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Grain Size Effect on Multi-Stage Micro Deep Drawing of Micro Cup with Domed Bottom

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KEYWORDS: Deformation behavior, Deformation defect, Grain size effect, Multi-stage micro deep drawing, Thickness variation

A two-stage micro deep drawing system was designed and developed to manufacture a micro cup with domed bottom. The copper blank was annealed at three different conditions to obtain different grain sizes in such a way to study the grain size effect on the deformation behavior and thickness variation of the micro part. To investigate the instantaneous effect and deformation behavior, finite element simulation was used to simulate the whole drawing process. It revealed that the fracture in the place with the thinnest thickness in the micro part drawn from a circle blank with residual stress induced in blanking can be easily happen and the deformation load in the first-stage decreases more than that in the second-stage with the increase of grain size. Moreover, the micro part with a larger grain size has more nonuniform thickness and severer thinning around the punch corner. The surface roughness at the bottom of micro part increases with the grain size. The surface roughness at the wall of it, however, decreases with the deformation stage mainly due to the ironing effect. The research promotes the understanding of grain size effect on multi-stage micro deep drawing and facilitates the development of microforming process.

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1. Introduction

Nowadays, microparts are increasingly needed in numerous industrial sectors such as consumer electronics, jewelry, watch, micro unmanned aerial vehicle (UAV) and micro sub-systems/components. Microforming, for fabrication of parts or its geometrical feature with at least two dimensions in sub-millimeter range by micro-scaled plastic deformation, plays an important role in micromanufacturing arena for its high productivity, low cost and net-shape of the formed parts.[1-3] As a significant microforming process, multi-stage micro deep drawing has different process behaviors and performance from the traditional macro deep drawing and thus the conventionally established macro-scaled forming knowledge may not be fully accurate and efficient in design of micro deep drawing processes and product quality assurance and control. In-depth understanding of the micro-scaled plastic deformation mechanism and developing methods to avoid defect formation and ensure quality of the parts made by multi-stage micro deep drawing thus become an eluded and tantalized issue and fully addressing this issue will contribute to the development of micromanufacturing technologies.[4,5]

Recently, a number of researchers have made their efforts in developing micromanufacturing processes for fabricating microparts. Gong et al.[6] conduced a novel study in conducting micro deep drawing of conical-cylindrical cups by using pure copper C1100 with the thickness of 0.05 mm. Wang and Gong et al.[7,8] manufactured a series of micro cups with diamond-like carbon (DLC) coated tools. On the other hand, Vollertsen et al.[9] optimized an analytical model for acquiring the size-dependent friction function in sheet metal forming. The function was implemented in finite element method (FEM) simulation and validated by comparing the corresponding results with physical experiments. Singh et al.[10] explored the effect of ironing process on the thickness distribution of the drawn cups under warm forming using finite element code LS_DYNA. Kim et al.[11] reported that the finite element analysis (FEA)-aided tool design could be carried out for multi-stage deep drawing and rolling process of a rectangular cup with a large aspect ratio, which is defined as the ratio of the height to the minor axis of the cross section. Similarly, Chan et al.[12] demonstrated that the FEA simulation could be used as an effective tool to aid the design of multi-stage drawing process and tooling for production of a final round cup with the inner diameter of 3 mm and the height of 12.06 mm.

Furthermore, there are many studies on size effect. Simons et al.[13] investigated the size effect in tensile testing of thin cold rolled and annealed Cu foils. They indicated that there is a clear dependence of the mechanical behavior on the thickness of foils in tensile test when the samples with the same processing condition are compared. Xu et al.[14,15] studied the size effect on the formability of sheet metal in micro scale plastic deformation. It revealed that the forming limit curve decreases with the ratio of thickness to grain size in both physical experiments and finite element simulation. This founding facilitates the development of the successful and reliable microforming process. Chan et al.[16-18] investigated the size effect on microforming including micro-extrusion and micro-upsetting processes of pure copper and provided an in-depth understanding of size effect in microforming. Fu et al.[19] conducted the micro blanking and deep drawing compound process using copper sheet. They found that the deformation load decreases and inhomogeneous deformation occurs with the increase of grain size. Deng et al.[20] conducted the compression experiments of the pure copper cylinder for investigation of surface deformation behavior from three aspects, i.e., specimen size, asperity size, and grain size. The study revealed that the increase of grain size leads to the decrease of interfacial friction, and the decrease of grain boundary strengthening leads to the decrease of friction force. In addition, to simulate size effect influence, Lai et al.[21] proposed a micro-scaled material model, which combines the surface model with single-crystal and polycrystalline theories by introducing size dependent and independent terms. The results show that the flow stress of micro-scaled material is between the lower bound of signal-crystal model and the higher bound of the polycrystalline model. Lu et al.[22] also developed a material model but based on the grained heterogeneity in terms of shape, grain size, deformability, and specimen dimension. To control the grain shape in steady status, centroidal-voronoi algorithm has been used in this study, and the grain deformability is represented as its hardness obtained from nano-indentation. Numerical simulation results obtained from the finite element model show a good agreement with the experimental results from two aspects, i.e., the flow stress curves and the profile of the deformed parts.

With the similar research purpose but more focused on product quality, Yeh et al.[23] established a mathematical model to simulate the material behaviors in terms of thickness and grain size. The results based on the finite element analysis show that the thickness variation and stress distribution in cylindrical micro cup drawing are reasonable, which suggests that the proposed mathematical model can be used for estimating thickness and grain size influence. Chen et al.[24] found that the hardness of plastic deformation process is decreased with the specimen size. Furthermore, Shimizu et al.[25] characterized the deformation behavior of the industrially produced rolled metal foils and clarified the impact of anisotropic properties on micro-sheet formability to facilitate the unstable deformation behavior, such as thickness reduction etc. Altinbalik et al.[26] made an effort to obtain the FEM solution of sheet thickness variation and experimental verification under different blank holder forces in deep drawing process.

Although there are numerous researches on micro parts development by using microforming processes, there are still fewer investigations on micro sheet metal parts produced by multi-stage micro deep drawing. The present study is to fabricate a micro cup with a domed bottom and the inner diameter of 1.0 mm and the height of 2.07 mm by multi-stage micro deep drawing. Furthermore, FEM simulation is used to explore and investigate the behaviors and performance of the multi-stage micro deep drawing. The aim of this research is to study deformation behaviors and process performance in multi-stage micro deep drawing and explore how the grain size affects them and further the quality of micro deep drawn part.

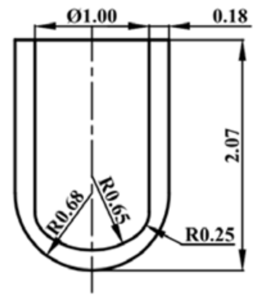


Fig. 1 Dimensions of the micro deep drawn part with domed bottom (Dimensions in mm)

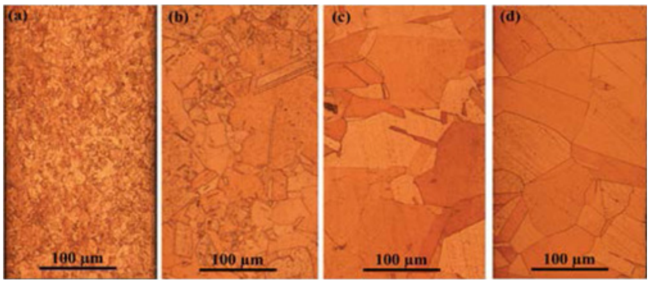


Fig. 2 Microstructures of the as-received and the annealed specimens: (a) As-received; and annealed at (b) 500°C; (c) 600°C; and (d) 750°C

2. Materials and Methods

2.1 Dimensions of micropart and material preparation

In this research, the design of micropart with the height of 2.07 mm, the inner diameter of 1.0 mm, and the outer diameter of 1.36 mm is shown in Fig. 1. Pure copper, which is widely used in microelectronics, is selected as the testing material. The pure copper blanks with the thickness of 0.2 mm were annealed at 500, 600 and 750°C with the holding time of 1, 2 and 3 hours, respectively, in a protective argon condition to avoid oxidation. After polished and etched in a solution of 5 g $FeCl_3$, 15 mL HCl and 85 mL H_2O for 8~12 seconds, the heat treatment samples were examined with optical microscope to reveal their microstructures and shown in Fig. 2. It is found that the grain size increases with the heat treatment temperature from 25.5 μm at 500°C to 89.8 μm at 750°C. The specific grain sizes of the as-received and the annealed pure copper foils are presented in Table 1. In addition, the tensile tests were conducted in a MTS machine to obtain the material properties of the as-received and the annealed samples at different annealing temperatures. The dimensions of the dog-bone testing specimen based on the ASTM-E8 standard were designed to facilitate the tensile tests and shown in Fig. 3. A standard extensometer with the length of 25 mm was utilized to measure the strain accurately. In tensile test, the

Table 1 Grain sizes of the as-received and the annealed pure copper foils

Material condition	Grain size (μm)
As-received	7.7
Annealed at 500°C	25.5
Annealed at 600°C	68.8
Annealed at 750°C	89.8

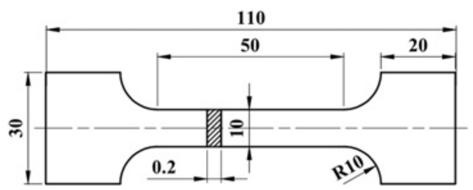


Fig. 3 Dimensions of the testing specimen (Dimensions in mm)

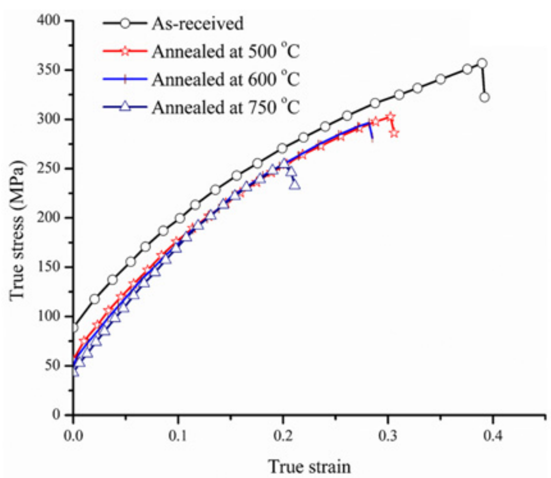


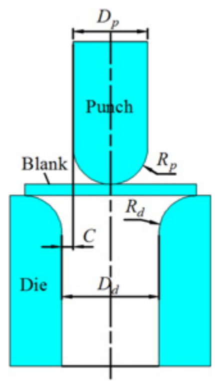
Fig. 4 True stress and strain curves of the as-received and the annealed pure copper foils

crosshead velocity was 0.1 mm/s in all the tensile tests. Three tests were made to decrease the experimental error and demonstrate the repeatability of the experiment. The true stress and strain curves of the as-received and the annealed pure copper foils are shown in Fig. 4. It is observed that the as-received pure copper foil has the maximum flow stress and fracture strain than other annealed ones. Although the true stress and strain curves of different annealed pure copper foils are very close, the true stress increases with the decrease of annealing temperatures. It also indicates that the true stress decreases with the increase of grain size in the pure copper.

2.2 Forming process analysis and design

To obtain a defect-free micro cup, it is critical to identify the number of drawing stages and drawing ratio in the whole micro deep drawing. In this paper, the total drawing ratio of the final product is 3, exceeding the limit drawing ratio of pure copper in a single-stage micro deep drawing, which is usually about 2.1, discussed by Gong et al..[6] A multi-stage micro deep drawing is thus required to fabricate the final

Table 2 Dimensions and parameters in each micro deep drawing stage (mm)



Parameters	First-stage Deep Drawing	Second-stage Deep Drawing
D_p	1.3	1.0
D_d	1.7	1.36
R_p	0.65	0.25
R_d	0.5	0.8
C	0.2	0.18
D_p: Diameter of drawing punch		
D_d: Diameter of drawing die		
R_p: Radius of drawing punch		
R_d: Radius of drawing die		
C: Unilateral drawing clearance		

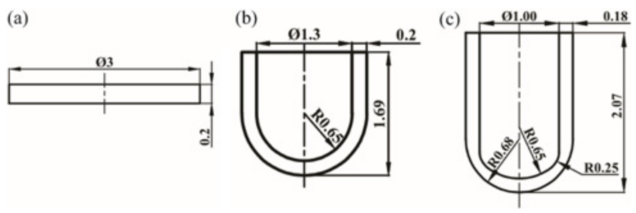


Fig. 5 Dimensions of the blank and the drawn parts: (a) Original blank, (b) Semi-finished part, and (c) Final part (Dimensions in mm)

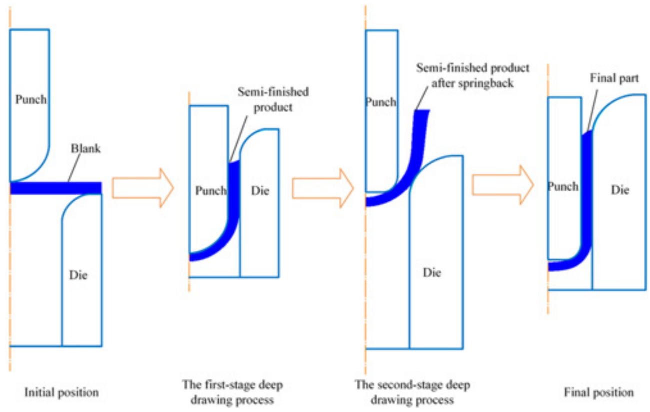


Fig. 6 The FEM models in each stage of micro deep drawing

micropart and two-stage drawing is employed. Table 2 shows the dimensions and parameters of the two-stage micro deep drawing die sets. Fig. 5 presents the profile of the intermediate part in each stage. The diameter and the thickness of the original blank are 3 and 0.2 mm, respectively. The sheet blank was drawn to the cylindrical die with the diameter of 1.7 mm by the first domed punch with the diameter of 1.3 mm to obtain the semi-finished part. The first drawn part was then redrawn to the final micropart with the inner diameter of 1.0 mm and the height of 2.07 mm.

In this study, the FEM software Deform-2D was used to simulate the two-stage micro deep drawing. The FEM models in each stage in the micro deep drawing are given in Fig. 6. A half of micro deep drawing

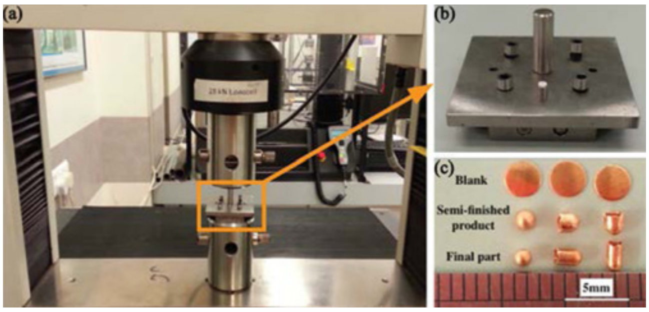


Fig. 7 Experimental setup: (a) Testing platform, (b) Tooling, and (c) Drawn parts

was simulated for symmetrical geometry. The half of initial blank was meshed into 3000 quadrilateral elements and 3171 nodes. And the blank type was elastic-plastic.

2.3 Experimental setup

The multi-stage micro deep drawing experiments were carried out using a MTS testing machine with a load cell of 25 kN for recording the real-time deformation load and punch stroke. Fig. 7 shows the testing platform, tooling and the drawn parts. There is no blank holder in the multi-stage micro deep drawing die sets. In addition, the punch velocity is 0.01 mm/s and oil lubricant was applied in each stage of micro deep drawing process.

3. Results and discussion

3.1 Defects analysis

Generally, blanking is not an important operation in macro deep drawing, while it deserves to be considered in micro deep drawing due to its significant effect on the deformation of micro part. According to Fig. 4, the as-received pure copper blank has larger fracture strain than other annealed blanks. It should thus be drawn to the micro part via micro deep drawing with more ease, but reality is not. Therefore, the following forming strategies were proposed to investigate the influence of blanking on micro deep drawing.

Strategy I: The pure copper sheets with the thickness of 0.2 mm were firstly annealed at 500, 600 and 750°C with the holding time of 1, 2 and 3 hours, respectively. The annealed and the as-received pure copper sheets were secondly blanked into the circle blanks with the diameter of 3 mm. The annealed-blanked circle blanks were then employed in the first-stage micro deep drawing. The results show that fracture occurred in all the micro parts drawn by the annealed and the as-received blanks in the first-stage micro deep drawing.

Strategy II: The pure copper sheets with the thickness of 0.2 mm were firstly blanked into the circle blanks with the diameter of 3 mm. The circle blanks were secondly annealed at 350, 500, 600 and 750°C with the holding time of 1, 1, 2, and 3 hours, respectively. The pure copper blanks were annealed at 350 °C for the holding of 1 hour to relieve residual stress. The blanked-annealed circle blanks were then employed in the first-stage micro deep drawing. The results reveal that all the micro parts were successfully fabricated, including the micro

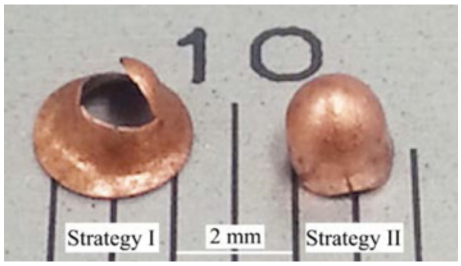


Fig. 8 Micro parts drawn by the as-received pure copper blanks using different forming strategies

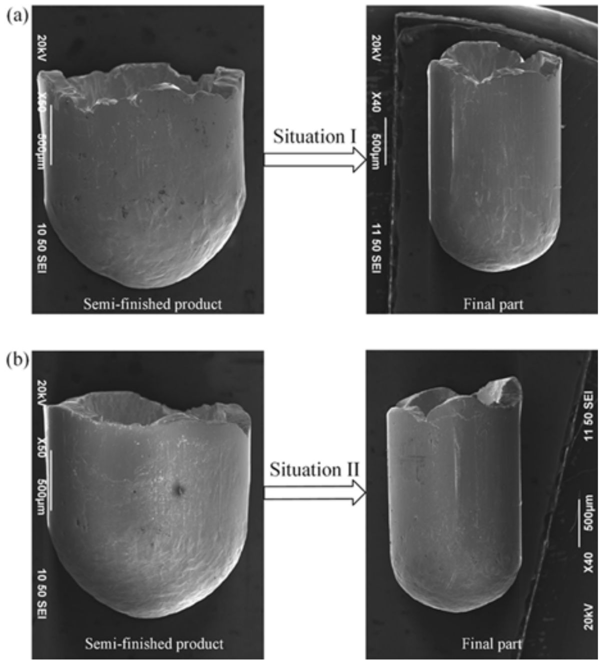


Fig. 9 Scanning electron microscope images of micro parts in each stage micro deep drawing process: (a) Situation I, and (b) Situation II

parts drawn by the as-received pure copper blanks with the stress relief annealing heat treatment.

Fig. 8 shows the micro parts drawn by the as-received pure copper blanks using different forming strategies. It can be seen that the micro part drawn by the as-received pure copper blank is torn at the drawing punch corner in forming strategy I, while the micro part drawn by the as-received pure copper blank with stress relief annealing using forming strategy II was successfully fabricated. The fracture occurring in the place with the thinnest thickness in the micro part drawn by the as-received pure copper blank is mainly caused by the residual stress induced in blanking process.

In addition, earing, the wavy edges at the open end of micro parts drawn by the first-stage and the second-stage micro deep drawing, is presented in Fig. 9. It is resulted from the material anisotropy, namely the different material properties induced by the deformation texture in different directions. There are two situations about the earing development during the multi-stage micro deep drawing.

Situation I: When the earing appears in the first-stage micro deep

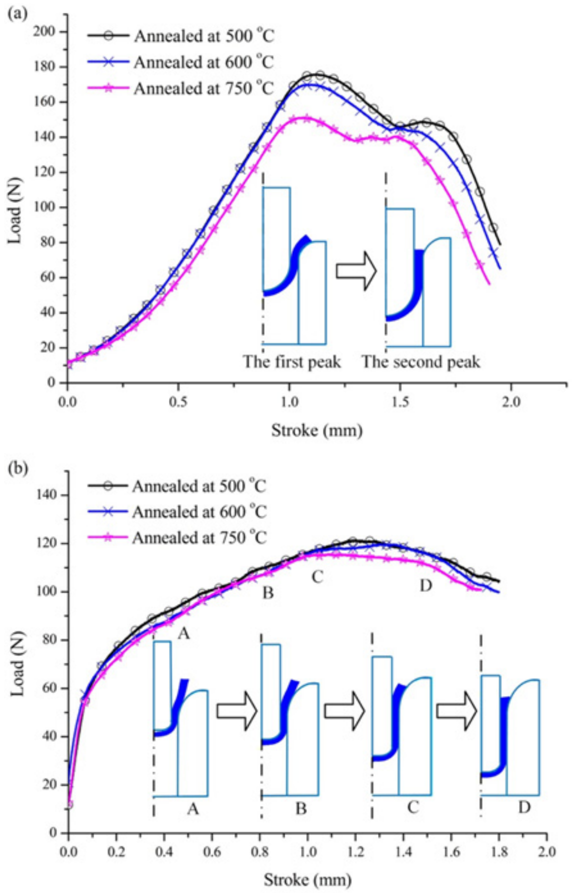


Fig. 10 Load-stroke curves: (a) The first-stage, and (b) The second-stage

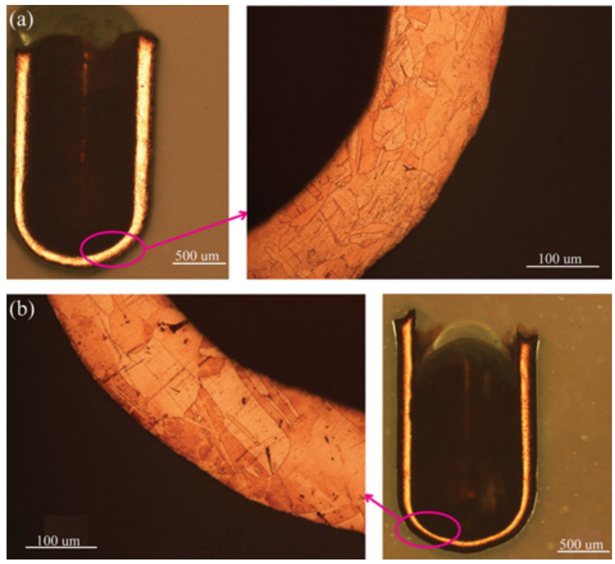


Fig. 11 Microstructures of the final parts in the second micro deep drawing stage. Annealed at (a) 500°C; and (b) 750°C

drawing, the ear with a larger difference in height was developed after the second-stage micro deep drawing, as shown in Fig. 9(a). It is mainly due to the greater material deformation for multi-stage micro deep drawing than that for single-stage micro deep drawing.

Situation II: When the earing and misalignment exist simultaneously and make the height difference of semi-finished product more considerable in the first-stage micro deep drawing, the final part with a larger height difference was made after the second-stage micro deep drawing, as shown in Fig. 9(b). There is a much larger height difference than that in Fig. 9(a).

3.2 Deformation behavior

Punch loading is an important parameter in multi-stage micro deep drawing. Fig. 10 shows the relationship between deformation load and punch stroke in each stage of micro deep drawing. The value in it is the average of all the tests. Generally, all the curves in each micro deep drawing stage have almost the same tendency. In Fig. 10(a), the deformation load increases firstly to the maximum point, and then decreases to form the first peak in the first micro deep drawing stage. When the thick flange is drawn into the clearance between punch and die, the second peak occurs. However, there are not obviously two peaks in the load-stroke curves as shown in Fig. 10(b), where four feature points show the whole second-stage micro deep drawing. In addition, the peak loads with different annealing temperatures in the first micro deep drawing stage are much larger than those in the second-stage micro deep drawing. The main reason is that the deformation decreases in the second-stage micro deep drawing. Furthermore, it can be observed that the deformation load decreases with the annealing temperature, while the decrease of deformation load in Fig. 10(b) is considerably slighter than that in Fig. 10(a).

The difference of deformation loads at different annealing temperatures can be explained by the influence of surface grain size and the grain boundary strengthening behavior. According to the surface layer model, the surface grains have fewer constraints to deformation and low flow stress, while the inner grains have larger flow stress due to more constraints. This describes the influence of surface grain size and Hall-Petch relationship can illustrate the grain boundary strengthening behavior. In Fig. 2, the grain size increases with annealing temperature. For the blanks with the same thickness, the fraction of surface grains increases with grain size along thickness direction. Thus the flow stress and deformation load of material decrease with the increase of grain size.

Actually, the characteristic of grain boundary has a close relationship with grain size effect on material strengthening in deformation process. The grain boundary prohibits slip propagation, further causing dislocation pile-up and grain boundary strengthening effect. Fig. 11 shows the microstructures of the final parts in the second-stage micro deep drawing, using the blank annealed at 500 and 750°C, respectively. From the figure, it can be seen that the corner of the part annealed at 750°C consists of only 1 to 2 grains along the thickness direction. Therefore, the blank with a larger grain size and less number of grains across its thickness has a relatively low density of grain boundaries, which results in a lower restriction to deformation, and the low deformation load. However, it can be seen the grain size has a less significant effect on the deformation load during the second micro deep drawing stage.

Generally, friction coefficient in physical experiment of multi-stage micro deep drawing is difficult to accurately measure mainly due to the interactivity of lubricant, surface of tooling and the surface roughening

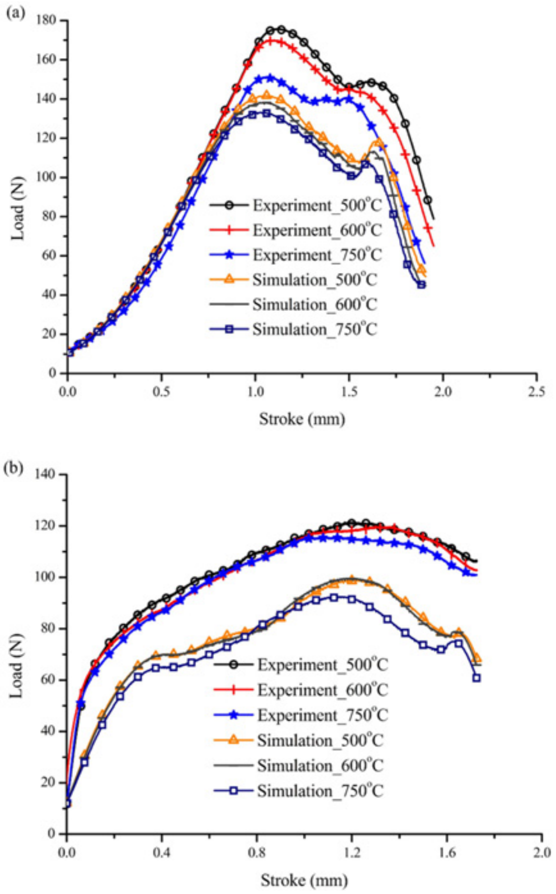


Fig. 12 Comparison of the experimental and simulated load-stroke curves: (a) The first-stage and (b) The second-stage

of blank etc., in deformation process, mentioned by Fu et al..[19] In this research, the friction coefficients of punch-blank and die-blank interfaces were set to be 0.1 and 0.05, respectively, in numerical simulation considering the better surface finish of die than that of punch. Fig. 12 shows the load-stroke curves determined by experiment and simulation in each micro deep drawing stage. It can be observed that there is a deviation between experiment and simulation for different annealing temperatures in each micro deep drawing stage. However, the load variation has the same trend in simulation and experiment. On the other hand, the deformation behavior of material in multi-stage micro deep drawing process could be inhomogeneous and there could be some difference of frictional behavior between microforming and macroforming. The simulation in this study does not take into account these influencing factors. Thus, the deviation of deformation load in simulation and experiment is mainly caused by the inhomogeneous deformation behavior of materials and the different interfacial friction behaviors in physical experiments and frictional simulation, also reported by Fu et al..[19]

3.3 Thickness variation

To investigate the thickness variation of microparts, the micro parts were grinded to the axis-crossed position instead of cutting and then its profile was examined by using optical microscope. The thickness variation of micro part was obtained through measurement of the axis-

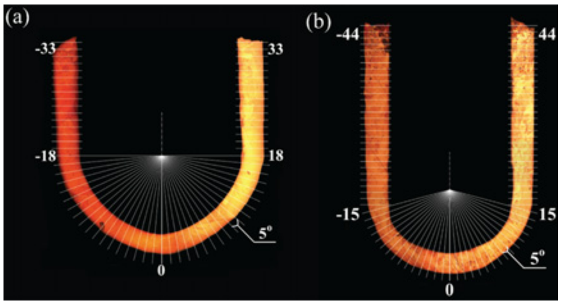


Fig. 13 Schematic illustration of the thickness tracking nodes in the micro parts: (a) Semi-finished product and (b) Final part

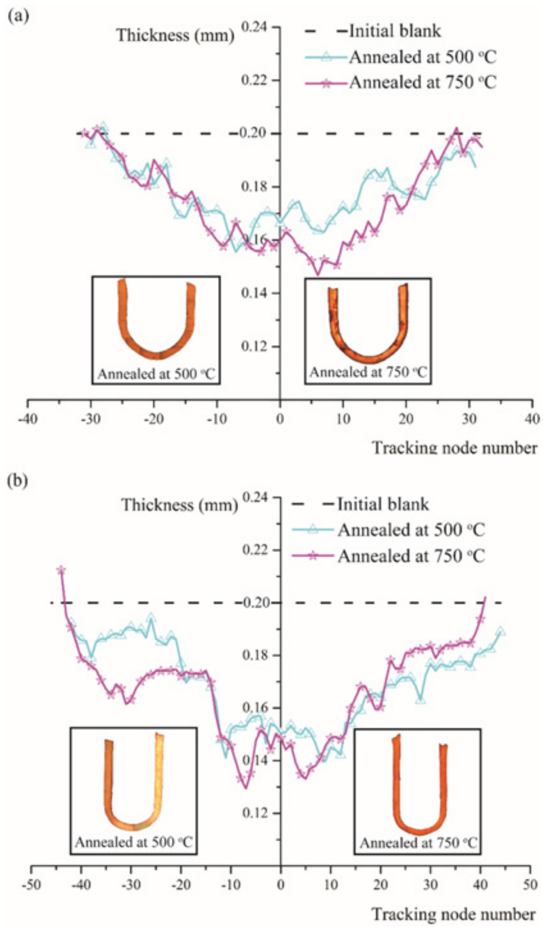


Fig. 14 Thickness variation of the micro parts: (a) The first-stage and (b) The second-stage

crossed profile. Figs. 13 and 14 show the schematic illustration of the thickness tracking nodes and the thickness variation of micro parts in each stage of micro deep drawing, respectively. It can be observed that the nonuniform thickness distribution and severe thinning around the punch corner of the micro part made by the blank annealed at 750°C are more significant than that drawn by the blank annealed at 500°C. The maximum thickness thinning is approximately 25% and 35% of the initial blank thickness for the micro parts drawn by the blank annealed at 750°C in the first-stage and the second-stage micro deep drawing,

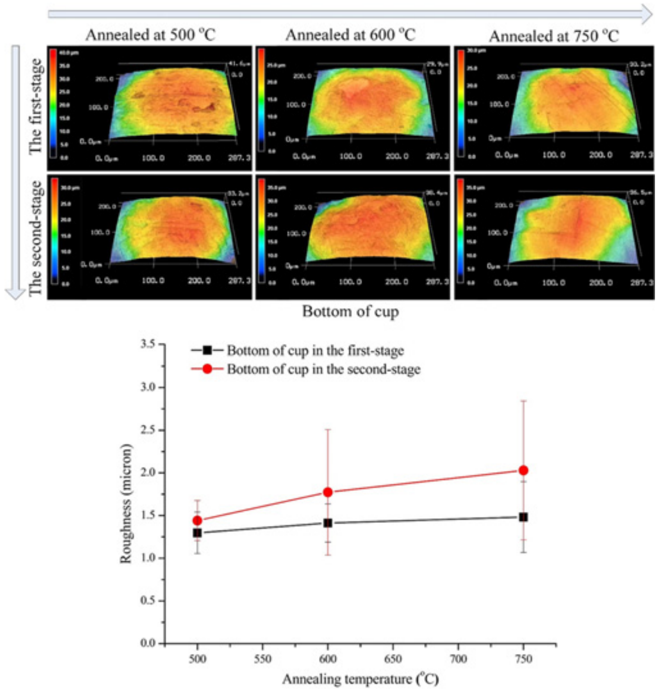


Fig. 15 Roughness at the bottom of the cup drawn by different annealed blanks in two continuous stages of micro deep drawing

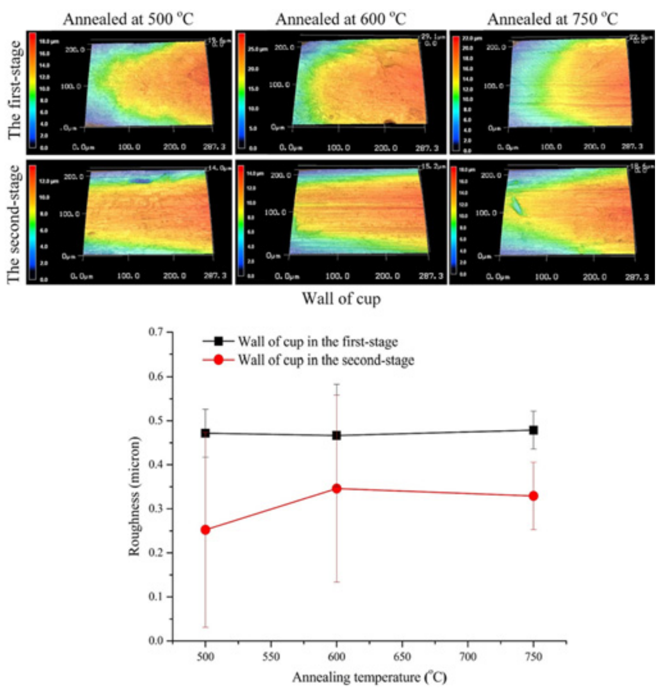


Fig. 16 Roughness at the wall of the cup drawn by different annealed blanks in two continuous stage of micro deep drawing

respectively, larger than the values of about 20% and 30% for the micro drawn part drawn by using the blank annealed at 500°C.

The nonuniform thickness of micro parts in different annealing temperatures is mainly due to the surface roughening induced by plastic deformation in the multi-stage micro deep drawing. In this paper, the

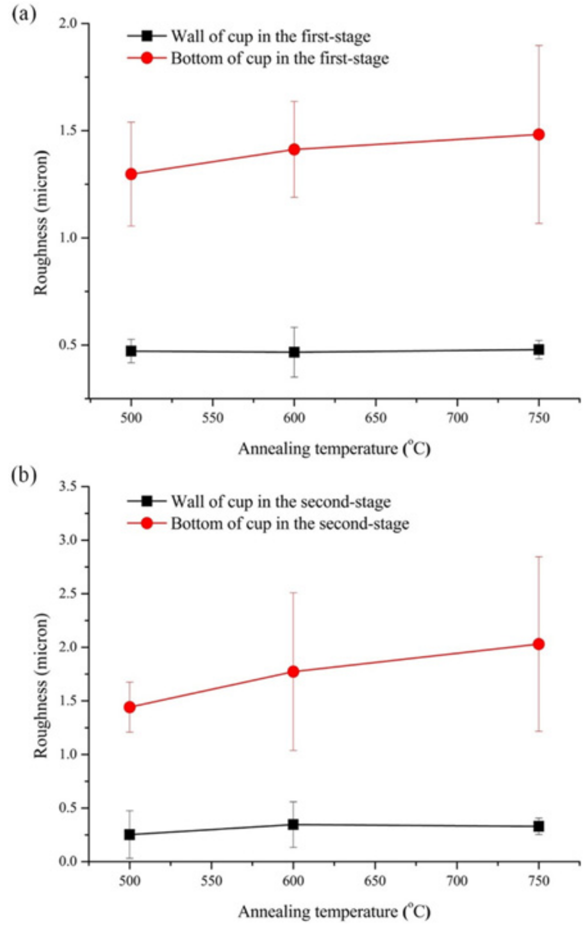


Fig. 17 Comparison of the roughness at the wall and the bottom of the cup drawn by different annealed blanks: (a) The first-stage and (b) The second-stage

confocal laser scanning microscope was used to observe the change of surface roughness. It can be clearly observed from Fig. 15 that the roughness at the bottom in the second-stage is significantly larger than that in the first-stage with the increase of annealing temperature from 500, 600 to 750°C. According to the non-uniformity of the thickness mentioned by Shimizu et al.,[25] the larger surface roughness causes the larger non-uniformity in thickness. Considering the larger surface roughness of the micro part drawn by the blank annealed at 750°C, it is affected by grain size, grain orientation and grain rotation during the plastic deformation. The blank annealed at 750°C has a few grains or single grain along the thickness direction, less constrained in deformation due to the large fraction of surface grains. These grains can rotate out of their original position by gliding along the grain boundaries to result in the rougher surface, reported by Simons et al.[13] as well.

In addition, the roughness at the wall of the cup in each stage of micro deep drawing is quantitatively investigated and shown in Fig. 16. It can been observed that the roughness at the wall of the cup drawn by different annealed blanks is almost the same in the first-stage drawing, while the roughness at the wall of the cup in the second-stage is lower than that of each in the first-stage. In this research, the decreased unilateral clearance in the second-stage has an ironing effect for the wall of the cup, which makes its surface roughness smaller than that in the first-stage.[27] Furthermore, Fig. 17 presents the comparison of roughness at the wall and the bottom of the cup drawn by three different annealed blanks in each stage. The roughness at the wall of the cup is lower than that of the bottom of the cup for both stages.

4. Conclusions

In this research, a two-stage micro deep drawing system was developed for micro deep drawing of a cup with domed bottom. Physical experiments were conducted to study the deformation behavior, process performance and the grain size effect on deformation behavior and thickness variation of the micro drawn parts. FEM simulation was conducted to explore and study the micro deep drawing. The following conclusions are drawn based on the physical experiments and simulation.

(1) Blanking significantly affects the micro part's deformation during the micro deep drawing. The residual stress generated increases the potential of fracture occurrence in the thinnest thickness of the micro part.

(2) Earing becomes severer in multi-stage micro deep drawing. When earing appears in the first-stage micro deep drawing, the ear with a larger height difference is developed after the second-stage drawing.

(3) Deformation load decreases with the increase of grain size in multi-stage micro deep drawing, while the grain size effect is not obvious in the second-stage micro deep drawing. The fraction of surface grains increases with grain size for the blank with same thickness, which causes the decrease of flow stress and deformation load. In addition, the blank with a larger grain size and less number of grains across its thickness has a relatively low density of grain boundaries, which results in a lower restriction to deformation, and the low deformation load.

(4) The load determined by simulation qualitatively agrees with experiment in each micro deep drawing stage. The inhomogeneous deformation behavior of material and different friction behaviors are the main reasons for the deviation of the deformation loads between simulation and experiment.

(5) The micro part with larger grains has more nonuniform thickness and severer thinning around the punch corner. It is mainly resulted from the larger surface roughness at the bottom of micro part. For the blank with large grain size, a few grains or single grain along the thickness direction can rotate out of their original position by gliding along the grain boundaries to result in the rougher surface, causing the nonuniform thickness during the multi-stage micro deep drawing process. In addition, the decreased unilateral clearance in the second-stage has an ironing effect on the wall of the cup, which makes its surface roughness smaller than that in the first-stage. Furthermore, the roughness at the wall of the cup is smaller than that of the bottom of the cup for both stages.

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