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Size effect on friction in scaled down strip drawing

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Abstract Friction conditions have important influence on the metal forming process. This is even more significant in microforming because of size effect. Friction size effect was studied in this paper. The specimen material was copper alloy T2 which was thermally treated at 873 K for 12 h in nitrogen atmosphere. The specimens were manufactured by wire cutting with initial width of 8, 4, 2, and 1 mm, and length of 80 mm. The experiments were carried out at room temperature on a universal testing machine under four kinds of lubrication conditions. The results showed the friction size effect was not found without lubrication. However, the friction size effect took place when lubricated with soybean oil, castor oil, and petroleum jelly. The friction coefficient increased distinctly with the miniaturization of the specimen size. The reason for this phenomenon was also discussed in this paper.

Introduction

Over the last decade, the need of miniature parts dramatically increased because of the rapid development of microelectro mechanical systems (MEMS) and electronic industry [1, 2]. Microforming, which is a newly developed technology to produce parts or structures of at least two dimensions in sub-millimeter range using metal forming methods, becomes one of the most popular ways to form miniature parts because of its mass production, high efficiency, high precision, short duration, low cost, and no pollution [3, 4]. Although metal forming is well understood, it is not wise to apply macroforming to microforming directly because of size effect. Size effect on flow stress, which is widely studied, is well understood and quantitative description is available. However, the research on friction size effect is comparatively limited [5].

Friction between the billet and the die is one of the most important factors affecting the whole process of metal forming, such as forming energy, forming limit, surface quality and geometry of the product, tool life and so on [6, 7]. It is essential to clarify the friction coefficient in the forming process. This is even true in microforming because of size effect. Size effect on friction in micromassive forming was studied by doing ring compression, cylinder compression, and extrusion tests according to similarity theory. Messener et al. [8] studied that the friction coefficient increased from 0.12 to 0.22 with the initial specimen diameter decreasing from 4.8 to 1 mm in ring compression. Guo et al. [9] found that the friction factor increased 0.11 when the specimen diameter decreased from 8 to 1 mm in scaled down cylinder compression. Engel et al. [1, 10, 11] investigated the double cup extrusion tests and found that the friction factor dramatically increased from 0.02 to 0.4 with the specimen diameter decreasing from 4 to 1 mm with the lubrication of extrusion oil. However, the friction size effect was not found without lubrication or when a solid lubricant was used. A mechanical–rheological model was also developed based on the experiment results and Wanheim/Bay friction law [5]. Krishnan et al. [12, 13] revealed that the friction coefficient decreased about 0.06 in microextrusion without lubrication while the pin

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diameter decreasing from 2 to 0.57 mm by comparing the finite element method and experimental results. Further investigations show that friction coefficient did not depend on the grain size, interface pressure, and area of contact. Takatsuji et al. [14] used a novel microextrusion apparatus to study the friction behavior in microextrusion. The results showed that the extrusion force did not depend on the grain size in the no-lubrication condition. However, the extrusion force decreasing with increasing grain size when using lubricants. Compared to micromassive forming, the research on microsheet forming is quite limited. Vollertsen et al. [15, 16] investigated macro and microdeep drawing and revealed that the absolute friction coefficient in microforming was much greater than that in macroforming. Friction and scattering in deep drawing increased by miniaturization, the friction coefficient can increased by more than a factor of 2. Hu et al. [17, 18] developed a new friction test method to study the tribology size effect and derived a friction coefficient function from the results of the investigations.

Compared to ring compression, extrusion, and deep drawing, strip drawing is a very simple method of determining the friction coefficient and it can well simulated the friction condition of the flange in deep drawing and was commonly used in macroforming [19]. The purpose of this work was to investigate the influence of the lubrication condition on the friction coefficient and size effect on friction in scaled down strip drawing by experimental research and theoretical analysis.

Experimental

Experimental principle

A schematic of strip drawing between two opposing plat punch surfaces which are wider than the strip is shown in Fig. 1. To avoid the lubricant be scraped off, a radius should be fabricated at the entry of the punch. The friction coefficient in strip drawing can be simply computed by the following equation:

$$\mu = F/(2N) \tag{1}$$

where μ is friction coefficient, F is friction force, N is normal force

Die material and dimension

Tool steel alloy Cr12MoV was chosen as die material, the hardness was HRC 60. The specific chemical composition is shown in Table 1.

The shape and dimension of the die are shown in Fig. 2.

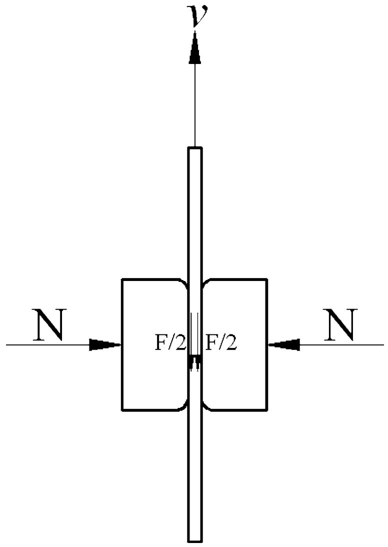


Fig. 1 Schematic of strip drawing

Specimen material and dimension

Copper alloy T2 strain hardened rolling sheets with thickness of 0.32, 0.16, 0.08, and 0.04 mm were used. The specific chemical composition is shown in Table 2.

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 (LSCM) as shown in Fig. 3. The average grain size was about 20 μm for all the specimens.

After heat treatment, the sheets were manufactured by wire cutting with initial width of 8λ mm (λ was the scaling factor with values of 1, 0.5, 0.25, and 0.125, respectively). The length of all the specimens was 80 mm. After cutting, the specimens were washed in the 20% sulfuric acid, cold water, and hot water for 10 min, respectively. The surface roughness of the treated specimens was about 0.6 μm.

Experimental device

The experimental device can be seen in Fig. 4, which was designed based on a universal testing machine. The friction force F and the normal force N can be acquired from the load cell 1 and the load cell 2, respectively.

Experimental parameters

The experiments were carried out at room temperature. The punch surface was fabricated by electrical discharge machining. The average punch roughness R_a was about 0.8 μm and the scanning electron microscope (SEM) image is shown in Fig. 5.

Table 1 Chemical composition of Cr12MoV (wt%)

C	Si	Mn	Cr	Mo	V	S	P	Ni	Fe
1.4–1.6	≤0.4	≤0.6	11–13	0.5–1.2	0.2–0.5	≤0.03	≤0.03	<0.5	Balance

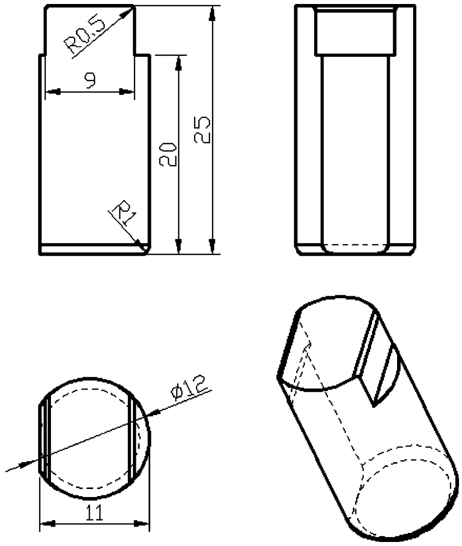


Fig. 2 Shape and dimension of the die

Table 2 Chemical composition of T2 (wt%)

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

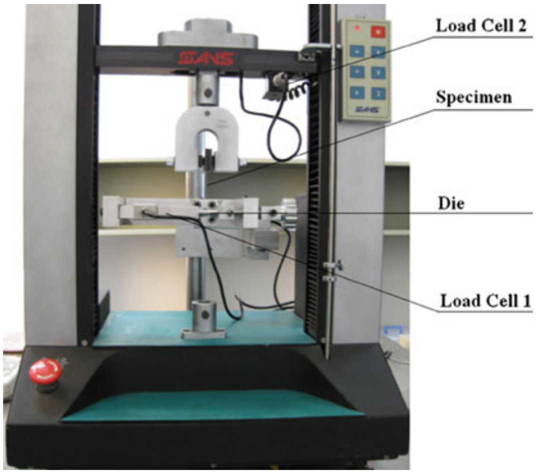
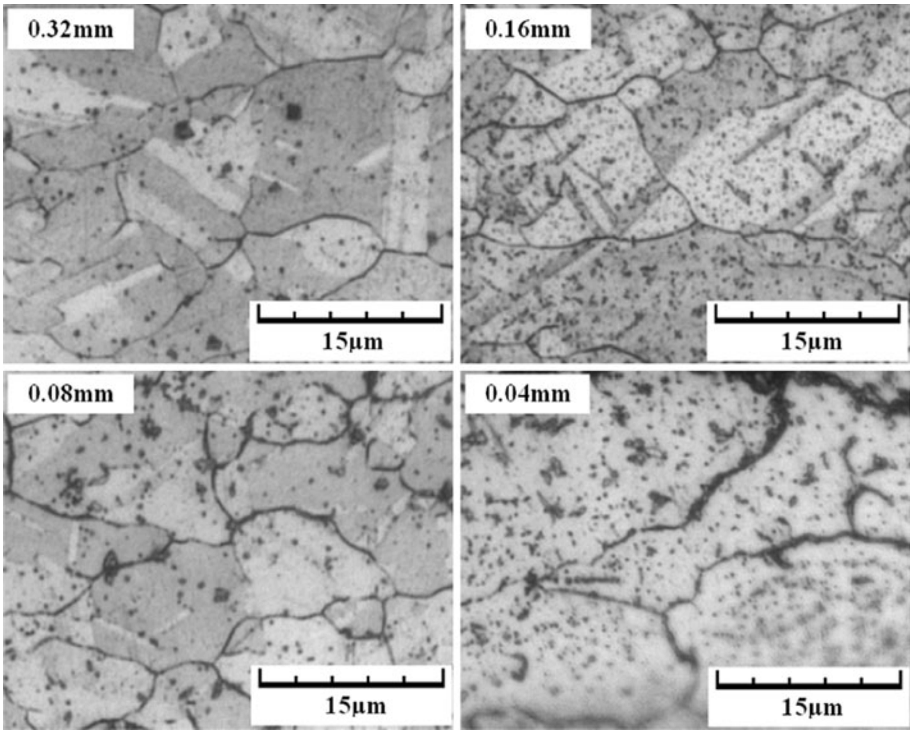


Fig. 4 Experimental device of strip drawing

According to the similarity theory, the drawing velocity v was 0.4λ mm/s. The drawing direction was parallel to the rolling direction. The normal pressure p was 0.4λ MPa. To study the influence of lubricated conditions on friction size effect, four lubricated conditions were used: without lubrication, lubrication with soybean oil, castor oil, and petroleum jelly. The densities of soybean oil, castor oil,

Fig. 3 LSCM images of specimens after annealing



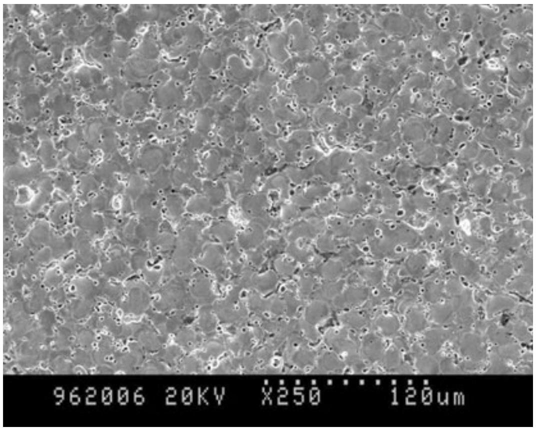


Fig. 5 SEM image of the punch surface

and petroleum jelly were 0.92e^3, 0.93e^3, and 0.82e^3 kg/m^3, respectively. The quantity of the lubricant used for each specimen was 50 mL/m^2. The dynamic viscosity of soybean oil, castor oil, and petroleum jelly at room temperature were 0.05, 0.61, and 1.08 Pa s, respectively.

Results

Size effect

The effect of lubrication condition on size effect is shown in Fig. 6. It can be seen in Fig. 6a, the friction coefficient without lubrication keeps constant with the decrease in the specimen size. The average friction coefficients are 0.231, 0.231, 0.227, and 0.223 at the scaling factors 1, 0.5, 0.25, and 0.125, respectively. However, in Fig. 6b–d, the friction coefficient with the lubrication of soybean oil, castor oil, and petroleum jelly increases with the decrease in the specimen size. Friction size effect took place. The average friction coefficients are 0.138, 0.142, 0.189, and 0.224 with the lubrication of soybean oil, 0.141, 0.145, 0.178, and 0.234 with the lubrication of castor oil, 0.143, 0.144, 0.174, and 0.224 with the lubrication of petroleum jelly at the scaling factors 1, 0.5, 0.25, and 0.125, respectively.

Surface topography

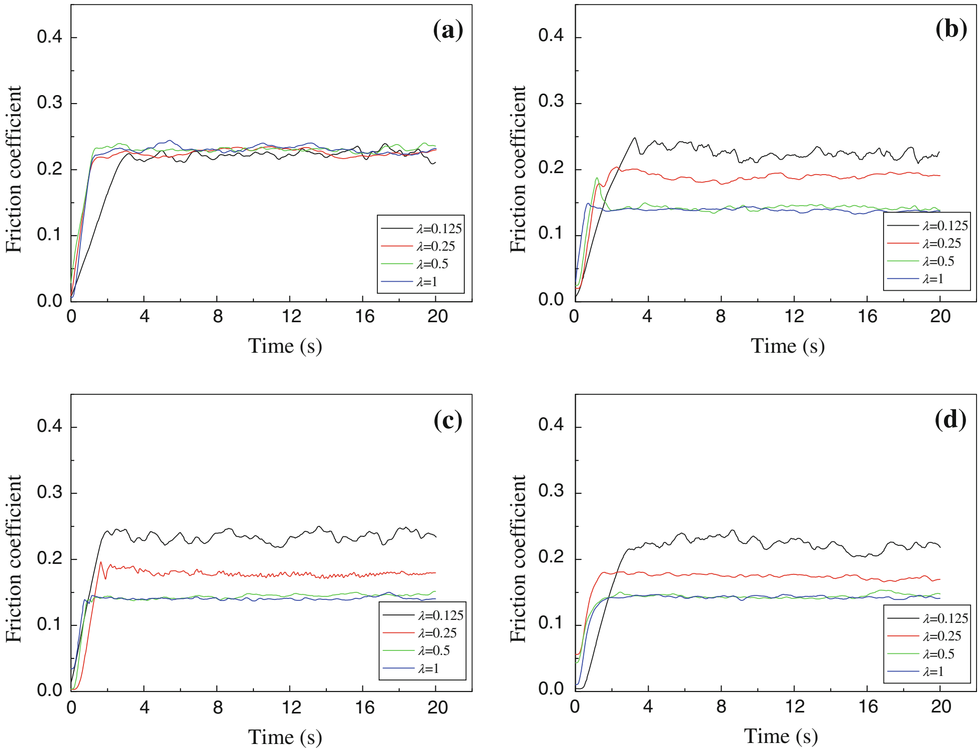
The SEM images of the deformed surface topography (take $\lambda = 0.125$ and $\lambda = 0.5$ for example) are shown in Fig. 7.

It is clear from Fig. 7a that the scuffing was severe in the edge and center for both $\lambda = 0.125$ and $\lambda = 0.5$. It is also clear in Fig. 7b–d, the scuffing was severe in the edge and center for $\lambda = 0.125$. However, the scuffing was severe in the edge but obscure in the center for $\lambda = 0.5$.

Discussion

The fact that the friction factor increased with decreasing the initial specimen diameter under the lubrications of soybean oil, castor oil, and petroleum jelly can be

Fig. 6 Effect of lubricated conditions on size effect **a** without lubrication, **b** lubricated with soybean oil, **c** lubricated with castor oil, and **d** lubricated with petroleum jelly



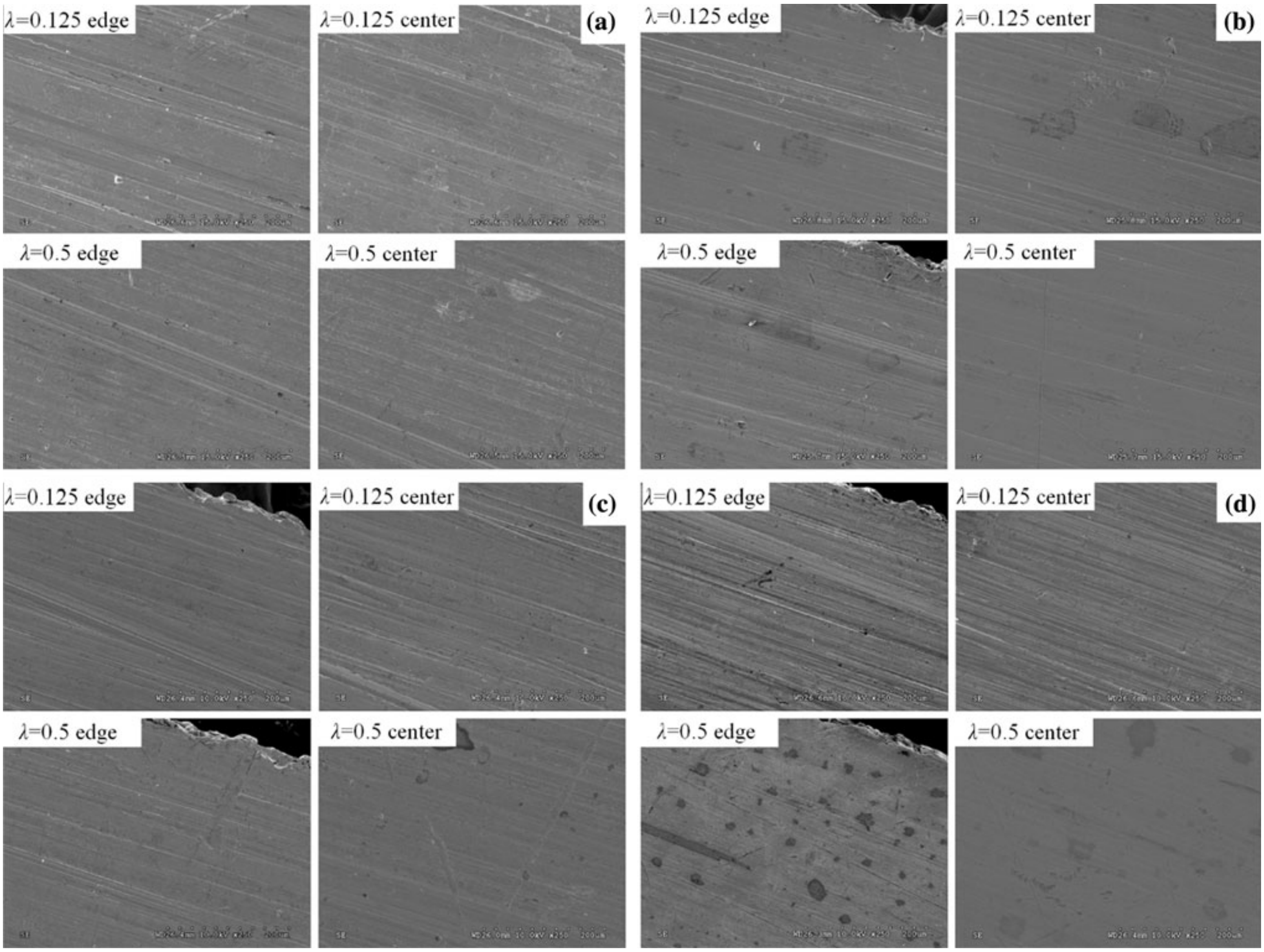


Fig. 7 SEM images of the deformed surface topography **a** without lubrication, **b** lubricated with soybean oil, **c** lubricated with castor oil, and **d** lubricated with petroleum jelly

explained by the fraction of real contact area. When a normal pressure and a drawing velocity apply to the surface of the lubricated sheet, the scuffing was generated because of the interaction between the punch and sheet. Because of the normal pressure, the pressure of the lubricant increased, which results in the lubricant being trapped in the wave troughs of the sheet or overflow [20, 21]. The wave troughs which have connection with the edge of the surface cannot keep the lubricant. With the increase in the normal pressure, the lubricant escapes and is not able to transmit the forming load. The forming load only applies on the wave crests of the sheet, which is the same as that without lubrication, and results in a higher contact stress, a higher fraction of real contact area, a severe scuffing, and a higher friction. On the contrary, the lubricant gets trapped in those wave troughs which do not have connection with the edge of the surface and transmits part of the forming loads during forming, thus reduces the normal pressure on the wave crests of the sheet which result in a lower contact stress, a lower fraction of the real contact area, an obscure scuffing, and a lower friction. The width of the wave troughs which have connection with the edge of the surface is constant for a specific lubricant [11]. With the miniaturization of the initial specimen diameter, the fraction of the wave troughs which have connection with the edge of the surface increased, resulting in a higher friction. However, when there is no lubricant, the ratio of the wave troughs which have connection with the edge does not affect the friction condition, thus the friction size effect was not found without lubrication.

Viscosity is an internal property of a fluid that offers resistance to flow. If the dynamic viscosity of the lubricant is high, the lubricant is difficult to overflow. That means the quantity of the lubricant with lower dynamic viscosity overflowed much more than the lubricant with higher dynamic from the wave troughs which have connection with the edge of the surface [16]. This is why the friction coefficient only increased 0.031 while lubrication with petroleum jelly at the scaling factor decreased from 1 to 0.25, but the friction coefficient increased 0.051 while lubrication with soybean oil with the scaling factor decreased from 1 to 0.25. However, when the scaling factor decreased to 0.125, all the friction coefficients with the lubrications of petroleum jelly, castor oil, and soybean oil were almost the same and approached to that without lubrication. This is because all the lubricants overflow including petroleum jelly whose dynamic viscosity was the highest.

Conclusions

According to the scaled down strip drawing experiments and analysis, the following results can be concluded:

1. Friction size effect occurred with the lubrication of soybean oil, castor oil, and petroleum jelly. However, friction size effect was not occurred without lubrication.
2. Friction size effect can be explained by the fraction of real contact area.
3. The lower of the dynamic viscosity of the lubricant, the more remarkable the friction size effect.

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