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Liang Luo

University of Wollongong, ll895@uowmail.edu.au

Zhengyi Jiang

University of Wollongong, jiang@uow.edu.au

Dongbin Wei

University of Wollongong, dwei@uow.edu.au

Kenichi Manabe

Tokyo Metropolitan University

Hideki Sato

Tokyo Metropolitan University

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Abstract

Micro forming is a key technology for an industrial miniaturisation trend, and micro deep drawing (MDD) is a typical micro forming method. It has great advantages comparing to other micro manufacturing methods, such as net forming ability, mass production potential, high product quality and complex 3D metal products fabrication capacity. Meanwhile, it is facing difficulties, for example the so-called size effects, once scaled down to micro scale. To investigate and to solve the problems in MDD, a combined micro blanking-drawing machine is employed and an explicit-implicit micro deep drawing model with a voronoi blank model is developed. Through heat treatment different grain sizes can be obtained, which affect material's properties and, consequently, the drawing process parameters, as well as produced cups' quality. Further, a voronoi model can provide detailed material information in simulation, and numerical simulation results are in accordance with experimental results.

Keywords

drawing, deep, numerical, micro, experimental, study

Disciplines

Engineering | Science and Technology Studies

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Experimental and numerical study of micro deep drawing

Liang Luo¹, Zhengyi Jiang^{1,a}, Dongbin Wei^{1,2}, Ken-ichi Manabe³, and Hideki Sato³

¹ School of Mechanical, Materials & Mechatronic Engineering, University of Wollongong, Wollongong NSW 2500, Australia

² School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney NSW 2007, Australia

³ School of Science and Engineering, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji-shi, Tokyo 192-0397, Japan

Abstract. Micro forming is a key technology for an industrial miniaturisation trend, and micro deep drawing (MDD) is a typical micro forming method. It has great advantages comparing to other micro manufacturing methods, such as net forming ability, mass production potential, high product quality and complex 3D metal products fabrication capacity. Meanwhile, it is facing difficulties, for example the so-called size effects, once scaled down to micro scale. To investigate and to solve the problems in MDD, a combined micro blanking-drawing machine is employed and an explicit-implicit micro deep drawing model with a voronoi blank model is developed. Through heat treatment different grain sizes can be obtained, which affect material's properties and, consequently, the drawing process parameters, as well as produced cups' quality. Further, a voronoi model can provide detailed material information in simulation, and numerical simulation results are in accordance with experimental results.

1. Introduction

Micro forming technology has drawn global attention on the background of an industrial miniaturisation trend [1]. Comparing to other micro manufacturing methods, it has obvious advantages, such as capacity to handle metals, potential of mass production and ability to generate complex 3D structures. Micro deep drawing, an important micro forming technology, shares all the superiorities of micro forming while faces problems introduced by reduced sizes. One of these problems is positioning and transporting of raw material in drawing process. Correspondingly, a combined blanking-drawing process was developed and realised by researchers [2]. Therefore, preparation of raw material for deep drawing and performance of deep drawing can be conducted within one step. Variance of material properties at micro scale is another problem which has been observed by many researchers [3, 4]. Relative theories, such as the surface layer model [5] and the modified surface layer model [6], were carried out as explanations for the decrease of metal flow stress in micro scale.

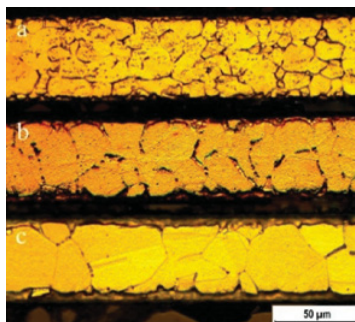
^a Corresponding author: jiang@uow.edu.au

Table 1. Heat treatment method and grain size after each heat treatment.

Group	Heating temperature/°C	Heating time/min	Average grain size/ μm
1	975	2	10
2	1050	2	20
3	1100	2	40

Table 2. Parameters of materials' properties.

Group	Strength coefficient K/MPa	Strain hardening index N	Elastic modulus E/GPa
1	1771 ~ 1908	0.324 ~ 0.405	189.0 ~ 220.0
2	959.3 ~ 1073	0.212 ~ 0.249	185.7 ~ 221.7
3	957.1 ~ 1068	0.227 ~ 0.294	183.3 ~ 216.9

**Figure 1.** Microstructures of sheets heated under different temperatures (a) 975 °C (b) 1050 °C and (c) 1100 °C.

In our research, stainless steel SUS304 sheets, being heat treated at different temperatures for micro deep drawing, were tested for their microstructures and performed micro tensile tests. At the same time, a combined blanking-drawing process was adopted in experiments. Further, an explicit micro deep drawing model with a subsequent implicit springback model were developed to simulate deep drawing process and springback behaviour after drawing process, respectively. In these two simulation models, a voronoi model for a blank [7, 8] was developed based on actual microstructure of the blank.

2. Experiments

2.1 Heat treatment

Stainless steel SUS304 sheets with a thickness of 50 μm were heated at different temperatures for two minutes under an argon gas protection ambience, and microstructures of these sheets were observed under a metallurgical microscope. With different heat treatment temperatures, different grain sizes can be obtained, as shown in Fig. 1. Based on the peak heating temperature, sheets were divided into three groups. Table 1 shows the classification of each group and their general grain sizes.

2.2 Micro tensile tests

Tensile tests were then conducted to obtain mechanical properties for simulation on a micro tensile tester. Taking size effects into account, the tensile test samples were scaled down, and therefore the width of each sample is only one millimetre, as shown in Fig. 2(a). Correspondingly, an image processing program was developed in MATLAB to calculate strain without contact with samples. Figure 2(b) displays the true strain stress range of 10 repeated tests and their mean value for each material group. Table 2 lists the parameters of strain stress curves fitted with the power law equation. With a low heating

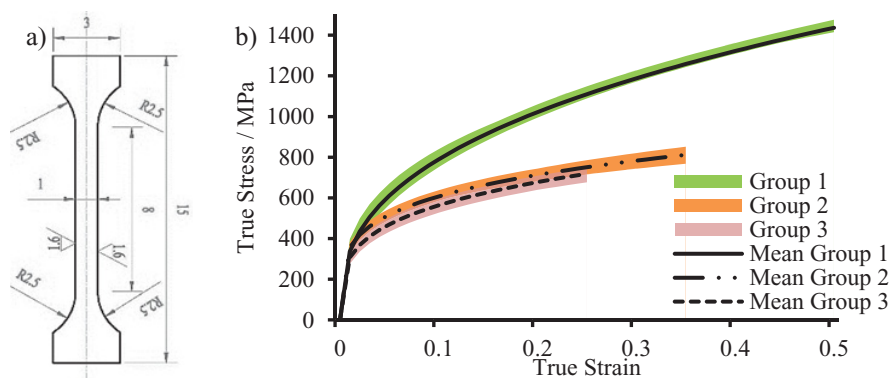


Figure 2. (a) Tensile sample and (b) true strain stress curve of each material group.

Table 3. Parameters of MDD machine and process.

Punch diameter	Die diameter	Radius of punch fillet	Radius of die fillet
0.8 mm	0.975 mm	0.3 mm	0.3 mm
Drawing speed	Blander gap	Friction condition	Initial blank diameter
0.1 mm/s	0.055 mm	Dry friction	1.6 mm

temperature, grains are small and the flow stress is high. That is because the annealing effect which eliminates the work hardening of the raw sheets is weak at low heating temperature. Additionally, with a few grains in the thickness, randomness of each grain's properties significantly impacts the overall properties of the samples and leads to great scatter of samples' properties when there is one or two grains in thickness. The total elongation also decreases with the increase of grain size as a few grains in thickness direction cause fast development of micro cracks and early fracture of tensile samples.

2.3 MDD experiments

Figure 3(a) displays the whole MDD machine, and key parameters of the MDD machine and drawing process are listed in Table 3. The drawing forces of 10 times experiments for each material group were recorded and their average values are shown in Fig. 3(b). The drawing force has a relatively slow increase initially, and a fast yet constant increase until reaching a peak value. After remaining this peak value for short time, drawing force of each group decreases to a non-zero value at the end of process. Initially, the resistance of bending dominates the drawing force while other forces are small. As the process continues, large deformation causes high flow stress, and simultaneously friction force increases due to increased contact forces. Therefore, the drawing force rises significantly at the later period. Further, Group 1 has higher force increase and decrease speeds and smaller residual force than that of the other two groups. High elastic modulus and plastic modulus are in accordance with the high force increase speeds in the first half drawing process. Moreover, high tensile strength corresponds with the large peak drawing force. Large strain hardening index represents good formability and indicates weak springback behaviour characterised by small residual force at the end of drawing process.

Table 4 lists the average geometrical values of drawn cups in each group. The difference between outer and minimum inner diameters was defined as the maximum distance, and the deviation between outer and maximum inner diameters was defined as minimum distance. Then, their relative difference, calculated from Eq. (1), was employed as a judgement of wrinkles. With the increase of grain size, wrinkling phenomenon becomes significant. That is because that a few grains on the thickness direction decrease deformability and, consequently, compression stability on the flange of blank is

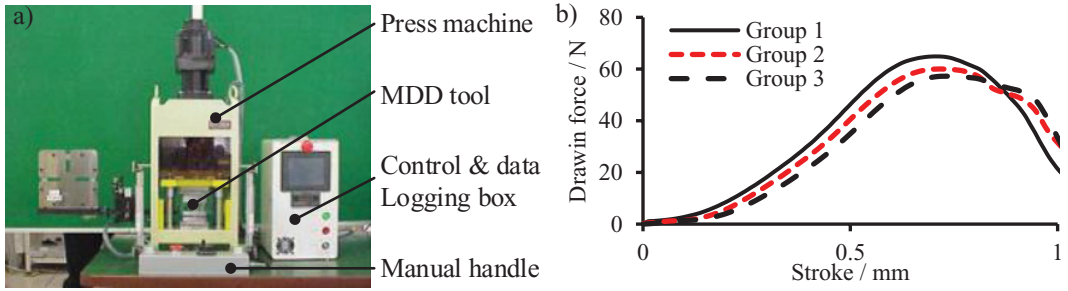


Figure 3. (a) Micro deep drawing machine and (b) drawing forces of each material group.

Table 4. Key parameters of MDD process and formed cups.

Group	Min inner diameter/ μm	Max inner diameter/ μm	Outer diameter/ μm	Max distance/ μm	Min distance/ μm	Wrinkles/%
1	787.083	816.645	941.092	77.004	62.223	24.546
2	780.558	814.277	938.137	78.789	61.930	27.334
3	789.532	831.042	950.033	80.251	59.496	35.091

weak. Therefore, the blank is easy to wrinkle and needs great wrinkles to compensate this compression instability.

$$Wrinkles = \frac{Max\ distance - Min\ distance}{Max\ distance} \times 100\% \tag{1}$$

3. Simulation

Due to the axisymmetrical geometry, a quarter of model was built to accelerate computing speed, and correspondingly symmetrical boundaries were applied on the straight edges of the blank. All the geometric parameters are the same as that of real machine, and the parameters of material properties were obtained from the aforementioned tensile tests. All parts in this model are of shell elements including a deformable blank following fully integrated element formulation and other rigid parts with Belytschko-Tsay element formulation. Figure 4 displays (a) the MDD model with (b) the voronoi blank model and (c) a drawn cup, respectively. In the voronoi model each voronoi cell represents one grain, and they have similar size to the general grain size on the blank. All these grains were categorised into five groups, and each group’s material properties are different from each other while in accordance with the micro tensile test results. Commonly used 3-parameter-barlet material model is employed for the blank. Further, a special surface-to-surface contact method for forming process in LS-DYNA is adopted for monitoring contact behaviours where the friction coefficient was set as 0.1. The MDD model was calculated explicitly, and then only the formed blank part was exported for a subsequent implicit springback simulation in LS-DYNA. Due to the axisymmetrical shape, one point on each symmetry boundaries is fixed to limit rigid motion of the cup. Additionally, the cup’s material and elemental information is identical to that in the former explicit simulation. Finally, simulation results can be compared with the cups in experiments. All the simulation models were run on a high performance computing (HPC) cluster in the University of Wollongong.

Drawing force from simulation of Group 1 is shown in Fig. 5(a) and thickness distribution at the mouth of the drawn cup is presented in Fig. 5(b). The drawing force in simulation has the same trend with that of experiment, however, with a higher peak drawing force and lower residual force than that of experimental one. Additionally, due to the introduction of voronoi model, thickness at cup mouth is

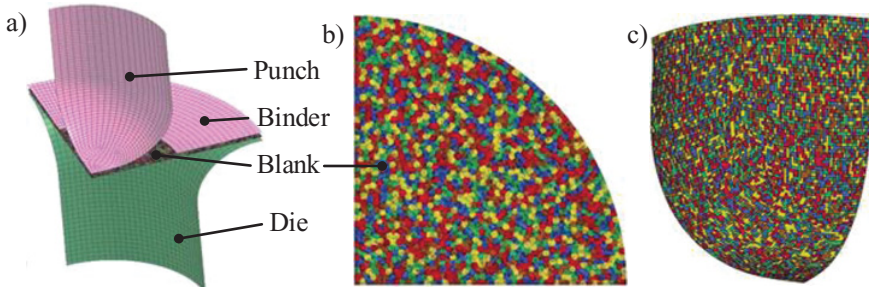


Figure 4. (a) MDD simulation model, (b) voronoi blank model and (c) drawn cup.

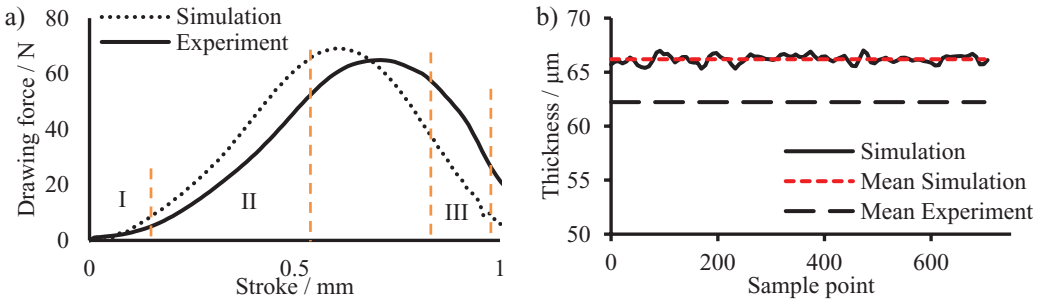


Figure 5. (a) Drawing force and (b) thickness distribution.

uneven and different from that of a normal blank model with the same properties estimation resulting in equal thickness distribution.

4. Comparison

Numerical and experimental results were then compared as listed in Table 5. The drawing force in experiment increases slower than simulation results. That lies in that randomly distributed grains with different mechanical properties on the blank cannot identically represent actual blank deformation behaviour. The earlier occurrence of peak drawing force in simulation than that of experimental one comes from an over estimated strain hardening effect in simulation model. According to Eq. (2) [9], flow stress, $\bar{\sigma}_t$, increases faster in simulation due to the greater strain hardening effect than that in experiments, whereas radial strain, $\ln \frac{R_t}{r_0}$, has almost the same decreasing speed to that in experiments. As the radial tension is a primary force of drawing force, two factors of radial stress have an overall result as the early occurrence of peak radial tension and the peak drawing force. This also explains the higher peak drawing force in simulation than the experimental one. Due to the change of friction condition at the end of the drawing process, residual drawing force in experiment is much higher than that in simulation.

$$\sigma_{rmax} = 1.1\bar{\sigma}_t \ln \frac{R_t}{r_0} \quad (2)$$

where σ_{rmax} is the maximum radial stretch stress, $\bar{\sigma}_t$ is the average flow stress, R_t is the current radius of the blank, and r_0 is the inner radius of flange on the blank.

The average wall thickness at the cup mouth in simulation is quite close to that of experimental one. Moreover, the thickness distribution at cup mouth is irregular which is similar to the simulation results.

Table 5. Comparison between experimental and simulation results.

Items	Experimental	Simulation	Error
Force slope I / N/mm	27.27	25.49	6.53%
Force slope II / N/mm	124.80	148.50	-18.99%
Force slope III / N/mm	-212.00	-207.10	2.31%
Peak force / N	64.88	69.18	-6.63%
Peak force stroke / mm	0.71	0.61	13.99%
Residual force / N	16.35	6.07	62.86%
Average wall thickness at cup mouth/ μm	62.223	66.199	-6.01%

5. Conclusion

Heat treatment can effectively change the material's microstructures and mechanical properties. Grains grow with the increase of heating temperature, and material parameters, the strength coefficient and strain hardening index, decrease with the significant annealing effect after high temperature heating.

Grain size affects micro deep drawing process and cup quality. Drawing force of each group has similar trend, however, smaller grain size group has higher peak drawing force and lower residual force than that of the material groups with larger grain sizes. Moreover, wrinkling level aggravates with the growth of grains.

The MDD model with the voronoi blank model can successfully simulate micro deep drawing process. The simulation results are close to experimental results and their errors are acceptable.

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