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ORIGINAL ARTICLE

Microdeep drawing of C1100 microsquare cups using microforming technology

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Abstract Microdeep drawing has great potential in microsystem technologies, electron industries, new energy, etc. Microsquare cups with internal side length of 1 mm were formed in this study. The blank material was pure copper C1100 with a thickness of 50 μm which was annealed in vacuum condition at 573 and 723 K for 1 h, respectively. The experiments were conducted with an electronic universal testing machine. Three kinds of different lubrication conditions and blank holder force (BHF) were used, and the experimental velocity was 0.05 mm/s. The results showed that a microsquare cup with a limiting drawing ratio (LDR) of 1.89 was well formed. Compared to the as-received blank, the annealed blank decreased the drawing force and the earings and increased the LDR. The polyethylene (PE) film, which decreased the drawing force and increased the LDR, was much better than other lubrication conditions. The wrinkles decreased with the increase of the BHF under a specific value.

Keywords Microdeep drawing · Microsquare cups · Annealing process · Lubrication conditions · BHF

1 Introduction

In recent years, the demands on micrometallic parts are continuously increased with the rapid development of microelectronics, microsystem technologies, new energy, and biomedical. Micromanufacturing technologies, such as LIGA, microelectric spark, micromachining, and laser forming, can realize bulk production with high accuracy; however, they were limited in efficiency, materials, and costs. Microforming, a kind of metal-forming process to form microparts with at least two dimensions less than 1 mm, has been prompted in the past 10 years because of its high precision, high efficiency, low cost, low duration, and no pollution [1].

Microdeep drawing is one of the research focuses in microforming because of its advantages in manufacturing uncorks, hollow, and thin-walled microparts. Erhardt et al. [2] applied laser irradiation in transparent mold to improve the formability of the microdeep drawing blank. Saotome et al. [3] studied the characteristics of thin sheet steels under 0.2 mm in thickness on a special microdeep drawing apparatus. Vollertsen et al. [4–6] investigated macrodeep and microdeep drawings with different materials. The results showed that the microcup was much more difficult to be formed, and the friction coefficient was higher than that in macroforming. Justinger et al. [7] revealed that the cup geometry was much more affected by microstructure than punch velocity in microdeep drawing. Manabe et al. [8] developed a high-precision sequential blanking and drawing setup and fabricated a microcup with 0.5-mm diameter using stainless steel 304 ultrathin foils. Besides, a surface roughness-based model was also applied to analyze the microdeep drawing process. Chen et al. [9] confirmed that thickness, grain size, and foil thickness to grain diameter greatly influenced the LDR in microdeep drawing. Shimizu et al. [10, 11] reported that the surface asperities greatly affected the microformability and microforming accuracy in microdeep drawing. Geng et al. [12] simulated microdeep drawing of copper single crystal by using crystal plasticity theory, and the results were similar to the experiments. Gong et al. [13, 14] formed a microcylindrical cup with a LDR of 2.2 and investigated the

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effect of different lubricants on microsheet forming. Hu et al. [15] indicated that the drawing force was decreased by using DLC-coated microdeep drawing mold. Fu et al. [16] studied grain and feature size effects in microblanking and deep drawing compound process by experimental research and finite element analysis. Gau et al. [17] studied microdeep drawing with two ironing stages by using stainless steel 304 which was annealed at 1050 °C with grain size of 45 μm. Wang et al. [18] formed a pure gold microcup by using DLC-coated female die, and the effects of lubricants on cup thickness were also discussed. Irthiea et al. [19] successfully formed a stainless steel 304 microcup by using flexible tools which dramatically decrease the cost and improve the forming quality. Huang et al. [20] applied ultrasonic vibration on microdeep drawing process, and the results showed that the LDR was increased.

With the miniaturization of specimen size, the material property, mold design, blank holder force (BHF), friction, and lubrication were significantly changed because of size effects. Although microdeep drawing was widely investigated in these years, most of the processing parameters were determined by macrodeep drawing according to the similarity theory. However, the parameters obtained by this method did not coincide with the actual conditions. Thus, crack and wrinkles were often observed, with low precision of the formed microdeep drawing parts, small LDR, and low surface quality. Microcylindrical cup and microsquare cup are two kinds of typical microdeep drawing parts. Microsquare cup was much more difficult to be formed, and there were few studies on it. A microsquare cup with internal side length of only 1 mm was formed in this study. Besides, the effects of annealing temperature, lubrication conditions, and BHF on drawing force, LDR, earings, and wrinkles were also studied.

Fig. 2 Compound punch-dies and blank holders

2 Experimental setup

2.1 Principle and mold

The internal side length of microsquare cups was only 1 mm in this study. If a single operation mold was used, the positioning of microblank to the drawing die was quite difficult. To overcome it, a microblanking and deep drawing compound mold was developed, as shown in Fig. 1. Firstly, a copper

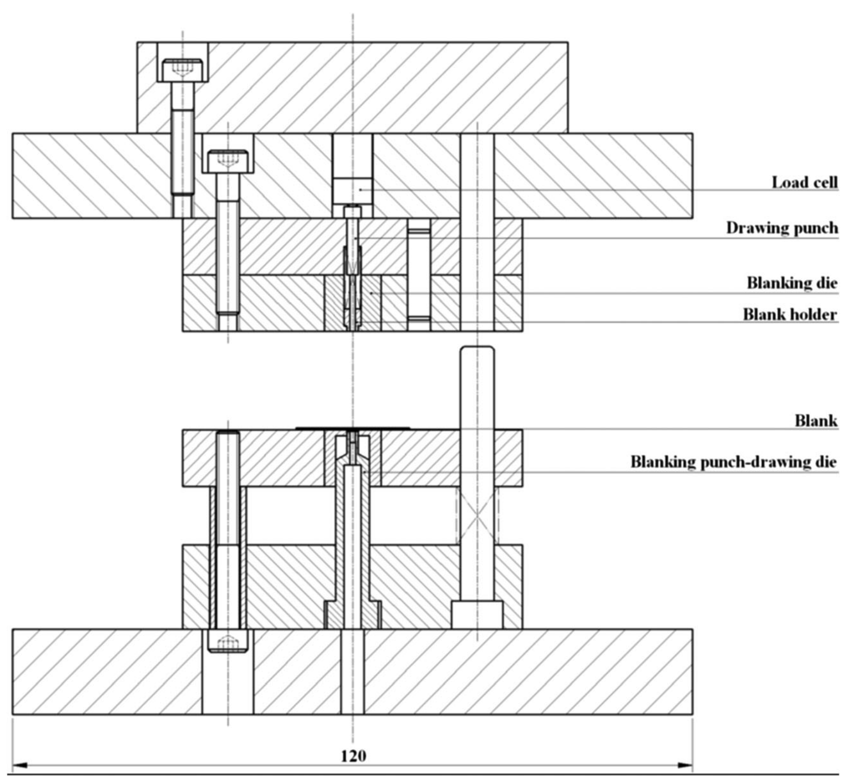


Fig. 1 Schematic of microblanking-deep drawing die

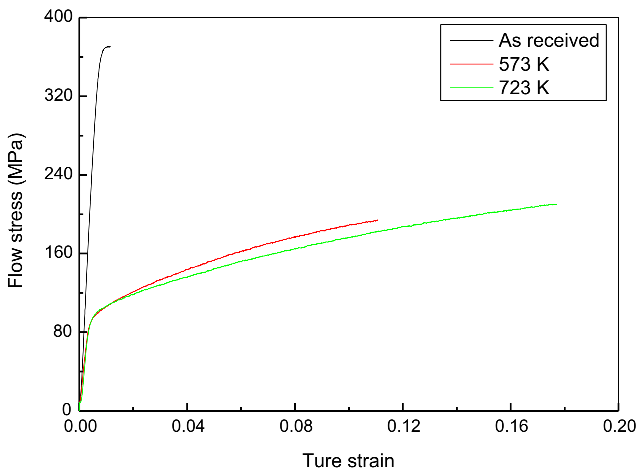


Fig. 3 Flow stress-true strain curves of 50-μm-thick C1100 sheets

C1100 thin sheet was put on the blanking punch-drawing die; when the upper mold moved down, a circular blank was formed by the blanking punch and die. Secondly, the blank was pushed into the deep drawing die by the deep drawing punch. At the same time, a proper BHF was generated by the spring and applied to the drawing blank. Lastly, a microsquare cup was made when the drawing punch was downward to a proper distance. A microload cell, used to measure the drawing force accurately, was installed in the upper mold.

To make full use of the forming ability of raw material and reduce the cost of forming process, a LDR is required. The drawing ratio (DR) K is given by the equation:

$$K = C_0 \Big/ C_p \tag{1}$$

where C_0 is the circumference of the drawing blank, and C_p drawing punch. To study the LDR in microdeep drawing, die insert structure was used, and a series of compound punch-dies and blank holders with different diameters were manufactured, as can be seen in Fig. 2.

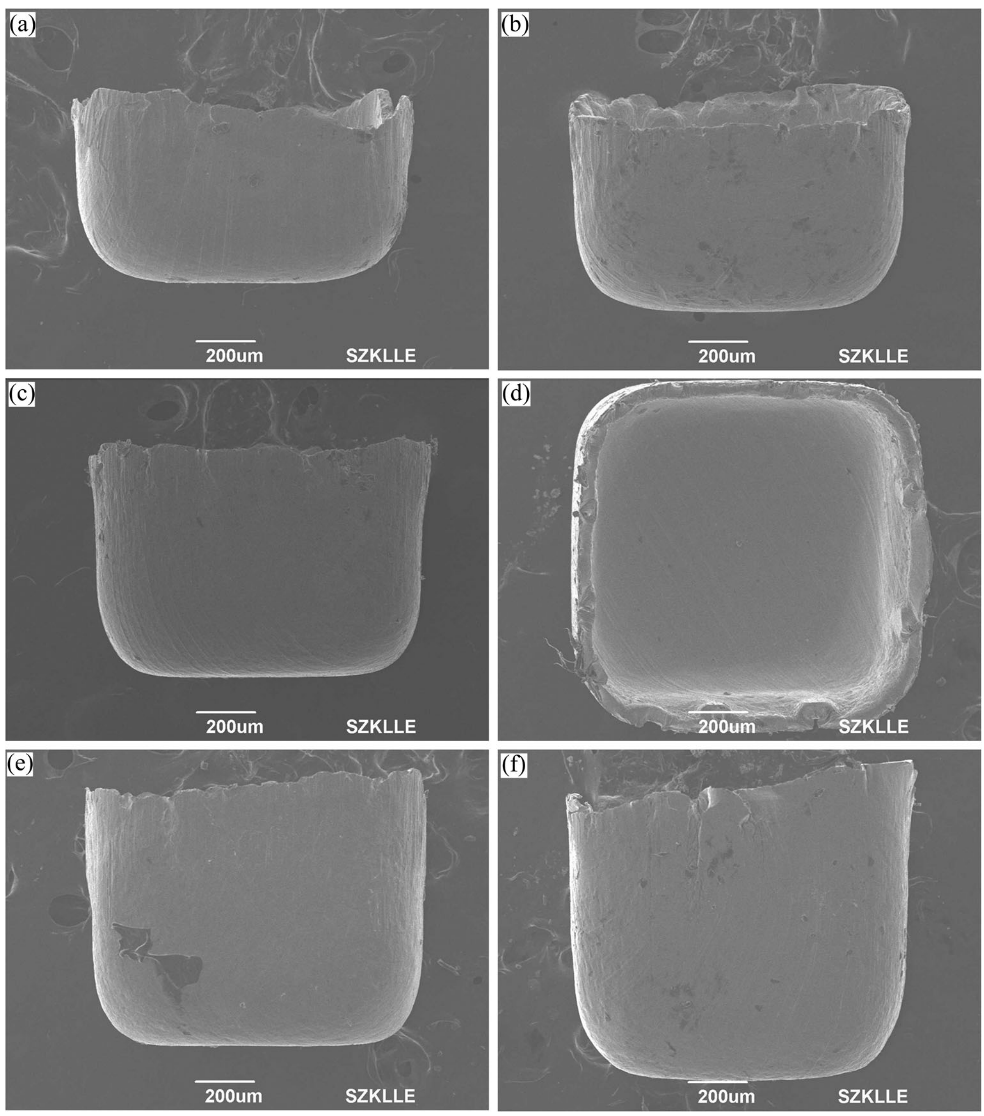


Fig. 4 SEM images of microsquare cups with different DRs: **a** K=1.55, **b** K=1.63, **c** K=1.72, **d** K=1.72 (top view), **e** K=1.80, and **f** K=1.89

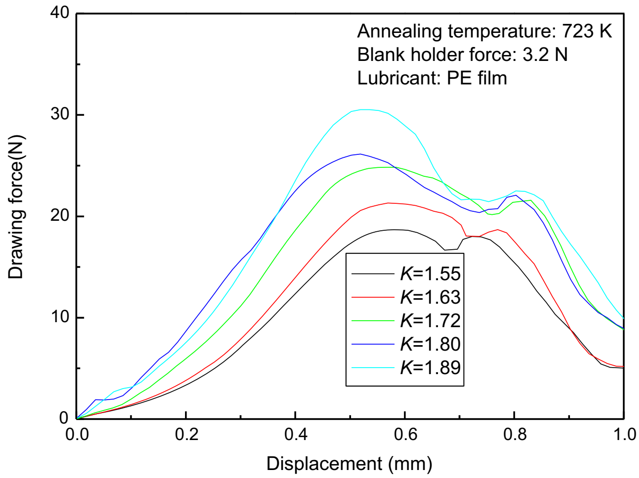


Fig. 5 Drawing force-displacement curves with different DR

2.2 Blank and die material

Pure copper C1100, commonly used in microsystem technologies and electronic industry because of its excellent electrical and thermal conductivity, was chosen as blank material. The raw material was hard rolled sheet, with the thickness of 50 μm. The chemical compositions were as follows (wt.%): Cu ≥99.90, O ≤0.06, Pb ≤0.005, S ≤0.005, Bi ≤0.002, Sb ≤0.002, and As ≤0.002.

To increase the plasticity of the thin copper sheet and investigate the effects of annealing temperature on microdeep drawing, the raw materials were annealed at 573 and 723 K for 1 h in vacuum conditions, respectively. The true strain-flow stress curves of the sheet which was obtained by uniaxial tensile tests on a Zwick/Roell Z050 universal testing machine, as shown in Fig. 3. The elongation increased with increasing the annealing temperature, and the flow stress decreased with increasing the annealing temperature. However, the tensile stress of the materials annealed at 573 and 723 K was almost the same.

Tool steel alloy SKD11, widely used as punch and die material in microforming, was chosen as mold materials. The hardness of the mold materials was 60 HRC after quenching. The specific chemical compositions were as follows (wt.%): Cr 11~13, C 1.4~1.6, Mo 0.5~1.2, V 0.2~0.5, Mn ≤0.6, Ni <0.5, Si ≤0.4, S ≤0.03, P ≤0.03, and Fe, balance.

2.3 Experimental parameters

The experiments were performed on a SANS CMT5504 electronic universal testing machine. The drawing velocity was 0.05 mm/s. Two kinds of lubricants were used. One was castor oil, the viscosity of which was 0.61 Pa s. Another was PE film; the thickness of which was 7 μm. The lubricants were added between the drawing blank and drawing die. The maximum BHFs were 3.2, 4.8, and 6.4 N. The blanking punch diameters were 1.8, 1.9, 2.0, 2.1, and 2.2 mm; the drawing clearance was 0.05 mm; the drawing punch side length was 1 mm; the drawing die side length was 1.1 mm; and the drawing punch and die radius was 0.2 mm.

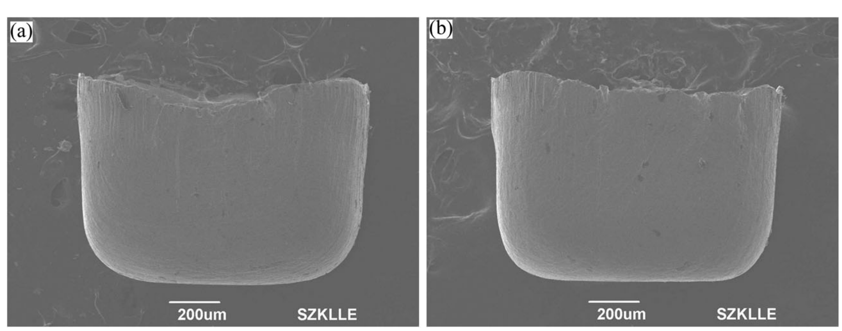
3 Results and discussion

3.1 Microsquare cups

The scanning electron microscope (SEM) images of microsquare cups with different DR are shown in Fig. 4. The blank was annealed at 723 K, the maximum BHF was 3.2 N, and the lubricant was PE film. The LDR reached 1.89 under this experimental condition. It was clear from the figures that the microsquare cups were well made, with the straight side walls. There were only a few wrinkles in the edge when the DR was large, and the wrinkles increased with the increasing DR. This was because the tangential compression stress increased, and the resistance ability of buckling decreased with increasing DR. However, the BHF was constant for different DR in this experiment, thus, the wrinkles occurred. There were obvious wrinkles in microdeep drawing of cylindrical cups with large drawing ratio in current researches [4, 7].

Figure 5 shows the drawing force-displacement curves. There were two peaks in each curve. This was similar to microdeep drawing of microcylindrical cups [10, 20]. The drawing force increased with the continuous of the deep drawing process and the first peak occurred. The maximum drawing force increased with the increase of the DR, and the maximum drawing force increased by 69.4 % when the DR increased from 1.55 to 1.89. This could be explained by the

Fig. 6 SEM images of microsquare cups: **a** as-received blank and **b** blank annealed at 573 K



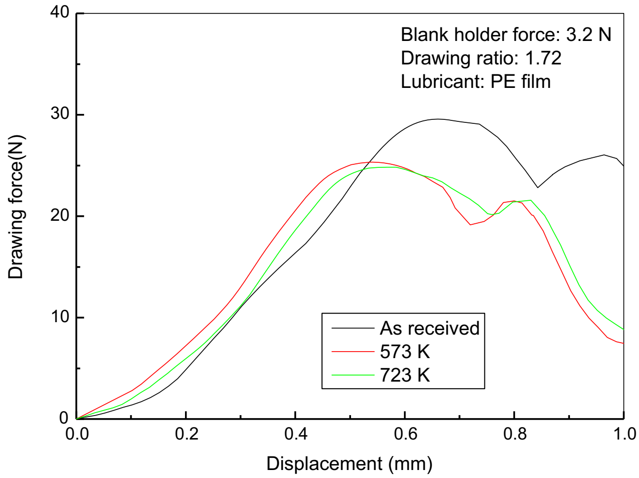


Fig. 7 Drawing force-displacement curves with blanks which annealed at different temperature

increasing deformation degree and the increasing deformation resistance of the flange. The forming of the second peak in the curves was due to the blank thickening and wrinkles on the flange. Firstly, the flange would be thickened in the deep drawing process according to the plastic deformation theory. Secondly, the flange would be wrinkled if insufficient blank holder force were applied. When excessive materials were pushed into the drawing die, they were much more difficult to flow into the drawing clearance. To continue the deep drawing process, a higher deep drawing force was needed.

3.2 Annealing temperature

Experiments were carried out to investigate the effect of annealing temperature on microdeep drawing. The maximum BHF was 3.2 N, and the lubricant was PE film. The LDR of the blank annealed at 573 and 723 K were 1.80 and 1.89, respectively. However, the as-received blank was only 1.72. Microsquare cups with a DR of 1.72 are shown in Figs. 4c and 6. There were earings on the edge of the cup in Fig. 6a, b. Due to the anisotropy of the blank, the velocity of the blank pushed into the die was different in the deep drawing process, which results in the earings and different thickening of the flange. The earings, generated by the anisotropy of the blank, cannot be eliminated. The raw copper sheets, which were hard rolled, contained serious anisotropy. The anisotropy can usually be weakened by the annealing process. Thus, the earings of the cups, formed by the annealed blank, were diminished compared to the cups formed by the hard rolled blank. Similar results were found in the deep drawing of millicylindrical and microcylindrical cups [18, 19].

The drawing force-displacement curves can be seen in Fig. 7. The first peak force of the as-received blank was about 4 N higher than that annealed at 573 and 723 K. When other parameters were the same, the drawing force increased with increasing the tensile stress of the blank. According to Fig. 3, the tensile stress of the raw material was much higher than that annealed at 573 and 723 K, which resulted in a higher maximum drawing force. The second peak force of the as-received blank was about 4.5 N higher than that annealed at 573 and 723 K. Because the anisotropy of the as-received blank was more serious than the other blanks, which result in the earings were much more serious. Thus, a higher deep drawing force was needed for the earings pushed into the drawing die clearance.

3.3 Lubrication conditions

Figure 8 shows the microsquare cups formed without lubrication or lubricated with castor oil. The blank was annealed at 723 K, with the maximum BHF of 3.2 N, and the DR of 1.72. The microsquare cups were cracked. However, the microsquare cup was well formed when being lubricated with PE film, as shown in Fig. 4c. There were only a few scratches observed in the surface of the microsquare cups which lubricated with PE film. This was much better than that without lubrication or liquid lubricants. The average surface roughness R_a of the side walls of the microsquare cups were determined by the laser scanning confocal microscope (LSCM). It was about 0.3 μm with the lubrication of PE film. However, it was about 0.4 μm without lubrication or castor oil. It meant the PE film much better than castor oil and without lubrication condition and was suit for microdeep drawing.

Figure 9a shows the drawing force-displacement curves with a DR of 1.72. The drawing force of the microsquare cups lubricated with castor oil and without lubrication were increased with the continuous of the deep drawing process until the microcup cracked. Figure 9b shows the drawing force-

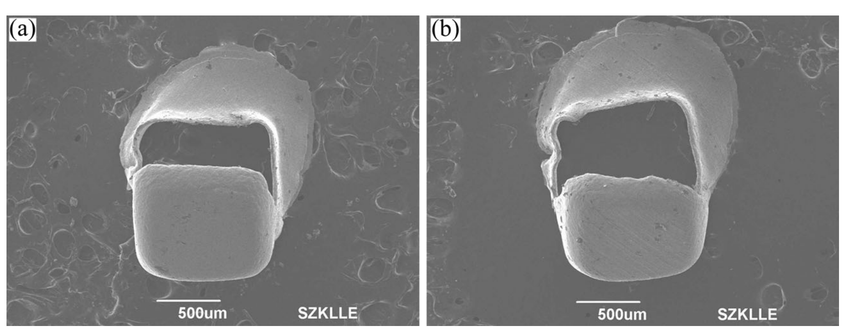


Fig. 8 SEM images of microsquare cups: **a** without lubrication and **b** lubricated with castor oil

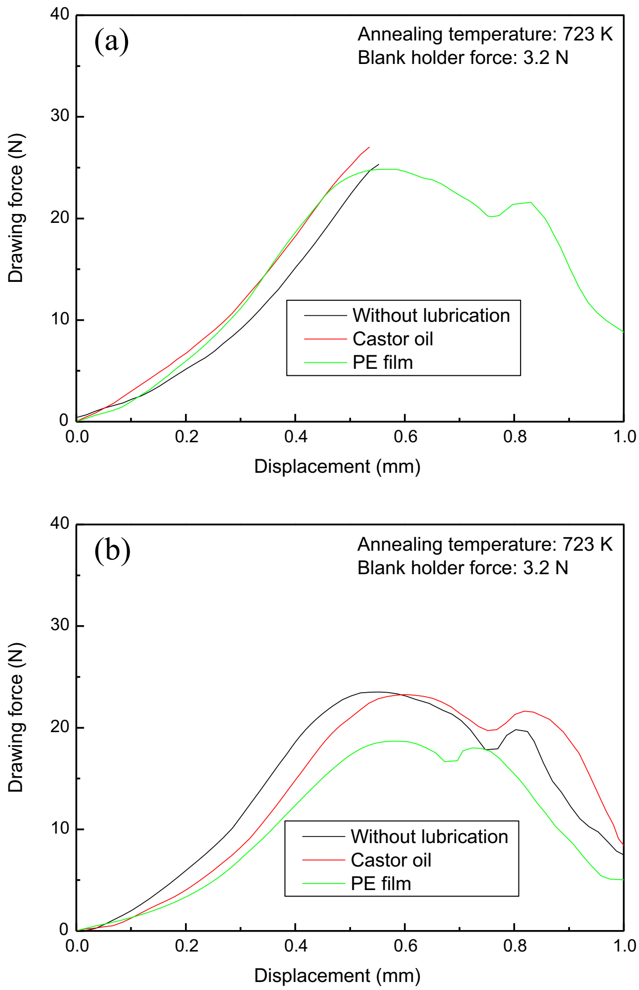


Fig. 9 Drawing force-displacement curves under different lubrication conditions: **a** K=1.72 and **b** K=1.55

displacement curves with a DR of 1.55. The maximum drawing force which was lubricated with PE film was much lower than that lubricated with castor oil or without lubrication. This was because the PE film, always between the blank and die interface, transferred part of the forming load throughout the microdeep drawing process. However, friction size effects occurred in microforming when a liquid lubricant was used in microforming. Most of the castor oil was overflowed, and the forming load could only be applied to the drawing blank, which results in a higher contact stress, a higher fraction of

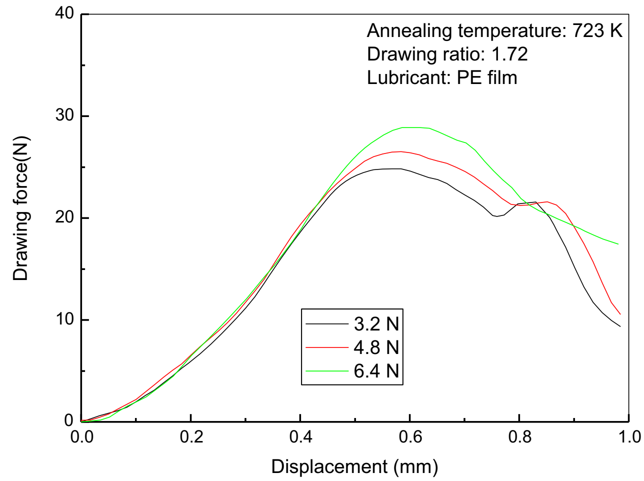


Fig. 11 Drawing force-displacement curves with different BHF

real contact area, and a high friction coefficient. When the blank was reduced to a certain size, the friction coefficient was almost closed to that without lubrication. Thus, drawing force was much higher than that lubricated with PE film.

3.4 Blank holder force

The BHF in microforming was much more difficult to be controlled than macroforming. The blank holder force in microdeep drawing was much more difficult to be controlled than macroforming, and improper blank holder force results in wrinkles on the rim and cracks on the bottom. To study the influence of BHF on microdeep drawing, experiments were done under the conditions that blank was annealed at 723 K, the lubricant was PE film, with the DR of 1.72. Microsquare cups were formed with different BHFs are shown in Figs. 4c and 10. The microcups were well formed, and the wrinkles decreased with the increasing BHF. When there was no BHF, or the BHF was small, the material could flow freely, which resulted in wrinkles in the rim of the cup. When there was appropriate BHF on the blank, the material could generate sufficient stretching, neither wrinkles nor cracks occurred. When the BHF was too large, the friction force between the blank and die increased, the blank would be cracked on the bottom of the cup. Besides, the scratches on the die and the surface of the microcup increased.

Fig. 10 SEM images of microsquare cups with different maximum BHF: **a** 4.8 N and **b** 6.4 N

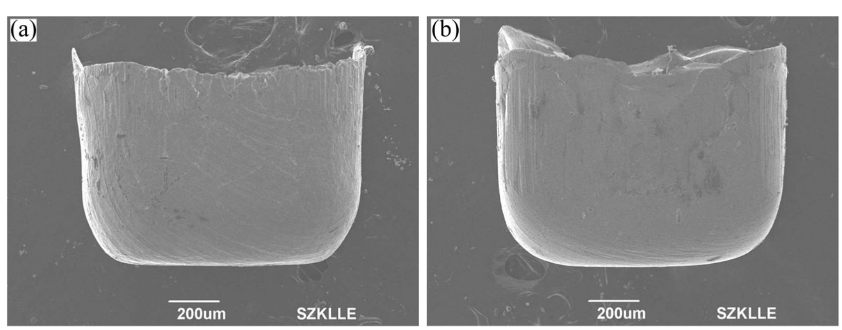


Figure 11 shows the drawing force-displacement curves with different maximum BHFs. The maximum drawing force increased with the increasing BHF. The microcup cracked when the maximum BHF was larger than 6.4 N. This was because the material could not be flowed when the blank holder was too large. However, the deep drawing punch compelled the material to stretch, which resulted in crack. It also showed that the second peak of the drawing force-displacement curves decreased with the increasing BHF, because the wrinkles diminished with the increasing BHF, and the flange could be easily pushed into the die clearance.

4 Conclusions

Microdeep drawing experiments were conducted with an electronic universal testing machine with C1100 thin sheet. The influence annealing process, lubrication conditions, and BHFs on microdeep drawing process were investigated. The results are as follows:

1. Microsquare cup with an internal side length of 1.0 mm was successfully formed, and its LDR reaches 1.89.
2. By using the annealed blank, the LDR was increased; the drawing force decreased; the earing was diminished.
3. Compared to other lubrication conditions, the drawing force was decreased, and the LDR was increased by being lubricated with PE film.
4. The wrinkles diminished with the increasing BHF; however, the microsquare cup cracked when the maximum BHF was larger than 6.4 N.

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