EXPERIMENTAL INVESTIGATION INTO EFFECTS OF ACOUSTIC ENERGY FIELD IN MICRO-FORMING PROCESS

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A micro-forming experiment set-up was designed to investigate the drawing formability of micro-square cups based on ultrasonic vibration. Effects of drawing height of micro-square cups were studied with varying specimen thickness, grain size, die and vibration amplitude. The fracture quality at the corner of the micro-square cup was also determined. This study of micro-square cup drawing suggests ultrasonic vibration can be used for plastic forming and exhibits extremely application value in the field of micro-parts manufacturing.

Keywords: Ultrasonic vibration; Grain size; Deep drawing height; Fractures

1. Introduction

Metal forming is a suitable technology for mass-production of micro-parts because of its low costs, high quality and high production efficiency. Requirements for miniature metal parts, especially micro-square cups, has been greatly raised by the trend of miniaturization in different fields such as medical devices, sensor and wearable electronics. The relatively deep drawing height (H/r) with a ratio of deep drawing height to fillet radius is an indicator reflecting the formability of micro-square cups of important parameters. Thus, the ideal and simple operation to increase H/r becomes an investigation topic.

Since the discovery of flow stress reduction after superimposition [1], ultrasonic vibration on single crystal zinc during tensile test namely the ‘Blaha effect’ has been developed for more than 60 years. Applying ultrasonic vibration in the plastic forming process has many advantages, such as the decrease of forming force and friction between the sheet metal and die interface[2], and prevention of wrinkling and tearing[3], and thus has been successfully applied in deep drawing[4], bending[5], extrusion[6], and other areas of plastic forming[7]. Mostafapur et al. introduced the mothed of pulsating blank holder system in micro-cylinder parts process and increased the limit drawing ratio (LDR) of 1-

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mm-thick aluminum 1050 alloy sheets to 8% compared with a static blank holder [8]. Pasierb and Wojnar found ultrasonic vibration reduced the deformation force in both deep drawing and drawing processes [9]. Jimma et al. carried out ultrasonic vibration-assisted deep drawing experiments on stainless steel 304 sheets with thickness of 0.5mm[10], an oscillation frequency of 20 or 28 kHz was applied to the blank holder, and the LDR increased from 2.38 to 2.77, and radial vibration in the thickness direction of the blank holder or die helped to increase the drawing ratio. At present, ultrasonic vibration assisted metal plastic forming mainly concentrates on wire drawing, forging and extrusion, but rarely on the ultrasonic vibration assisted micro-deep drawing.

Therefore, a stainless steel 304 sheet metal forming experiment set-up was designed to investigate the drawing formability of micro-square cups based on ultrasonic vibration. Effects of deep drawing height of micro-square cups were studied with varying sample thickness, grain size, die type and vibration amplitude. The scaling factor λ was introduced to analyze the sensitivity of three types of dies to the ultrasonic vibration. Four 40-um-thick specimens with different grain sizes were prepared, and the influences of vibration amplitudes and grain sizes on the deep drawing height were analyzed with or without ultrasonic vibration. The fracture quality at the corner of the micro-square cup was determined for the thickness of 200 um, and the influence of ultrasonic vibration on fracture quality at varying vibration amplitudes was investigated.

2. Experimental

Stainless steel 304 was selected for the experiments with the chemical composition showed in Table 1. To prevent oxidation of the stainless steel, heat treatment was carried out in vacuum conditions. Specimens were placed into quartz tubes, which were then vacuumed before sealing. The heat treatment conditions and average grain sizes were summarized in Table 2.

Table 1

Chemical composition of stainless steel 304 (wt.%)

C	Si	Mn	P	S	Ni	Cr
0.08	0.75	2	0.045	0.03	8-10.5	18-20

Specimens were etched according to Corrosion of Metals and Alloys--Test Methods for Intergranular Corrosion of Stainless Steels (GB/T 4334-2000) by using oxalic acid (100 g) and distilled water (900 ml) for metallographic examination. Typically, a specimen and a stainless steel cup were poured into a 10% oxalic acid solution and acted as the anode and cathode, respectively. Then the mixture was etched at the current density of 1 A/cm2 and 25 ºC in an oxalic acid solution for 5-10 min. Specimens after etching were cleaned with running water and dried. Grain sizes were measured by a 500 magnification metallographic microscope.

Table 2

Heat treatment conditions and average grain size of stainless steel 304

Average grain size	T(ºC)	Hold time(min)	Cooling mode
Φ11.5 um	950	5	Free cooling
Φ13.7 um	950	10	
Φ16.9 um	950	15	
Φ24.6 um	1050	15	

In order to introduce ultrasonic vibration into the deep drawing of micro-square cup, a special forming device was designed so that the acoustic energy can be properly transmitted from the transducer to the specimen. The micro-square cup deep drawing set-up used here consisted of a punch, a die, a blank holder, and an ultrasonic system that included an ultrasonic generator, an ultrasonic transducer and a concentrator (Fig. 1). The ultrasonic generator was set at power of 2 kW to provide frequency of 19.891 kHz, three different longitudinal oscillation amplitudes of 3.9, 7.8 and 10.4um were performed during deep drawing. The concentrator transferred the oscillation from the transducer to the die.

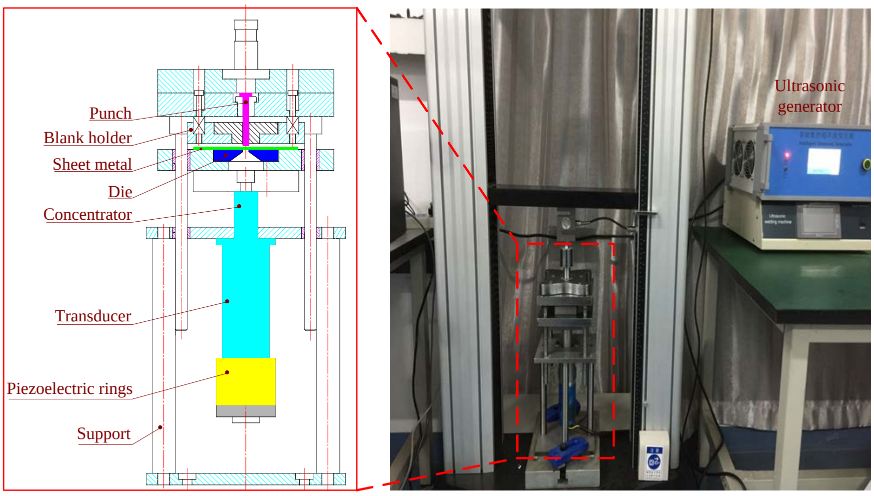


Fig. 1. Micro-square cup deep drawing set-up

The experiments were performed on a 30-kN MTS testing machine. Deep drawing heights were determined by using stainless steels 304 with three blank thicknesses of 40, 100 and 200 um, and the effect of three die sizes on the deep drawing height was also analyzed. The different micro-forming dies are shown in Fig. 2. The clearance between the punch and die varied with the blank thicknesses, and 3% of the long sides of the punch. Punch sizes, specimen machining dimension and thicknesses were alternately changed according to the scaling factor λ=1, 0.5, 0.2. Namely, at the thickness of 40, 100 and 200 um, the corresponding specimen machining dimension was 20×10, 10×5, and 4×2 mm^2, respectively. The drawing forces in the punch sizes of 10×5, 5×2.5 and 2×1 mm2 were 4250, 910 and 95 N, respectively. In the whole experiment, the drawing speed was set to 0.01mm/s. The surface of the punch and the inner surface of the die were polished, and at least four blanks were used in each case for improving the accuracy and repeatability of the experiment.

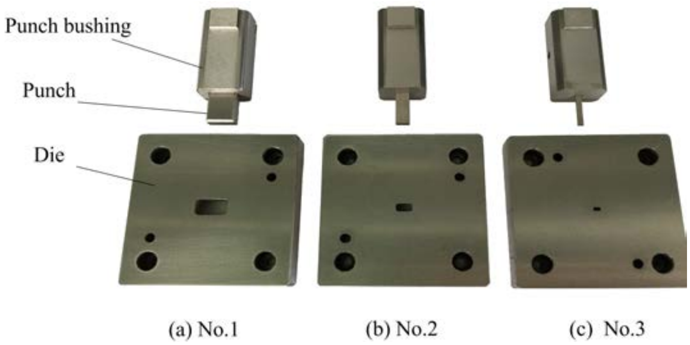


Fig. 2. Micro-forming molds with different sizes

3. Results and discussion

The drawing height increased by intensifying the oscillation amplitude. Tables 3-5 show the influence of drawing height with different specimen thicknesses and die size at the same range of oscillation amplitude. The drawing height increased from 0.79 to 1.1 mm at the sheet thickness of 200 um (Table 3), from 0.3 to 0.44 mm at the thickness of 100 um (Table 4), and from 0.19 to 0.24 at the thickness of 40 um (Table 5).

Table 3

Drawing height H1 of No.1 die

Thickness (um)	Amplitude (um)	Height (mm)
200	Not variation	0.79
	3.9	0.97
	7.8	1.0
	10.4	1.1

Results showed the drawing height noticeably increased when ultrasonic vibration was applied for all thicknesses. Different thicknesses, die sizes and oscillation amplitudes all influenced the drawing height with obvious differences. The major reasons are due to two aspects. In the micro-square cup deep drawing process, the interface friction between the specimen and the die is reduced due to the ultrasonic excitation, that is, the surface effect of ultrasonic vibration. Another aspect is the volume effect of ultrasonic vibration, including the decrease of flow stress, reduction of internal friction, dynamic effect of high frequency vibrated tools, and thermal effect.

Table 4

Drawing height H2 of No.2 die

Thickness (um)	Amplitude (um)	Height (mm)
100	Not variation	0.3
	3.9	0.4
	7.8	0.42
	10.4	0.44

Table 5

Drawing height H3 of No.3 die

Thickness (um)	Amplitude (um)	Height (mm)
40	Not variation	0.19
	3.9	0.21
	7.8	0.23
	10.4	0.24

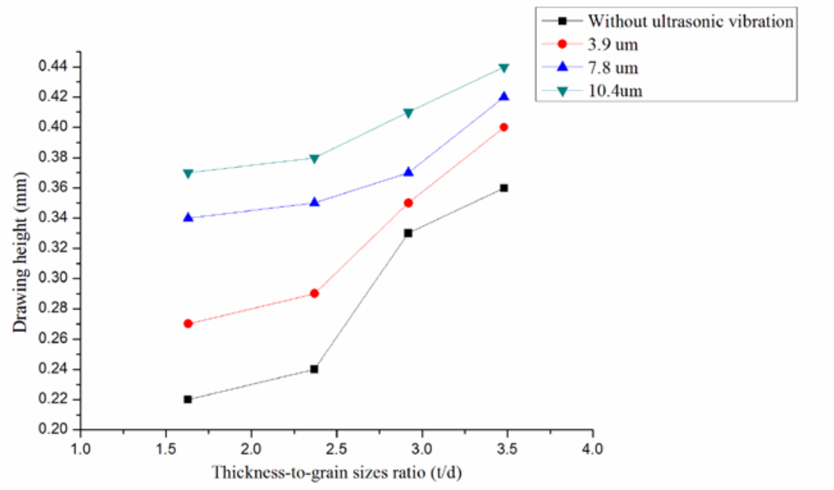
Analysis of experimental data showed the increasing rates in the drawing height for three different die sizes all slowed down at the oscillation amplitude 10.4 um. A previous study on ultrasonic vibration-assisted forming indicates ultrasonic softening is proportional to the oscillation intensity, but when the oscillation amplitude increases to a certain value, ultrasonic hardening appears[11]. That is, ultrasonic hardening is manifested as the increase of yield strength due to crystalline structural defects. The dislocations accumulated, interacted and served as pinning points or obstacles that significantly impeded their motion and prevented more dislocations from nucleation. Therefore, the oscillation amplitude 10.4 um slowed down the drawing height.

The drawing heights with scaling factor λ =1, 0.5, 0.2 for different dies, specimen thicknesses and oscillation amplitudes were determined. The drawing heights were little different between No.1 and No.3 dies (Table 6), but were different from No.2 die, which was significantly susceptible to ultrasonic vibration for thickness of 100 um, and ultrasonic hardening should be a dominant factor.

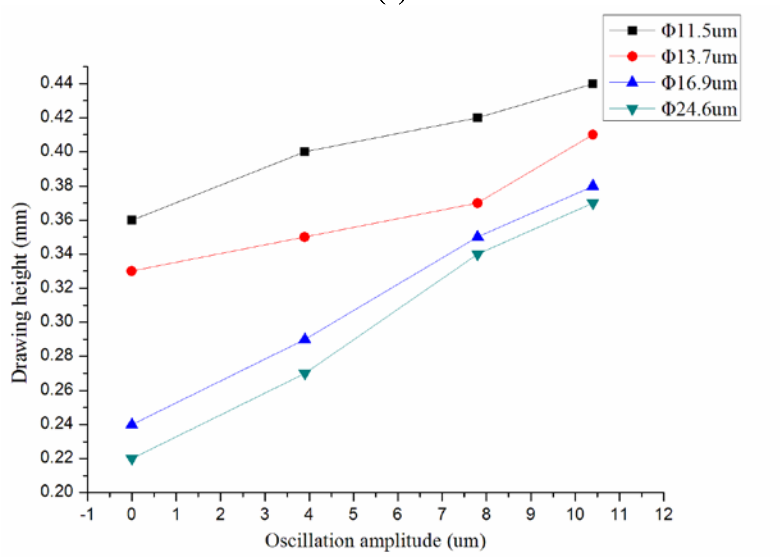
Table 6

Drawing height H with scaling factor λ =1, 0.5, 0.2

Amplitude (um)	No.1 die	No.2 die	No.3 die
	H_1 (mm)	H_2 (mm)	H_3 (mm)
3.9	0.97	0.8	1.05
7.8	1	0.84	1.15
10.4	1.1	0.88	1.2



(a)



(b)

Fig. 3. Drawing height curves with different oscillation amplitudes (a), thickness- to-grain size ratio (t/d) and (b) grain sizes for the thickness of 40 um. Drawing heights with different amplitudes.

The effects of grain sizes and oscillation amplitudes on the drawing height with were investigated for the thickness of 40 um. Figure 3 shows the thickness-to-grain size ratio (t/d) and the relationship between the drawing height of ultrasonic vibration- assisted micro-square cups and oscillation amplitudes. The drawing height increased significantly with the rise of t/d and was elevated with the intensification of oscillation amplitude (Fig. 3a). The drawing height increased with oscillation amplitude for different grain sizes and drawing height at the grain size of 11.5 um was substantially the largest, which comparison results are shown in Fig. 3b.

Explanation on these experimental results is that the ultrasonic energy is absorbed in highly localized regions such as dislocations, voids and grain boundaries. It may indicate ultrasonic energy was absorbed in these dislocations and the speed of dislocation was accelerated during deformation, which resulted in lower flow stress and larger plastic deformation in the micro-square cup forming.

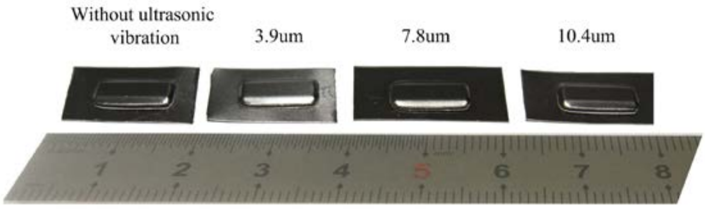


Fig. 4. Micro-square cup deep drawing results with different oscillation amplitudes for the thickness of 200 um

Bunget et al. designed a set of tooling for ultrasonic micro-extrusion and tested how ultrasonic oscillation influenced the forming load and surface finish [12]. Aluminum (AA 1100) and brass with different specimen sizes, extrusion processes and lubricants were introduced in these experiments. After the experiments, micrographs were taken using a scanning electron microscope to measure the surface quality. Results indicated the ultrasonic excitation improved the surface quality of micro-extrusion specimens. The experiment results of micro-square cups with the oscillation amplitude without ultrasonic vibration, and with ultrasonic vibration 3.9, 7.8 and 10.4 um for the thickness of 200 um are presented in Fig. 4.

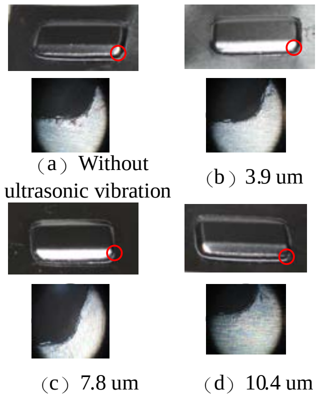


Fig. 5 Fractures at the corner of the micro-square cup with different oscillation amplitudes for the thickness of 200 um. Fracture quality (a) without ultrasonic vibration, and with oscillation amplitude of (b) 3.9 um, (c) 7.8 um, and (d) 10.4 um.

After amplification, the fractures at the corner of the micro-square cup became torn and irregular in the absence of ultrasonic vibration and were flattened with the increase of vibration amplitude (Fig. 5). This phenomenon may be attributed to the coupling of acoustic softening effects due to the increase of molding-filling performance that occurs due to the flow stress drop, acoustic hardening and the application of ultrasonic vibration reduces friction stress in the contact surface between the vibrated die and the specimen (surface effects) [13], [14].

4. Conclusions

An experimental study of three thicknesses (40, 100 and 200 um), different oscillation amplitudes (no vibration, 3.9, 7.8 and 10.4 um) and four grain sizes (Φ 11.5, 13.7, 16.9 and 24.6 um) of SUS304 with and without ultrasonic vibration following a micro-square cup drawing process was conducted. The influences of oscillation amplitude and grain size on the drawing height and surface quality were discussed.

1. By applying ultrasonic vibration assisted micro-square cup drawing, the drawing height increased depending on the specimen thickness, t/d and oscillation amplitude. At the same oscillation amplitude within 0-10.4 um, the drawing height increased from 0.19 to 0.24 mm, 0.3 to 0.44 mm, and 0.79 to 1.1 mm for thickness of 40, 100 and 200 um, respectively.

2. The oscillation amplitudes significantly affected the drawing height, and the increasing rate of drawing height for three die sizes all slowed down at oscillation amplitude 10.4 um.

3. With the rise of t/d, the drawing height increased, and the increasing rate was higher at larger oscillation amplitude for the thickness of 40 um, and was more obvious with the reduction of grain size within oscillation amplitude of 0-10.4 um.

4. The oscillation amplitude significantly affected the drawing height, and the increasing rate of drawing height for three die sizes all slowed down at oscillation amplitude 10.4 um.

5. Fractures occurred at the corner of the micro-square cup for the thickness of 0.2 mm. The fractures were torn and irregular in the absence of ultrasonic vibration condition but became flatter with the increase of vibration amplitude.

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