Study on size effects in micro deep drawing of stainless steel foil

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Abstract. In this paper, the mechanism of processing parameters, such as lubrication conditions, grain size and foil thickness, on micro deep drawing (MDD) of stainless steel 304 (SUS304) foil has been investigated. The dry and glycerin-based nano-additive TiO2 lubricant with different concentrations were selected to study the effects of lubrication on MDD process. Four stainless steel samples with different thicknesses of 20, 30, 40 and 50 μm were employed in this study. Each foil was annealed under 950, 980 and 1050 ℃ respectively to obtain different grain sizes of the samples. The formed cups qualities in terms of surface roughness, wrinkling and earing defects were analysed, and the punch force-stroke curves and the stress-strain curves were studied in MDD. The experimental results show that 4.0 wt.% glycerin-based nano-additive TiO2 lubricant has the best lubrication effects due to its lowest drawing force and the better surface quality obtained, and the SUS304 foil with thinner thickness required smaller punch force, while the surface is more uneven in comparison with the thicker SUS304 foil. Moreover, the SUS304 foils annealed at lower temperature had smaller grains, and subsequently had smoother surface textures than those of SUS304 foils with larger grains annealed at higher temperature. The findings of size effects from lubrication, grain size and foil thickness obtained in this study will enhance the mechanism understanding of SUS304 foil deformation in MDD.

1. Introduction

In order to reduce cost, pollution and volume, the miniaturisation trend has occurred among automotive, medical and aerospace fields. Consequently, the rapid development of miniaturisation in various fields has led to a strong demand for micro metal products, which could be generated from micro forming process. Micro forming process has been widely used in the fields of micro-electromechanical system (MEMS) and micro system technology (MST) [1]. Besides, micro forming is also famous for high productivity of intricate products. Micro deep drawing is considered as an elementary micro forming process to manufacture micro products with thin walls and is also being regarded as a significant technology in micro forming process [2]. In this study, the effects of glycerin-based nano-additive lubricants with 4.0 wt.%, 2.0 wt.%, 1.0 wt.% and 0.5 wt.% TiO2 and dry condition were investigated based on micro deep drawing process. The formed cup quality and the relationship between the drawing force and stroke under the above-mentioned lubrication conditions were studied for stainless steel 304 (SUS304) foils with thickness of 20, 30, 40 and 50 μm, respectively. Furthermore, thickness variation was considered as another reference factor to investigate how it affects the formability, surface characteristics and internal structure of cup. In addition, there are three heat treatment temperatures are
selected as variables to study what effect it brings to micro deep drawing process and the quality of the formed cup.

2. Experiments

2.1. Preparation of sample and lubricant
In order to investigate the effect of grain size on micro deep drawing of SUS304 foil and according to the melting point of the material, SUS304 foils with 50 μm in thickness were annealed under the temperatures of 950, 1050 and 1100 °C, respectively, thus by varying the temperature of heat treatment, the foils accompanied by different grain sizes were acquired. Another research aim is to study the effect of thickness on SUS304 foil during micro deep drawing, hence four stainless steel foils with different thicknesses of 20, 30, 40 and 50 μm were prepared. Last is to investigate the effect of glycerin-based nano-particle lubrication on micro deep drawing of SUS304 foil, thus the glycerin-based nano-particle lubricant with different concentrations were prepared using the automatic density measuring instrument and tube. As mentioned above, the lubricant in this study is composed of titanium oxide and glycerin.

2.2. Heat treatment
Heat treatment was used to release residual stress and improve mechanical characteristics of the material. Those stainless steel foils were heated at distinct temperatures under the protection of argon gas by KTL tube furnace to prevent oxidation of the material, and the cooling process also processed under the argon gas protection. The heat treatments were conducted at 950 °C for 95 min and at 980 °C for 98 min and at 1050 °C for 105 min for SUS304 foil. The heat treatment details are listed in Table 1.

| Material | Heating temperature |
|----------|---------------------|
| SUS304   | 950                 |
|          | 980                 |
|          | 1050                |

2.3. Micro tensile tests
The specimen used in the tensile test is shown in Figure 1. Micro tensile samples with 50 μm in thickness and 15 mm in length were manufactured to investigate mechanical properties, and the specimens were made into a shape that is easy to operate tensile test based on the ATSM standard description E8-04 [3].

During the tensile tests process, the microscope concentrated on the marked rectangular area and recorded elongation of the specimen in a video format, and divided it into separate images by MATLAB, thus the microscope was utilised to obtain images with high-resolution, and then were sent to MATLAB to process, where each frame was considered as a picture [4]. Edge detection can perform well owing to
the contrasting color between the sample gauge and background, and the gauge region was marked by comparing adjacent pixels with different colors, so it can be marked precisely. After the determination of gauge’s edges, the elongated length of sample can be figured by the program, and the distinction between two adjacent frames represents the elongation, during this process the specific strain value can be obtained [4]. Meanwhile, the force cell recorded force that was matched to each video frames, finally the true relationship curve between the stress and strain was obtained.

2.4. Micro deep drawing experiments
The experimental set up that consists of three primary parts namely movable punch, blank holder and clamping plate can be used to conduct the micro deep drawing experiments [5]. The stainless steel circular blanks are made from different thickness foils using the blanking punch and die sets, and then the foils were drawn into micro cups. In the micro deep drawing process, the glycerin-based nano-additive lubricant with 4.0 wt.%, 2.0 wt.%, 1.0 wt.% and 0.5 wt.% TiO2, respectively, is added into the gap among die, blank holder and stainless steel blank in order to reduce the friction force. The glycerin density was 1.26 g/cm³ under room temperature and the drawing force obtained from each lubrication category were recorded, finally their average value can be obtained. By comparing five stroke vs drawing force curves that drawn from different concentration lubricant groups can determine how the concentration of lubricant affects the micro deep drawing process. Besides, the SUS304 foils with different thicknesses were prepared to investigate the influences of thickness variation of foil on micro deep drawing, and the influence of grain size on the micro deep drawing of SUS304 foil was researched utilising stainless steel foil that was heat treated at distinct temperatures.

3. Results and discussion
3.1. Frictional size effect from lubricant with different concentrations of TiO2 during MDD process
SUS304 foil with 50 μm in thickness was used in the micro deep drawing process, and the foil was treated with glycerin-based nano-particle lubricant with different concentrations of TiO2 and dry condition to investigate the effects of lubrication on micro deep drawing of SUS304. The lubricant viscosity is a significant parameter for optimising drawing processes, and nano-particle lubricant is accompanied by higher viscosity that can reduce the occurring friction significantly. When lubricating with nano-particle lubricant, there exists closed lubricant pockets at interface where the friction is largely influenced during MDD [6]. Figure 2 illustrates the stretch of dry and lubrication in MDD.

![Figure 2](image)

Figure 2. The stretch of lubrication and dry friction in MDD [6].

The micro drawn cups under the glycerin-based nano-particle lubrication conditions and dry condition for as-received SUS304 foils are shown in Figure 3. It can be seen that the micro drawn cup parts were successfully produced under different lubrication conditions, and the properties of those micro parts were formed well with uniform shapes when the lubricant concentration varied in this study. It is clear to know that by increasing the concentration of nano-particle lubricant, the scratches in the micro cup become less and less, especially at the rim of the cup. The formed cups drawn under dry condition have the most scratches because of the direct contact of the blank and die, and the friction force increased
significantly because of the lack of lubricant in the lubricant pockets, so the wear and tear were unavoidable under large deformation.

**Figure 3.** Micro cup wall under the 0.5 wt.% glycerin based nano-additive lubricant of: (a) 0.5 wt.%, (b) 1 wt.%, (c) 2 wt.%, (d) 4 wt.%, and (e) dry.

Table 2 shows that the maximum distance of micro formed cups decreased while the minimum distance increased with some fluctuations as the concentration of lubricant increased from 0.5 to 4.0 wt.%. The phenomenon of wrinkling occurred during MDD process could be caused by several factors, such as the blank holder force, grain size, drawing speed, and clearance between the interfaces of blank and blank holder. When the grain size becomes larger, the wrinkling phenomenon can become more significant, this is mainly because that the decrease of grain number can lead to lower deformability, moreover, the blank needs wrinkles to compensate weak stability of compression on the rim of the blank, consequently the blank is quite easy to wrinkle.

**Table 2. Relative parameters of micro forming cups.**

| Lubrication condition | Max. inner diameter (μm) | Min. inner diameter (μm) | Outer diameter (μm) | Min. distance (μm) | Max. distance (μm) | Earrings | Wrinkles |
|-----------------------|--------------------------|--------------------------|--------------------|-------------------|-------------------|----------|----------|
| Dry                   | 449.82                   | 419.08                   | 480.38             | 40.56             | 71.3              | 14.88    | 43.11    |
| 0.5 wt.%              | 446.08                   | 416.14                   | 487.44             | 41.36             | 71.3              | 11.74    | 41.99    |
| 1.0 wt.%              | 449.77                   | 418.62                   | 494.26             | 44.4              | 75.64             | 10.81    | 41.18    |
| 2.0 wt.%              | 438.70                   | 415.58                   | 489.83             | 51.13             | 74.25             | 9.75     | 31.13    |
| 4.0 wt.%              | 437.04                   | 421.19                   | 489.30             | 52.26             | 68.11             | 6.22     | 23.27    |

In this research, the micro deep drawing process was chosen to study the influences of different lubrication conditions on the formability of SUS304 foil of 50 μm in thickness, and each lubrication condition of experiments was repeated 5 times and then the average drawing force was calculated to evaluate the effects. The comparison of the drawing force obtained from distinct lubrication conditions are shown in Figure 4.
It can be observed that the five curves have similar trend, initially the drawing force for each lubrication group increased smoothly until the blanking die and blanking holder reached to 24.3 mm, and then the punch force grew significantly until it reached a peak value of 85 N, after that the drawing force declined rapidly to a nonzero value owing to the strain energy kept in micro forming cups. The drawing force consists of friction force and bending resistance, initially the drawing force grows slowly, because of the bending resistance, and it is dominant in comparison with other force since the blank deforms largely. However, other force such as friction force was not so large at that moment. In following process, the contact region between the die and blank was gradually increased during the drawing process, hence the friction force increased to the maximum value while the bending force is relatively small. In the last step of the forming process the micro cups begin to release the strain energy that stored in it before, which makes the formed cups have a rebound trend.

In order to better evaluate the effectiveness of lubricant, the maximum drawing force and the last stroke drawing force for all experiments were analysed. Figure 5 illustrates the comparison of the reduction rate of the maximum drawing force and the maximum drawing force. The maximum punch load reduced with a small slope when the lubricant condition changes from the dry condition to 0.5 wt.% nano-particle lubricant, and then with an increase of the lubricant concentration, the reducing trend became faster. The reduction rate of the maximum drawing force under the lubricant conditions from 2.0 to 4.0 wt.% reached to the maximum value which was 1.99%.

3.2. Size effect of thickness variation of SUS304 foil on MDD
In this study, SUS304 foils with 20, 30, 40 and 50 μm in thickness were employed, and the foil of each thickness was annealed at 950, 980 and 1050 °C respectively, which aims to investigate the influences of thickness on micro deep drawing process. Figures 6 - 8 show the punch load and stroke curves for SUS304 foils with thicknesses of 20, 30, 40 and 50 μm and treated with distinct annealing temperatures, and it could be observed that the curves have quite different tendencies and shapes when the thickness of foil varies and there also exists some deviations among them.
It can be seen that the blanks of 40 and 50 μm in thickness have higher drawing force in comparison with that of 20 and 30 μm in thickness, and there were only one peak in the higher curves while there exists two peaks in the lower curves. As for the deep drawing process of 40 and 50 μm thick foils, the deep drawing force increased with a large slope to the maximum value, and then decreased significantly, the increasing tread of them were quite sharp, after remaining the peak value at about 89 and 75 N respectively for a short period, it decreased significantly to a nonzero value. Besides the maximum punch load, the last stroke punch load of 50 μm foil was also higher than that of 40 μm foil.

Figure 6. Load stroke curves under 950 ℃ for SUS304 foils with different thicknesses.

Figure 7. Load stroke curves under 980 ℃ for SUS304 foil with different thicknesses.

Figure 8. Load stroke curves under 1050 ℃ for SUS304 foil with different thicknesses.

Figure 9. Micro cups drawn from the foils with 50 μm in thickness annealed at (a) 950 ℃, (b) 980 ℃, and (c) 1050 ℃.
Figure 10. Micrograph of SUS304 foils with 50 μm in thickness annealed at (a) 950 °C, (b) 980 °C, and (c) 1050 °C.

Figures 11 - 14 show the load curves from the foils annealed at different temperatures for the foils with the thickness of 20, 30, 40 and 50 μm, respectively. It is clearly seen that there exist two peaks on the load curves with the thickness of 20 and 30 μm, and the curves have similar tendencies, and the first peak occurred at the strokes about 24.63, 24.74 μm in the cases of 950 °C annealed blanks with 20 and 30 μm thickness, respectively. The first peak values of foils with 20 μm in thickness annealed at higher temperature appeared slightly late in comparison with those of lower temperature annealed foils, while that with the thickness of 30 μm appeared quite early in comparison with the blanks annealed at 950 °C. Besides, the maximum drawing force occurred at the second peak values when the thickness of foils are 20 and 30 μm, and the maximum load of 20 μm foil occurred at about 25 mm when foils were annealed at 1050 °C, which was quite earlier than those blanks annealed at 950 and 980 °C, while the maximum loads of 30 μm blanks annealed at different temperatures occurred at approximately the same stroke at 25 mm. In summary, it can be seen that the blanks with 20 and 30 μm thickness annealed at lower temperature required larger forming loads than the blanks treated at higher temperature.

Figure 11. Load curves of the foils with 20 μm in thickness.

Figure 12. Load curves of foils with 30 μm in thickness.
3.3. Tensile tests

In this part, the SUS304 foils with 50 μm thickness were utilised to obtain mechanical properties by tensile tests. Figure 15 clearly shows the comparison between three forms of SUS304 foils. The as-received SUS304 foil requires the largest force to deform in comparison with heat treated at 950 °C and 980 °C for their largest yield stress and Young's Modulus. As received SUS304 foil requires more strain to reach the yield point in comparison with others, thus its elastic deformation process is the longest. The SUS304 foil annealed at 980 °C with the least elastic deformation needs the smallest strain to reach the yield point.

4. Conclusions

In this study, the size effects of the lubrication condition, foil thickness and grain size have been comprehensively investigated. SUS304 foil was chosen as the material that utilised in micro deep drawing process attributes to its high corrosion resistance, high ductility, high heat resistant, good cold forming ability and good mechanical properties, and it does not have heat treatment hardening effect. The drawing force and surface quality of micro cups drawn from stainless steel foils with different thicknesses of 50, 40, 30 and 20 μm were studied, it was concluded that the thickest foil required the largest drawing force, and it had the best surface quality among all foils under different thicknesses. In addition to the as-received SUS304 foil, the foils annealed at 950, 980 and 1050 °C were also studied in order to further investigate its forming behaviour by adjusting grain size and microstructure.
The glycerin-based nano-additive TiO$_2$ lubricants with different concentrations as well as dry condition were selected to study the influences of lubrication conditions on micro deep drawing process. The drawing force and the surface quality of micro formed cups under the mentioned lubrication conditions were also studied for SUS304 foil with 50 μm in thickness. The nano-particle lubricant has great effect in micro deep drawing processes, and the surface texture of micro forming cups drawn with 4 wt% glycerin-based nano-TiO$_2$ lubricant was the best compared with other lubrication conditions, which can be interpreted by the lubricant pocket theory, the nano-particles can enhance the dynamic viscosity and density of lubricants and assist to resist overflow phenomenon, subsequently the frictional size effects reduced due to the lubricants trapped in pockets by nano-particles. Both of the maximum drawing force and the last stroke drawing force of micro drawn cups increased with the decrease of lubricant concentration, and it reached to the highest value under without any lubrication condition. In addition, the micro tensile tests were conducted to investigate the mechanical characteristics of as-received SUS304 foil with 50 μm in thickness.

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