed as the polycrystalline aggregate [1, 21].

However, to optimize the significance of T/D on flow stress, results of numerous studies were investigated [15] and it concluded that the flow stress shows a decreasing trend with decreasing T/D value. Related results were observed in compression test [21] of CuZn15 and copper, and in bulging test of CuZn36. However, the Guo [15] discussed in his study that in some material tests, when the T/D is reduced near to range 2-4, an increase in flow stress had reported. Further, Molotnikov [23] conducted the tensile tests on Cu sheets and investigated the size effects (T/D) on material behavior and found the same trend in flow stress as T/D vary.

The researchers explained the influences of size effects on different material deformation behaviors in micro-forming with their models. All the models [5] directly added dimensions factors like T and D to conventional constitutive model to fit their experimental data. Engle and Eckstein [6] proposed the surface layer model to explain the variation in flow stress in micro-forming by separated the sample into two regions; inner region and a surface layer. After it, Lai [19] used the dislocation movements and modified the existing model by related the inner portion and surface layer of the sample as polycrystals and single crystal, respectively.

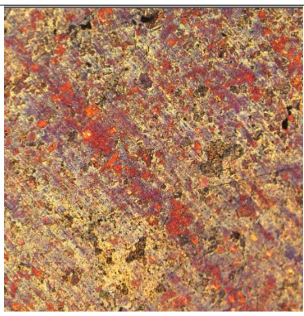
This paper established a hybrid model by linking the surface layer model with a composite model of polycrystal. We assumed that the dislocation in a grain is structured in a dislocation cell structure, and dislocation cell densities (cell interior and cell walls), evolving in the deformation process. Hence, internal material is treated as a two-phase composite structure. The experimental results are compared with simulation results and it is confirmed that they well matched.

2. Experimental work

2.1 Sample preparation.

The size effects were investigated using micro tensile test of pure copper foil. A pure copper foil with the thickness of 50 µm used for this research due to its wide applications in industries. After cutting all the samples in dogbone shape for the micro tensile test, all the samples were annealed at the temperature of 700°C for different times in order to gain different grain sizes. The samples were annealed in Ar air protection condition, the annealing conditions are presented in Table 1. The heat-treated samples etched using a solution of 5ml saturated aqueous sodium thiosulfate, 45mL water, 20g potassium metabisulfite for 10s. The microstructures (as shown in table 1) of the prepared samples were observed using a 3D laser-scanning microscope, as showing in Fig. 1. From Table 1 it is clear that the grain size increases by increasing the holding time under the same temperature range (700°C) of annealing.

Table 1. Microstructure and grain size of the specimen before the tensile test.

	Sample 1	**Sample 2**	**Sample 3**
Material	Copper	Copper	Copper
Thickness	50 µm	50 µm	50 µm
Time	5 min	10 min	20 min
Temperature	700	700	700
Microstructure			
Average grain size	19 µm	31 µm	40 µm
T/D	2.6	1.6	1.3

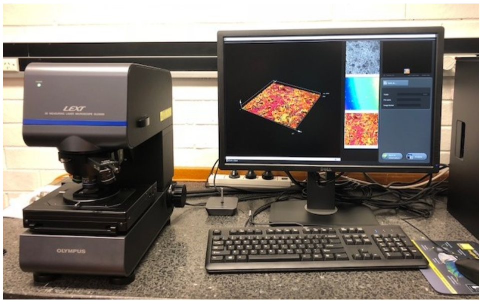


Fig. 1: 3D laser scanning microscope.

2.2 Micro tensile test.

The micro tensile tests were performed to investigate the mechanical properties of the prepared specimen, which are equipped with different T/D ratios. The dimensions of the tensile specimen can be seen in Fig. 2 (a). The tensile tests were conducted on METEX universal testing machine with a maximum capacity of 1KN as shown in Fig. 3. The 0.05 mm/s crosshead velocity selected for all the experiments and all the tests were repeated three times.

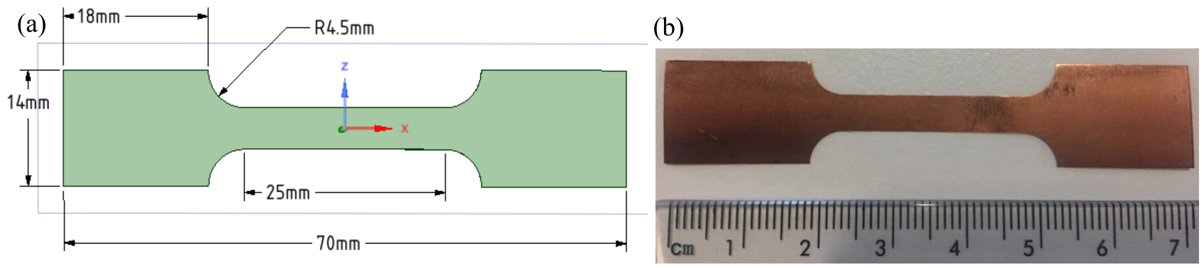


Fig. 2: The tensile test specimen. (a) Dimensions of the sample, (b) Real copper specimen

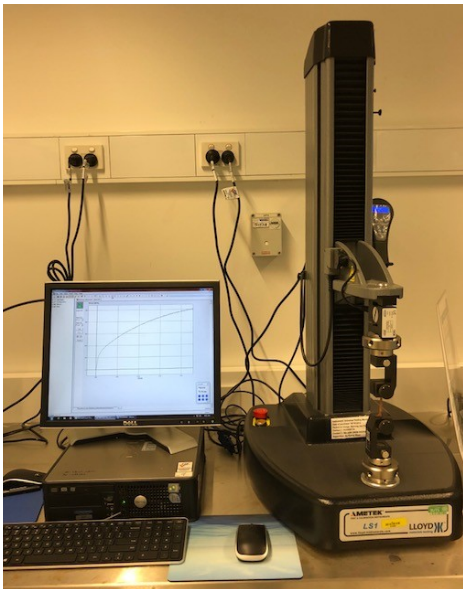


Fig. 3: METEX universal testing machine

3. Result and discussion

3.1 Effect of T/D on flow stress.

The impact of grain size (D) comparative to the sample thickness becomes very important, specifically when the sample is actually thin, and then the T/D effect is analyzed with flow curves. The true stress-strain curves of the copper samples with different grain sizes are shown in Fig. 4. The true stress-strain graphs represent the required stress to origin the further plastic flow in the material. Therefore, it is clear that the strain is directly linked to the flow stress, so, when T/D>1 the amount of grain boundaries and grain corner increases essentially, which leads the strain hardening ability. In other words, Anand [1] and Fang [22] explained that due to the increase of T/D ratio the grain boundary strengthening effect is enhanced and soften which leads the fluctuation of flow stress.

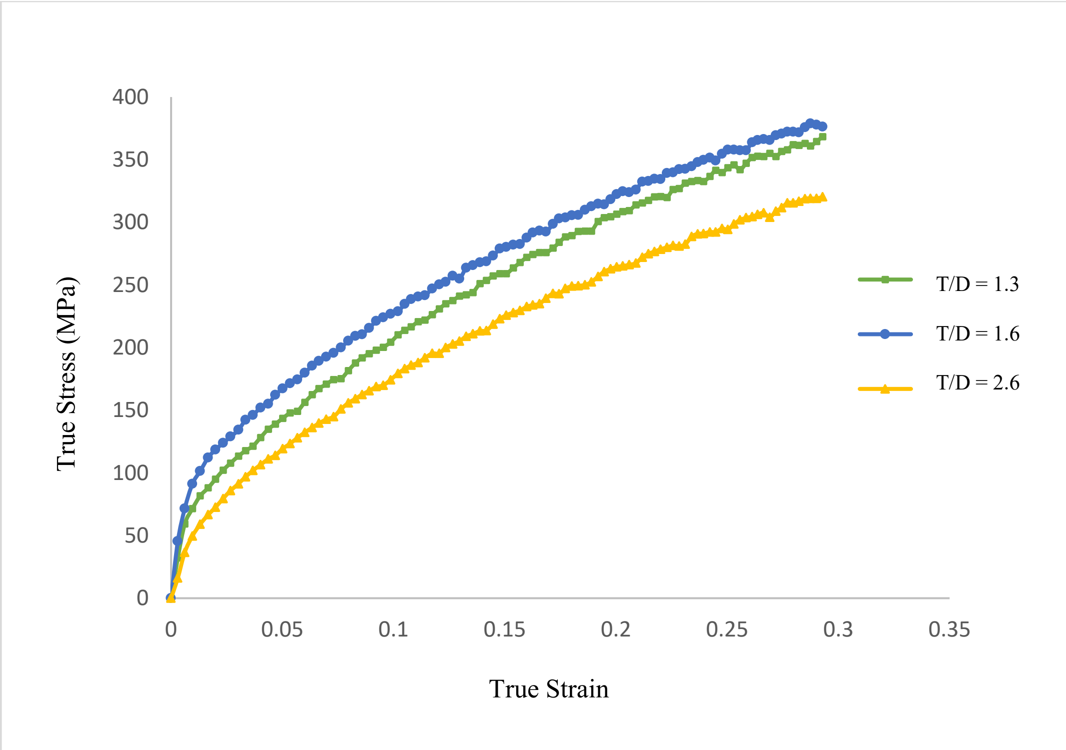


Fig. 4. The true stress-strain curve of copper samples annealed at 700°C.

Anand [1] investigated that for higher values of T/D (approximate 6 -18), flow stresses at different strain levels increased with an increase in T/D ratio. On the other hand, Anand [1] also explained that flow stress declines with the increasing of t/d ratio (when T/D is less than 3) because of the size effects. The same fluctuation can be observed here when T/D varies from 1.6 to 2.6. Because It is observed that the distribution of single grain to effect the distribution becomes less significant with an increase of T/D. In the thick sheet, it easy to analyze the effect of a large number of grains in the thickness direction but for the thin sheet, no mechanism has been developed yet. Therefore, the usage of traditional constitutional equations for thin samples to calculate the flow stress without taking the impact of grain size relative to the thickness (T/D ratio) possibly will lead major errors in the flow stress values. So, in this present work a modification in the existing constitutive equations done for the clear demonstration.

4. Constitutive model

In the surface layer model, when T/D >1 the cross-sectional area of the sample can be divided into the section of surface and interior grains, and the flow stress is calculated for each region. We can apply the surface layer model only when T/D is larger and equal to one (T/D>1, T/D =1) [22]. Surface layer model is represented by the weighted average of stresses in the inside portion and the outer layer of the sample, as following equation [21].

$$\sigma = \eta\sigma_{inner} + (1-\eta)\sigma_{surf} \tag{1}$$

Where σ is the total flow stress of the material, σ_{inner} is inside stress and σ_{surf} is the surface layer stress of the material. To express the fraction of inner portion to the complete material area the size factor η is employed. To calculate the η for the sheet sample with rectangular cross-section the following Eq. 2 can be used [20].

$$\eta = \frac{t-d}{t} \tag{2}$$

As it earlier stated that surface layer model is only applicable for T/D >1 and T/D =1 [22], not for T/D <1 (incomplete grain in the thickness direction). Fang [22] explained that the Hall-Petch relation is applicable for T/D <1 but when the average grain size goes up to 10 nm, it fails. Here, In this study by following the Eq. 1, the flow stress of the inner grains can be explained by the polycrystalline aggregate ($\sigma_{inner} = \sigma_s$), so the flow stress of inner grains is determined by dislocation cell structure. The grains located at the free surface of material have less hardening effect than the inner grains, so the strengthening effect in surface layer can be neglected [22]. Then the flow stress of the surface layer portion is equal to grain interior (cell interior), $\sigma_{surf} = \sigma_c$. From the viewpoint of dislocation accumulation strengthening or dislocation density, the inner grains can be treated as a two-phase composite structure. In terms of cell walls and cell interior, the two-phase composite model can be represented as following Eq. 3.

$$\sigma_s = (1-f)\,\sigma_c + f\,\sigma_w \tag{3}$$

Where the f is the volume fraction of cell walls or grain boundary (Eq. 4). σ_c and σ_w are the flow stresses of grain interior (cell interior) and boundary (cell wall) respectively.

$$f = f_\infty + (f_0 - f_\infty)\exp(-\gamma_r/\tilde{\gamma}_r) \tag{4}$$

Here f_0 and f_∞ are the initial value and saturation value of f, at large strains. The $\tilde{\gamma}_r$ describes the rate of decrease of f, the value of these parameters are selected from [23, 24] and used in the present study (f_0=0.25, f_∞ = 0.06 and $\tilde{\gamma}_r$ = 3.2). The strength of the wall and inner phase are as follows according to the Taylor relation.

$$\tau_w = \alpha G b \sqrt{\rho_w} \tag{5}$$

and

$$\tau_c = \alpha G b \sqrt{\rho_c} \tag{6}$$

Where G and b are the shear modulus and the magnitude of the dislocation burgers vector respectively, and α is a numerical constant (α = 0.25). ρ_w and ρ_c are the dislocation densities in the cell walls and cell interiors, respectively. The stresses σ_c and σ_w are related to the respective dislocation densities, and explained in equation 8 and 9, respectively. To include this effect into flow-rule, the shear stress has to relate to the tensile stress. So, here we employ;

$$\sigma = M\tau \tag{7}$$

Where M is taken as an average Taylor factor (M = 3.06) in polycrystalline material.

$$\sigma_c = M\alpha G b \sqrt{\rho_c} \tag{8}$$

and

$$\sigma_w = M\alpha G b \sqrt{\rho_w} \tag{9}$$

The dislocation density of cell interiors and cell walls are;

$$\rho_c = \alpha^* \left(\frac{1}{\sqrt{3}}\right)\left(\frac{\sqrt{\rho_w}}{b}\right)\gamma_w - \beta^* \left(\frac{6\gamma_c}{bd(1-f)^{\frac{1}{3}}}\right) - k_0 \left(\frac{\gamma_c}{\gamma_0}\right)^{-\frac{1}{n}} \gamma_c \rho_c \tag{10}$$

$$\rho_w = \left(\frac{6\beta^*\gamma_c(1-f)^{\frac{2}{3}}}{bdf}\right) + \left(\frac{(\sqrt{3})\beta^*\gamma_c(1-f)\sqrt{\rho_w}}{fb}\right) - k_0 \left(\frac{\gamma_w}{\gamma_0}\right)^{-\frac{1}{n}} \gamma_w \rho_w \tag{11}$$

In both equations (10 and 11), the d is the average dislocation cell size, which can be explained and linked to the dislocation densities by the following relation [23];

$$d = \left(\frac{K}{\sqrt{(1-f)\rho_c + f\rho_w}}\right) \tag{12}$$

Where K is constant. The parameters $\alpha^*, \beta^*, k_0,$ and n were executed from the previous studies [23, 24]. So, by using these equations the new rule of mixtures is developed and the flow stress in micro-forming can be expressed:

$$\sigma = (1 - \eta f)\,\sigma_c + f\,\eta\,\sigma_w \tag{13}$$

Finite element software ABAQUS implemented to comprised the above set of equations via UMAT user subroutine. The thickness of the specimen and the grain size and other material parameters provided as input quantities, in the subroutine.

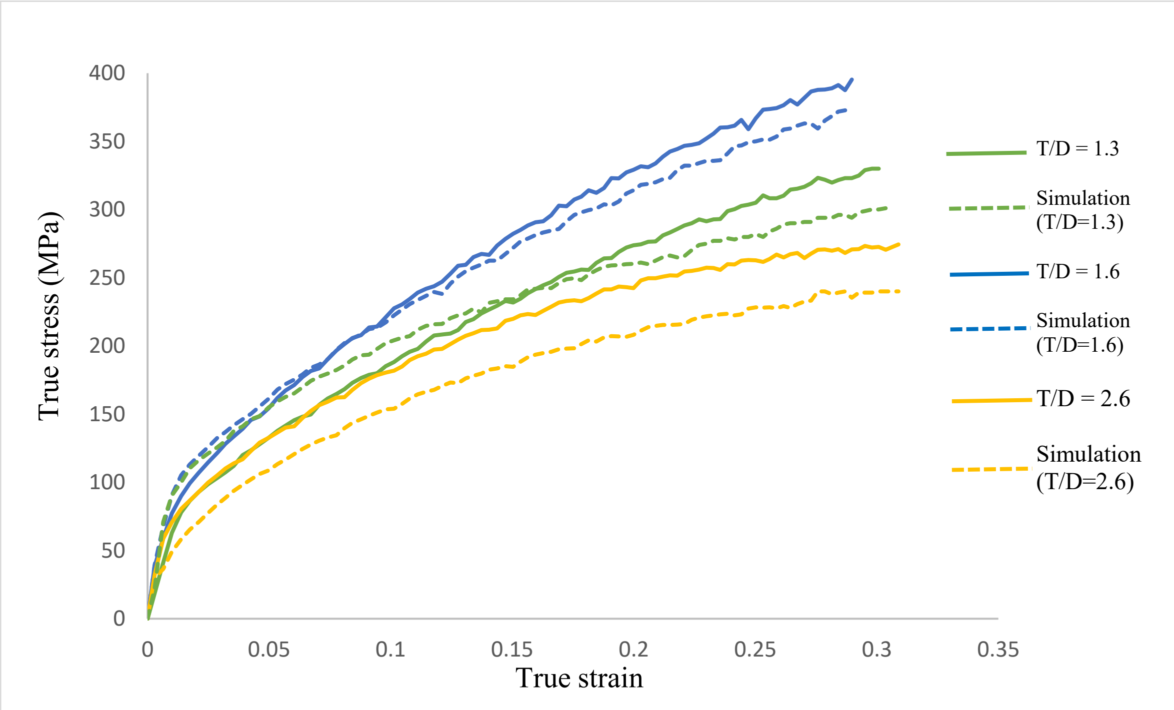


Fig. 5. Simulation vs experimental comparison of stress-strain curve.

The material parameters are identified in the last studies [23, 24] of the copper foil taken as reference. All the parameters α^*, β^*, b, f_0, f_∞, p_w, p_c, M, K, m and n are accepted from [23]. Fig. 5 represents the evaluation of the calculated and the experimental true stress-strain curves for T/D>1 condition. After finding a good agreement found between the calculations and experiments it is clear that the established hybrid model is proficient to calculate the relationship between stress and strain.

5. Conclusion

In this study, the influence of the T/D ratio on materials deformation behavior (flow stress) was investigated. In this study, the ratio of thickness to grain size is limited to larger than 1, which means that the specimen material can be considered as a polycrystalline aggregate. The following conclusions are obtained from this study:

. Plastic deformation (flow stress) incline with the increase in T/D ratio, but the flow stress start decreases with the increase of T/D when the values of T/D is close to the critical value (less than 3).

. A hybrid material model is developed with the consideration of T/D>1. The evaluation was made between simulation and experimental values, and a noble agreement verified the validity of the developed model.

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