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Size Effects on Mechanical Properties of Copper Thin Sheet in Uniaxial Tensile Tests

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Microforming offers a reliable method for mass production of micro parts with low cost and high precision. However, to form micro parts is more difficult than macro parts because of size effects. Uniaxial tensile tests are carried out to study the size effects on mechanical properties of copper C1100 thin sheet at room temperature on a universal testing machine. The materials are thermally treated at 873 K for 12 h in nitrogen atmosphere, and the specimens with thickness varying from 0.32 mm to 0.04 mm are manufactured by slow feeding wire cutting with initial gauge widths of 8, 4, 2, and 1 mm. In addition, a non-contact measurement device is developed to reduce the error of the contact measurement method. The results show that the size effects on mechanical property are obvious. The flow stress and elongation decrease dramatically with the decreasing specimen size. The reason for this phenomenon is also discussed by scanning electron microscope (SEM) observation and theoretical analysis.

Keywords: size effects, micro sheet forming, non-contact measurement, flow stress, elongation.

1. INTRODUCTION

Over the last decade, the demand for micro parts has increased dramatically due to the rapid development of micro-electromechanical-systems (MEMS) and the electronic industry [1, 2]. Microforming, which is a new micro fabrication technology, has become one of the most popular ways for mass production of micro parts with advantages of high efficiency, high precision, short duration, low cost, and no pollution in recent years [3]. Although metal forming is well studied and widely applied, it is not proper to transit macro metal forming to microforming directly due to the changed mechanical properties of the materials and the so called size effects [4].

Mechanical properties are the most important factor affecting the whole process of metal forming, such as forming loads, forming limit, springback, filling of the die, local flow behavior [5]. Size effects on mechanical properties, a basic problem in microforming, have been studied by compression, bending, bulging, and tensile tests according to similarity theory. Messener et al. [6] studied that the flow stress decreased by about 20 % with the initial specimen diameter falling from 4.8 mm to 1 mm in cylinder compression. Similar result was found by Guo et al. [7, 8] in scaled down cylinder compression with the specimen diameter ranging from 8 mm to 1 mm. This effect was also confirmed by Chen et al. [9] using micro-hardness tests after compression. Raulea et al. [10, 11] studied size effects on mechanical property by three-point bending, and the results showed that the yield strength and tensile strength dropped severely with the specimen thickness decreasing from 2 mm to 0.17 mm when the grain size was smaller than the specimen thickness. Michel et al. [12, 13] developed a specific hydraulic bulging device to study the size effects on flow stress and derived that the yield strength decreased by 40 % with the specimen thickness descending from 0.5 mm to 0.1 mm. Kals et al. [14] investigated size effects on mechanical property by uniaxial tensile test and revealed that the flow stress and ductility weakened with the specimen thickness decreasing from 1 mm to 0.1 mm. Michel et al. [13] and Gau et al. [15] also found that the flow stress declined with the decreasing specimen size in uniaxial tensile test with different materials.

Compared to cylinder compression, three-point bending, and hydraulic bulging, uniaxial tensile test are quite simple and extensively used to determine the mechanical properties of different materials. Although size effects on mechanical property have been studied by uniaxial tensile test in recent years, most researches concentrate in the comparative analysis of the experiment results with little attention paid to the mechanism. Additionally, the commonly used contact measurement method for uniaxial tensile test in macroforming may cause great error and is not suitable for microforming because the specimen is much thinner in microforming than in macro forming. This paper develops a non-contact measurement device and explores the mechanism of size effects on flow stress and elongation in micro sheet forming by theoretical analysis and SEM observation.

2. EXPERIMENTAL DETAILS

With excellent electrical conductivity, thermal conductivity, ductility and corrosion resistance, copper becomes indispensable in MEMS and the electronics industry. Pure copper C1100 strain hardened rolling sheets with thickness of 0.32, 0.16, 0.08, and 0.04 mm were used. The specific chemical composition is listed in Table 1.

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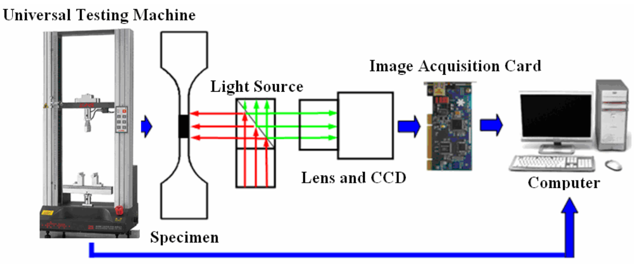
Table 1. Chemical composition of C1100 (wt.%)

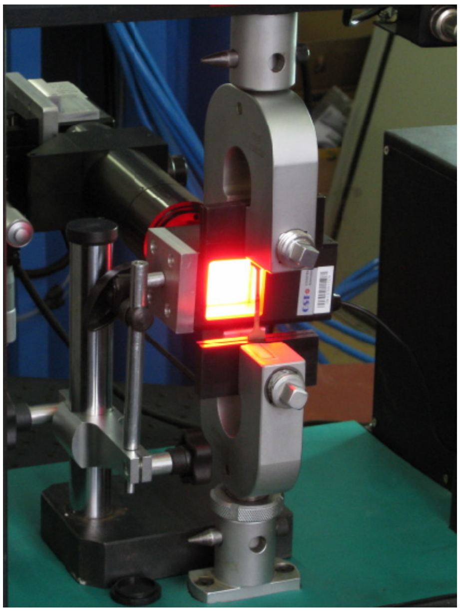
Cu	Bi	Sb	Pb
≥99.90	≤0.002	≤0.002	≤0.005
As	S	O	
≤0.002	≤0.005	≤0.06	

To improve the plasticity of the sheets, the raw materials were annealed at 873 K for 12 h in nitrogen atmosphere. Grain images of different sheets were captured and measured by a laser scanning confocal microscope, and the average grain size was about 20 μm for all sheets with different thickness.

To reduce the error of the contact strain measurement, a non-contact strain measurement device was developed in this study, as shown in Fig. 1. It consists of a universal testing machine, light source, telecentric lens, charge coupled devices (CCD), image acquisition card, computer and appropriate software. First, the lighting source lit up the marked sample, and the image with the marked information was focused by the telecentric lens and imaged on the CCD. Then, the CCD transformed the image signals into electrical signals and stored in the computer memory processing by the image acquisition card. Finally, the image collected by the software was used to calculate the amount of deformation of the marker.



a



b

Fig. 1. Non-contact measurement device: a – schematic; b – photograph

The instantaneous length of the gauge l, true strain ε, and true stress σ can be calculated by the following equations:

$$L = pn; \tag{1}$$

$$E = \ln(l / l_0); \tag{2}$$

$$\sigma = Fl / (A_0 l_0), \tag{3}$$

where p, n, l_0, F, and A_0 are pixel size, pixel quantity, original gauge length, instantaneous force, and original cross section of the specimen, respectively.

After heat treatment, the specimens were manufactured by slow feeding wire cutting with the ratio of gauge width to thickness being 25 along the rolling direction and all parallel lengths were 36 mm, as seen in Fig. 2.

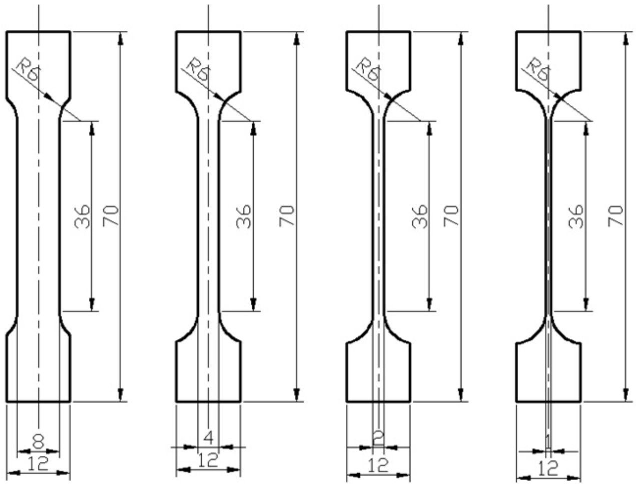


Fig. 2. Dimensions of the specimens with different thickness

The experiment was carried out at room temperature in the non-contact strain measurement device with a velocity of 0.4, 0.2, 0.1 and 0.05 mm/s according to the similarity theory.

3. RESULTS AND DISCUSSION

The specimens after tension test are shown in Fig. 3. Clearly, the elongation of the specimens is different: the thinner the specimen, the lower the elongation.

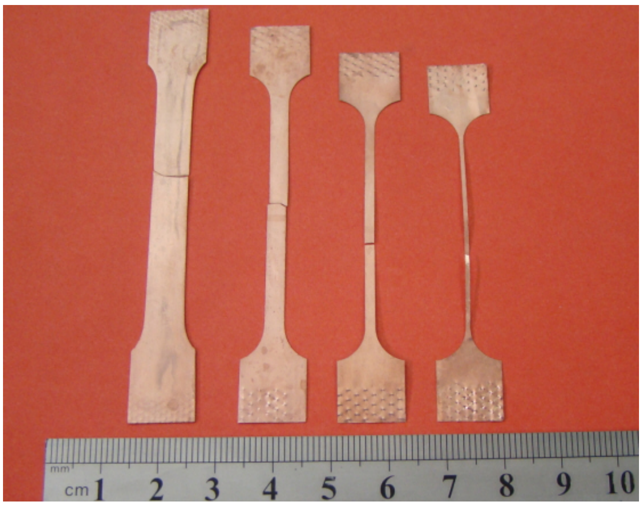


Fig. 3. Specimens with different thickness after tension test

The flow stress-true strain curves of specimens with different thickness are shown in Fig. 4. It can be seen that the flow stress and elongation decreased with the miniaturization of the initial specimen size.

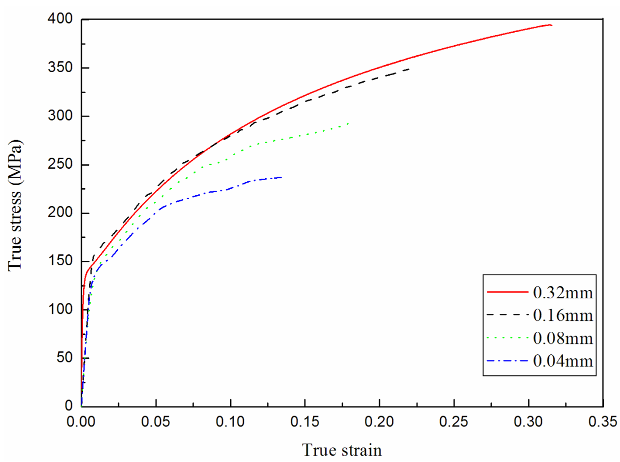


Fig. 4. Flow stress-true strain curves of specimens with different thickness

The tensile strength decreased by 40 % from 395 MPa to 237 MPa, and the elongation was reduced by 60 % from 37 % to 15 %, with the specimen thickness dropping from 0.32 mm to 0.04 mm, which is quite similar to the results reported by Hu and Vollertsen [16], where the flow stress and elongation decreased by about 40 % and 80 % respectively with the thickness of Al 99.5 sheet down from 2 mm to 0.02 mm.

The size effects on the flow stress are correlated with dislocations in the specimens and can be explained by the surface layer model [17], as seen in Fig. 5. The grains in the free surface are less restricted than those inside the specimen. Dislocations move through the grains inside the specimen and pile up at the grain boundaries rather than at the grains in the surface during the forming process, which results in better hardening and resistance against deformation and higher flow stress of the grains inside the specimen. With the decreasing initial specimen size, the ratio of the grains in the surface to those inside the specimen becomes larger, which results in lower flow stress.

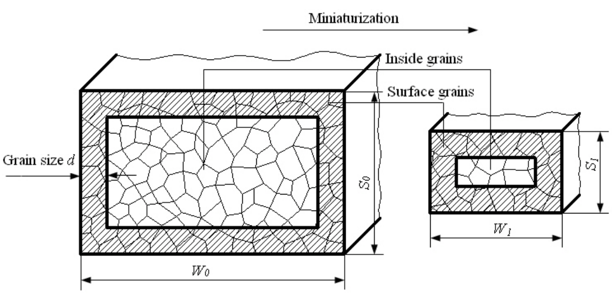


Fig. 5. Surface layer model

To clarify the mechanism of size effects on elongation, fracture morphology of different specimens was observed by SEM, as shown in Fig. 6. It can be seen from the SEM images that all fractures are plastic fracture. However, there are some differences in the fracture mechanisms. Figs. 6, a and b, show slip fragmentation patterns in both side and dimple bands in the center of the fracture and some holes in the large dimple, where the dimple becomes

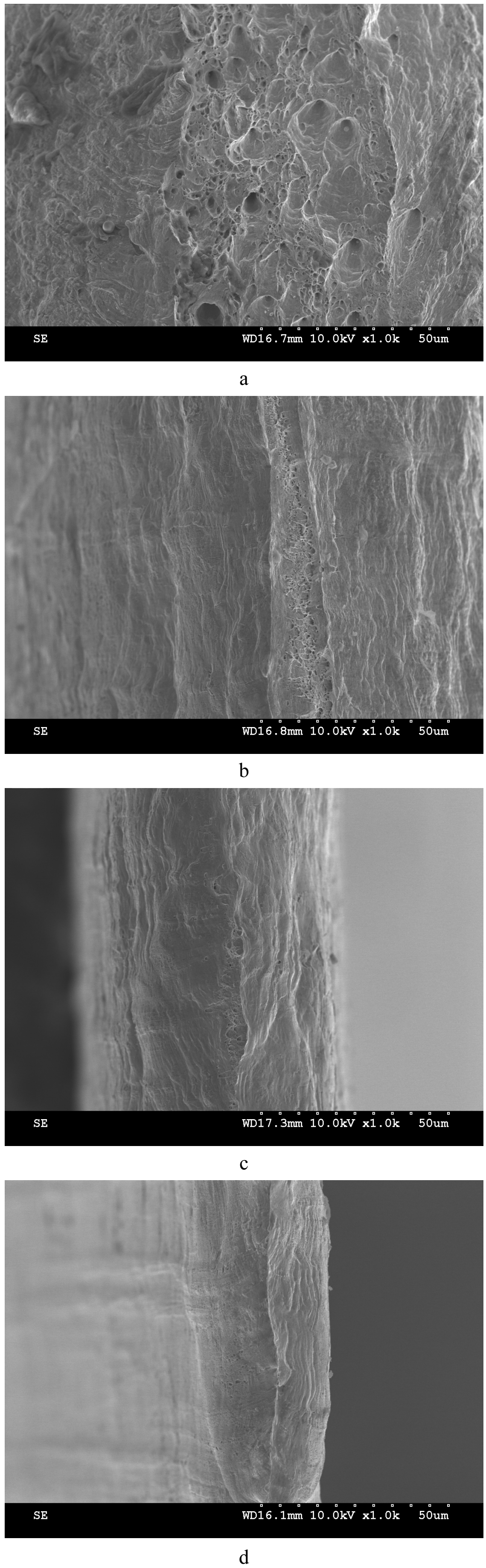


Fig. 6. SEM images of fractures of the tension specimens: a – 0.32 mm; b – 0.16 mm; c – 0.08 mm; d – 0.04 mm

smaller with the decreasing specimen size. This fracture belongs to the compound fracture of slip separation and dimple cracking. On the other hand, serpiform slip patterns in both side and sharp wedges in the center are observed in Figs. 6, c and d, which belongs to typical slip separation fracture.

The fracture processes of sheets with different thickness can be inferred from the fracture morphology. The thicker sheet necks down with slip deformation, and holes occur in the necked part and increase with ongoing deformation and finally form cracks. However, the thinner sheet necks down with slip deformation and cracks into sharp wedges. Thus, the fracture mechanism varies with the changing sheet thickness. The size and number of the dimples decrease with the decline of the sheet thickness and ultimately disappear. According to the fracture theory, the elongation of the dimple fracture is much higher than that of the slip separation fracture. Therefore, the elongation decreases with the decrease of the specimen size.

4. CONCLUSIONS

In the uniaxial tensile test, a non-contact measurement device is developed in this study to reduce the error of the contact measurement method, and the flow stress-true strain curves of specimens with different thickness are determined, which demonstrates the size effects on the flow stress and elongation. With the specimen thickness falling from 0.32 mm to 0.04 mm, the tensile strength decreases by about 60 % and the elongation declines by about 40 %, which can be explained by the surface layer model and different fracture mechanisms, respectively.

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