Simulations of hydro-mechanical deep drawing using Voronoi model and real microstructure model

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Abstract

Micro hydroforming is promising for fabricating complex micro components with a high aspect ratio. The aim of this study is to deepen the understanding of the size effects in micro hydroforming. Experimental work and FEM simulations of micro hydro-mechanical deep drawing (MHDD) were conducted. Voronoi model and real microstructure model were established. Real grain morphology can be considered in the real microstructure model. Local thinning in critical area of the drawn cups due to size effects can be predicted by the models. The simulation results agree with the MHDD test results.

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Keywords: Micro forming; hydro forming; deep drawing; size effects

1. Introduction

Microforming process is an appropriate technology to manufacture metallic components with at least two dimensions in the sub-millimeter range [1]. The current trend of an increasing application of microsystems technology can be seen in modern products where efficient production methods for the manufacturing of the required micro metallic components are necessary. Examples are to be found in the areas of medical engineering,
telecommunication and micro-mechatronics systems for automotive industry. Investigations have been conducted on micro sheet forming processes [2-6] such as micro deep drawing. The conventional micro deep drawing has been successful; however, it may not be suitable for fabricating some kinds of micro components such as micro painless needle with a long tapered shape. The micro needle can be used to deliver medication or monitor the level of drugs in a patient’s body without drawing blood. It is made of metal so its strength is high enough while its diameter must be tiny enough to penetrate the outer layer of the skin painlessly. Hydroforming is a specialized soft tool forming technology. The sheet hydroforming is further classified into sheet hydroforming with a punch (SHF-P) and sheet hydroforming with a die (SHF-D), depending on whether a male (punch) or a female (die) tool is used to form the part [7]. Micro hydroforming owns the following advantages comparing to conventional sheet forming process. (1) Only one rigid tool but not pair of tools is required as fluid is adopted as soft tool; (2) difficulty of positioning of pair of tools may be reduced; (3) repeatability and dimensional accuracy may be increased while springback and residual stresses are significantly decreased [7]; (4) uniform stretching of the material leads to improved mechanical properties of the component [8]. Metal forming technologies established in macro world cannot be simply scaled down to be applied in micro world, because it is impossible to scale down all parameters according to similarity theory [5]. A huge challenge exists because of geometrical sources, physical sources, and the change in the ratio between the surface and volume etc. Specific effects of miniaturisation have been observed in all areas of material, process, tools and machines/equipment. These have been well reviewed [1, 3, 4, 6]. Material behaviours, including flow stress, anisotropy, ductility and forming limit depend on specimen size. Flow stress decreases with decreasing specimen size, which has been explained by the surface layer model [1]. Materials characteristics influence forming forces, tribology, spring-back and product accuracy. One of the most important process parameters is friction [9-10]. Friction increases with decreasing specimen size, which has been explained by the model of open and closed lubricant pockets [11]. Micro hydro-mechanical deep drawing of SHF-P was carried out in this study. Experimental work and FEM simulation were conducted. New Voronoi model and real microstructure model were developed. Different material properties were assigned in Voronoi model and real microstructure model. Real grain morphology can be considered in the real microstructure model.

2. Experimental

Stainless steel SUS304-H foil (wt%, C: 0.05, Si: 0.60, Mn: 0.96, P: 0.035, S: 0.004, Ni: 8.05, Cr: 18.2, C: 0.05, Si: 0.6, Fe: balance) with a thickness of 50 ± 2µm was selected. Annealing was conducted in a KTL series tube furnace to obtain various grain sizes and release residual stress. A protective atmosphere of argon was supplied to prevent samples from oxidation. The samples were put in the furnace at room temperature, heated at a rate of 20°C/min, held for 2mins when the temperature reaches 975, 1050 and 1100 °C respectively, then cooled in the furnace. Accordingly, three groups of foil were obtained and designated H975, H1050 and H1100 respectively.

A Rtec Tribometer was employed for determining friction coefficients under dry lubrication micro deep drawing by conducting pin-on-disk tests. The pin ball with a diameter of 9.6 mm was fabricated. It is made of tungsten carbide that is as same as the material of the punch in deep drawing. The foil was fixed on a sample disk by applying superglue (liquid single-component cyanoacrylate monomer). The pin ball and the foil were cleaned by alcohol before the tests. The relative movement speed between the blank and the die in deep drawing was about 0.13 mm/s so the rotation speed of the disk was 1rpm. Two load sensors with a resolution of 0.001N were used. The friction coefficient under dry lubrication for each group of foil was obtained by averaging the values of three repeated test. They are 0.109 for H975, 0.166 for H1050 and 0.152 for H1100.

Micro tensile tests were conducted to obtain the stress-strain curves of the foils after annealing considering size effect, as shown in Fig. 1 (a). The stress-strain data were adopted in FEM simulations. The dimensions of micro tensile test samples are shown in Fig. 1 (b). A servo motor controlled by a computer drove a gear system to pull or push two gripping heads. Tensile force was measured using a load cell. An extensometer was not able to be used due to limited space. A video processing program was developed in MATLAB to calculate strain as a non-contact measurement under KEYENCE VHX-1000 digital microscope.

Deep drawing was conducted by employing a high precision desktop press machine (Fig. 2 (a)). The press machine has a maximum force of 30kN and maximum displacement of 40mm. Positioning accuracy is 1µm and repetitive positioning resolution is 3µm.
The micro hydro-mechanical deep drawing (MHDD) system was developed based on the micro deep drawing (MDD) system, as shown in Fig. 2 (b) and (c). A hydraulic station was linked to supply hydraulic pressure. Mechanical hydraulic oil with a viscosity of 46 cSt was utilized as the medium. The maximum available pressure is 30MPa. The key parts in the toolset were made of tungsten carbide. The surface of the punch was treated by plasma to increase its hardness and wear resistance. The speed of deep drawing is 0.1mm/s. Due to very small dimension of the toolset, there was no space for sealing parts. Tiny gaps between the die and blank holder and the blanking die and blanking holder exist. The gaps were about 2 - 4 µm, oil leakage was very small so the pressure lost could be ignored. On the other hand, the pressure increase in MHDD process due to the tiny compression was also ignorable. The surface of the foil was slightly polished using a soft eraser then cleaned in alcohol before deep drawing tests. The hydraulic pressure was increased from 5 to 30MPa at an incremental step of 5MPa. After deep drawing, the drawn cups were cleaned for one minute in alcohol in a ultrasonic cleaner. A KEYENCE VK-X1000 Laser Confocal Microscope was used for non-contact measurement of profile, roughness and thickness without sample preparation required.

3. Simulation

Three FEM models, i.e. normal model, Voronoi model and real microstructure model were established and run respectively using same LS-DYNA solver. The Voronoi tessellations are a special spatial partition where all points inside a Voronoi tessellation are closer to their associated generator than to any other generators [12-13]. There is no overlap between any two different Voronoi tessellations. This geometrical character is comparable to the crystalline distribution of metals where each grain has its own region and there are no overlaps between them. Voronoi tessellations have been adopted to represent microstructure of metals [14-16]. Centroidal Voronoi tessellations (CVT) where the generators coincide with the mass centroids of corresponding Voronoi tessellations are employed. The CVT simplifies the Voronoi structure through homogenization of all the Voronoi tessellations [17]. Although CVT cannot represent a real microstructure of materials, it may be analogous with material’s microstructure regarding general grains distribution, if carefully choosing density function. Furthermore, an optimization was developed and conducted to eliminate small features in the CVT while the size and distribution of the tessellations can be maintained. This can reduce the possibility of degenerate mesh being dominant, which is beneficial for achieving high quality meshing in the simulation of large deformation [18].
Voronoi tessellations were built and restricted to a quarter of a circle which represents a quarter of the blank, as shown in Fig. 3 (a). Two types of FEM models were established. In Type I model (Fig. 3 (b)), meshing is within each grain while in Type II model (Fig. 3 (c)), meshing is independent of the Voronoi tessellations. Based on the comparison, all shell elements inside a Voronoi tessellation can be identified and grouped in LS-DYNA. Although a same material model was used, different material parameters may be assigned to different grains, as indicated by different colors shown in Figs. 3 and 4.

![Fig. 3. Voronoi tessellations and FEM models (400 grains, average grain size=40 µm)](image)
(a) Voronoi tessellations; (b) Type I Voronoi FEM model; (c) Type II Voronoi FEM model

Real microstructure model uses real grain morphology instead of Voronoi tessellation. Both meshing of Type I and Type II can be applied. Fig. 4 shows the process of establishing the real microstructure model based on the real grain morphology of a H1100 sample. Because the number of FEM elements using the meshing of Type I is significantly higher than those in Type II and can cause much higher computation costs, the meshing of Type I was actually not adopted in the simulations.

Each grain has its orientation thus individual deformation behaviour, which should be presented in the Voronoi model or real microstructure model. However, it is very difficult to determine the parameters of each grain experimentally. All grains were categorised into five groups based on their sizes and each grain group was assigned a set of parameters in the range defined by the up and low limits in the micro tensile tests. The grains in the group of larger size were assigned lower flow stress while those in the group of smaller size were assigned higher flow stress.

4. Results and discussion

4.1. Microstructures after annealing and stress-strain curves

The microstructures of stainless steel 304 foil after annealing were observed under an optical microscope as shown in Fig. 5. The grain sizes were determined using Leica Grain Analysis software. The average grain sizes were around 10, 20 and 40 µm respectively corresponding to different annealing temperatures. Fig. 6 shows the true strain-stress curves obtained in micro tensile tests. The bands show the ranges between the up and low limits in each group. 3-Parameter-Barlat material model was adopted to describe flow stress.
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Fig. 4. Real microstructure model  
(a) real microstructure; (b) detecting grain boundaries in MATLAB; (c) finite element model.

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Fig. 5. Microstructures and distribution of grain sizes of stainless steel 304 foil after annealing at (a) 975°C; (b) 1050°C; (c) 1100°C.

Fig. 6. True strain-stress curves

Fig. 7. Maximum drawing forces

Fig. 8. A broken drawn cup of H975 after MHDD

4.3 Micro hydro-mechanical deep drawing

Maximum drawing force was compared among all simulation and experiments, as shown in Fig. 7. With the stress-strain relationships and friction coefficients obtained in the tests, all simulation models can predict maximum drawing forces successfully and very high accuracy was presented in the case of H1050 and H1110. This can verify the high accuracy of the results obtained in the micro tensile tests and friction tests. The validity of the methodology of the classification of grain group and the assignment of material properties in the developed models may be partly proved.

Fig. 9. Thickness distribution in the critical area on the drawn cup of H975  
(a) Voronoi model; (b) real microstructure model; (c) normal model.

Fracture is one major failure of the deep drawing process and it generally occurs at the bottom of the drawn cup that is near the area contacting punch nose. A drawn cup of H975 that got fracture in MHDD is shown in Fig. 8. The thickness distributions obtained in FEM simulations were shown in Error! Reference source not found. Fig. 9. The thickness of each element is determined using R value, which was set as 1 in this study. Non-uniform thickness distributions can be found in critical areas at the bottom of the drawn micro cup near punch nose by using Voronoi
model (Fig. 9 (a)) or real microstructure model (Fig. 9 (b)). Grains with different flow stresses respond differently to stress, which results in thinning in critical areas. These agree with the results of MHDD tests, where only part of the critical area on the drawn cup is significantly thinned. However, a normal FEM model in which homogenous material is assumed can only give uniform thickness distributions as shown in Fig. 9 (c).

5. Conclusions

A new micro tensile test was designed and conducted to successfully acquire the stress-strain curves of stainless steel 304 foils. All grains were categorised into five groups based on their sizes and each grain group was assigned a set of parameters in the range defined by the up and low limits in the micro tensile tests.

Voronoi model was established using centroidal voronoi tessellations (CVT) where the generators coincide with the mass centroids of corresponding Voronoi tessellations. Real microstructure model is based on real grain morphology. Meshing is independent of the Voronoi tessellations or grain morphology. Both FEM models can predict local thinning in the critical areas at the bottom of the micro cup that is near the area contacting punch nose, which agrees with MHDD tests results where only part of the critical area on the drawn cup is significantly thinned.

References