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ORIGINAL ARTICLE

Time factors and optimal process parameters for ultrasonic microchannel formation in thin sheet metals

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Abstract Micro-ultrasonic sheet-metal forming using molten plastic as a flexible punch is a new microforming technology useful for manufacturing micro-stamped thin sheet metals. In this paper, we researched how time parameters influenced the forming replication ability of microchannel forming. Our experimental results show that the forming replication ability of the method was improved by extending the ultrasonic action duration time and maintaining pressure time. An appropriate ultrasonic action duration time was determined by assessing the melting time of the plastic powder used as a flexible punch; an appropriate maintaining pressure time was determined by assessing the coagulation time of the molten plastic punch. When the ultrasonic action duration time was 0.5 s and the maintaining pressure time was 1.5 s, the forming replication ability of the microchannel reached 97 %. With further increases in the time parameters, the forming replication ability stopped rising, and the forming method produced parts with defects at a lower forming efficiency. Through these experiments, we obtained a set of optimal process parameters for microchannel formation.

Keywords Sheet metal · Ultrasonic wave · Microchannel formation · Replication ability · Time parameters

Along with the rapid expansion of miniaturized and micro-miniaturized products, the demand for microparts has mushroomed and the requirements for their production have become increasingly strict [1–3]. In recent years, interest has greatly increased in using micro-stamping methods to process microparts made from thin sheet metals with thicknesses of a few or tens of micrometers. Manabe et al. studied the formability of thin stainless steel and thin phosphor bronze sheets and the surface roughness of parts during microdeep drawing using a traditional mechanical stamping method and drew a microcup with 0.5 mm diameter using a 20-μm-thick stainless steel sheet [4, 5]. Behrens et al. [6] and Hu [7] used a 25-μm-thick stainless steel sheet and a 15-μm-thick aluminum sheet to draw 1.5 × 0.75 mm microrectangular parts, respectively, and studied the influence of die geometry on the drawing pressure and friction using a mechanical deep drawing method. Xu et al. used a mechanical method to conduct punching experiments at different diameters from 0.4 to 2.0 mm on 40–200-μm-thick brass and stainless steel sheets, studied the fracture surface of microholes and the size effects of micropunching of thin sheet metal [8], and developed a new kind of microforming system that was designed specifically for micropunching [9]. Huang et al. used an ultrasonic-assisted forming method and 100-μm-thick stainless steel sheet to draw a microcup with a 6 mm diameter and studied the relationship between the limit drawing ratio and punch-die interstice and wrinkles [10]. Schulze Niehoff et al. studied the influence of laser power density and pulse number on bulge height in the laser shock microforming method and bulged out a dome part with 1.4 mm diameter and 0.25 mm height using 50-μm-thick aluminum sheet [11]. Liu et al. used a the laser-driven flyer loading method to emboss a semicircular sectional microchannel of 160-μm width and 45-μm depth on a 20-μm-thick copper sheet, studied the influence of laser energy on the deformation mechanism and the change in the sample surface roughness [12], and conducted numerical simulation analysis of microchannel forming through laser shock

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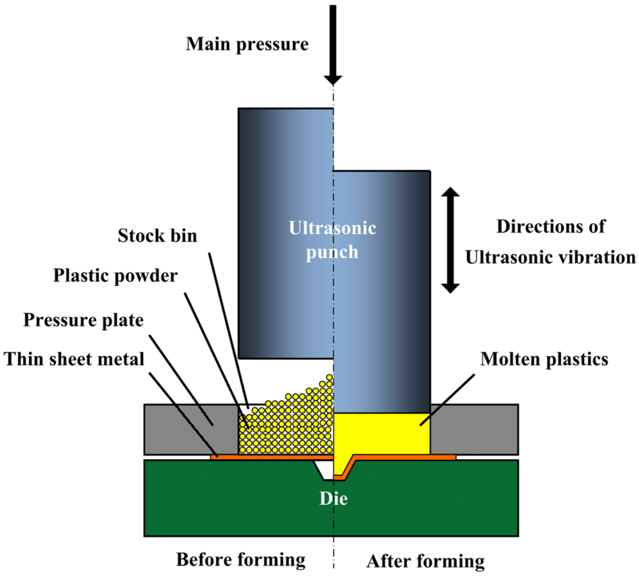


Fig. 1 Schematic of micro-USF

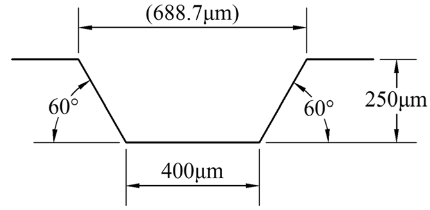


Fig. 2 Designed dimensions of the die microchannel section, with the true size shown in parentheses

embossing [13]. Zhang et al. used plasticine as a flexible support and formed craters with a 2–3-mm diameter and 0.1–0.4-mm depth using 17–35-μm-thick aluminum, copper, and titanium sheet. This was done by using a mold-free laser shock micro-drawing forming process and studying the section thickness distribution at the crater of the sheets and the influence of different materials and laser energies on microforming [14]. Zhao et al. used an electromagnetic forming method to bulge out 1.5-mm wide and 0.6-mm deep parallel channels on 100-μm-thick annealed T2 copper sheet and studied the part rebound and the relationship between voltage and channel-forming depth [15]. Besides these studies, many other scholars have conducted valuable research in the field of thin sheet metal microforming [16–22].

Traditional mechanical stamping methods that use rigid punches and dies still attract attention and are studied frequently. However, as part dimensions become smaller, punch and die fabrication and precise centering between the punch and die become more difficult. In contrast, some new microforming methods, such as laser and electromagnetic shock forming, avoid difficulties of traditional mechanical stamping methods by using flexible punches and single sided rigid dies. These new microforming methods of using flexible punch enabling formation at high speed while avoiding wrinkles in the blank, decreasing rebound, lessening the friction between the blank and die, and improving the deforming uniformity and forming limit of the blank.

Lacking basic theory, thin sheet metal micro-stamping forming is a new research area, and the capabilities and optimal process parameters of various forming methods must be studied further. By combining basic theory with technological improvements, experimental research can produce essential forming platforms, die, and workpieces; then, theory can determine the best way to improve the technology. Thus, it is important to determine the process capability and the application range of these forming methods while seeking out their fundamental forming laws and determining the optimal process parameters.

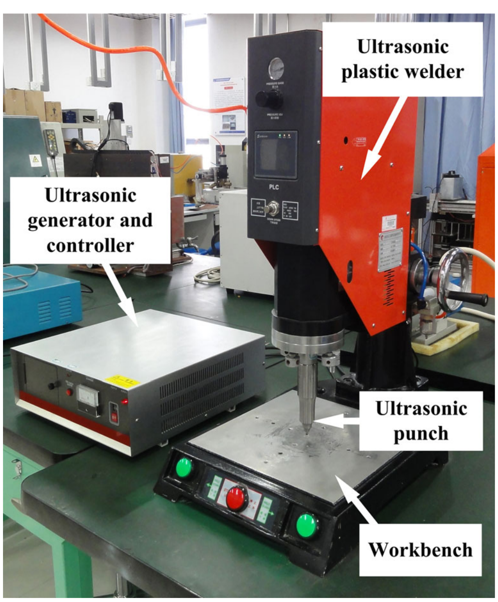


Fig. 3 Ultrasonic plastic welder

1 The micro-USF method

We propose a new thin sheet metal microforming method, micro-ultrasonic sheet metal forming using molten plastic as a flexible punch (abbreviated to as micro-USF), as shown in Fig. 1.

In this method, plastic powders in a stock bin are crushed and rubbed under high-frequency vibration and excitation of an ultrasonic head, then fused into a viscous fluid medium under high temperature and formed a flexible punch, through which the main pressure of the ultrasonic head is transmitted to the thin metal blank, which is extruded into the die cavity, forming the thin metal sheet.

Used as a viscous medium in the forming process, molten plastics can improve the deformation uniformity of the sheet,

Table 1 Major parameters of the ultrasonic plastic welder

Maximum power	Output frequency	Main pressure of ultrasonic head	Ultrasonic action duration time	Maintaining pressure time
2600 W	20 kHz	0–1.06 MPa	0–10 s	0–20 s

delay material necking, and increase the forming limit [23, 24]. Additionally, molten plastics were used as a flexible punch to transmit a part of the ultrasonic vibration to the thin sheet metals and dies. This provided the advantages of ultrasonic forming [25, 26], such as decreasing the friction between the blank and die and reducing the flow stress of the blank. The combined advantages of viscous medium forming and ultrasonic forming enable producing high-quality parts.

2 Forming replication ability and replication degree

We used a trapezoidal cross-section microchannel die, whose design dimensions are shown in Fig. 2.

To study the forming replication ability of micro-USF, we defined the replication degree R as the ratio between the microchannel sectional area S_s of the forming specimen and the die section area S_m:

$$R = \frac{S_s}{S_m} \tag{1}$$

The larger R was the closer the shape of the forming specimen was to the die shape and the stronger the replication ability was.

3 Forming platform and experiment conditions

An ultrasonic plastic welder (Shenzhen Hongri 2026) was used, as shown in Fig. 3. The major parameters are shown in Table 1; the ultrasonic power was adjustable with five gears, and the ultrasonic power and amplitude at various gears are shown in Table 2.

The ultrasonic power was 2080 W, corresponding to ultrasonic amplitude of 3.4 μm, and the main pressure of the ultrasonic punch was 0.6 MPa.

The forming die was made of 304 stainless steel, and a built-up construction of the die core and die ring was adopted for ease of manufacturing, as shown in Fig. 4a. The microchannel was processed on the surface of the die core as shown in Fig. 4b through WEDM in accordance with the designed dimensions in Fig. 2. Considering the possibility of dimensional errors, the section profile of the die and corresponding forming specimen should be measured on the same section; the actual sectional areas of the microchannel S_m and S_s were calculated and the replication degree R was determined using Eq. (1).

Table 2 Ultrasonic power and amplitude at various gears

Gear	1	2	3	4	5
Ultrasonic power (W)	1560	1820	2080	2340	2600
Amplitude (μm)	2.6	3.0	3.4	3.8	4.2

The forming material was a 50-μm-thick T2 copper sheet. Annealed at 300 °C, the average grain size was 5.3 μm and the ratio of thickness to grain size was 9.4. Figure 5 shows typical metallographic microstructure of annealed thin T2 copper sheet. Figure 6 shows an experimental specimen.

The plastic powder used was ethylene-vinyl acetate copolymer (EVA) with a mean grain size of 350 μm and a melting temperature of 90 °C. The specimens were observed with an ultra-high depth-of-field digital microscope (Keyence VHX-2000).

4 Preliminary determination of time parameters

The ultrasonic action duration time t_u and maintaining pressure time t_p are two important time parameters for micro-USF that affect its microforming replication ability. To improve the

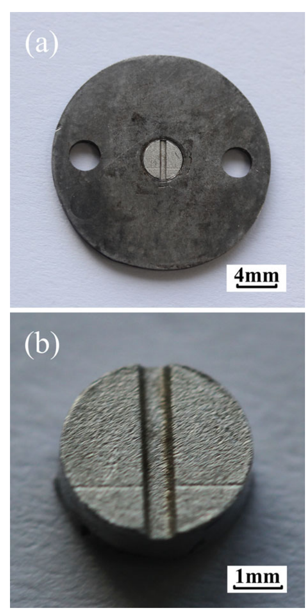


Fig. 4 Microforming die: **a** Built-up construction of die core and die ring; **b** Die core and microchannel

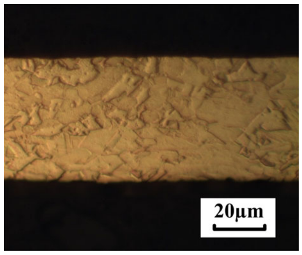


Fig. 5 Typical metallographic microstructure of annealed thin T2 copper sheet

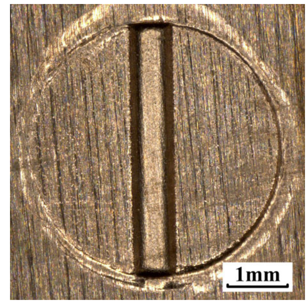


Fig. 6 Typical experimental specimen

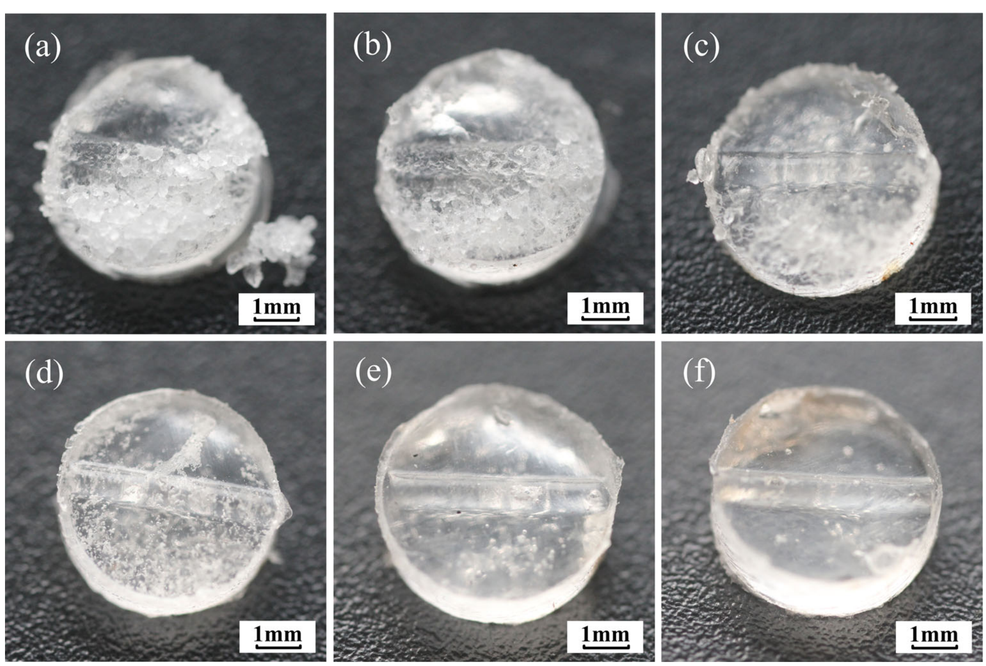
quality of parts, we need to determine the optimal time parameter combinations. We consider the shortest time for which no surface defects form in the workpiece and at which the maximum degree of replication can be obtained as a criterion for selecting the optimal time parameter combinations.

Lengthening the ultrasonic duration action time enabled the plastic powder to fully melt into a viscous fluid medium, efficiently and evenly transmit the main pressure of the ultrasonic head to the thin sheet metal blank, evenly and completely deform the blank, press the blank closer to the die cavity wall, and increase the forming replication degree of the workpiece. When the ultrasonic action persists too long, the high temperature generated from repeated collision and friction between the blank and the die cavity causes defects such as scorching and fracture to the thin sheet metal blank [21]. The ultrasonic load time should be sufficient to completely melt the plastic powders while avoiding scorching and fracture.

Figure 7 shows six solidified plastic punches formed with various ultrasonic action duration times. As the ultrasonic action time increased, so did the melting degree of the plastic powder. At less than 0.3 s, there were unmelted plastic powder particles; at 0.4 s, the plastic particles were mostly melted but the borders of a few plastic particles were still visible; after 0.5 s, the border disappeared and the plastic powders were fully melted. Thus, the ideal ultrasonic action time appeared to be 0.5 s.

After stopping the ultrasonic action and during the initial stage (before the molten plastics solidified and when they had good fluidity), the maintain pressure was able to further deform the blank and increase the replication degree. As the molten plastics solidified, the fluidity of the molten plastics decreased and the strength increased. To prevent rebound from reducing the replication degree, the maintain pressure was in the shape of the stable workpiece and was able to reduce rebound. When the main pressure was removed before the molten plastics were solidified, the workpiece was able to be deformed because of its viscidity when the ultrasonic head was raised, and the unstable shape of the workpiece had a risk of rebounding seriously. When the time that the pressure was

Fig. 7 Plastic punches at various ultrasonic action duration times: **a** 0.1 s; **b** 0.2 s; **c** 0.3 s; **d** 0.4 s; **e** 0.5 s; **f** 0.6 s



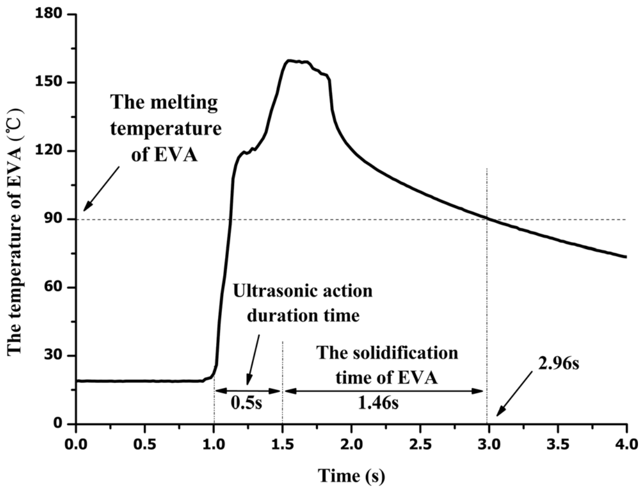


Fig. 8 EVA temperature over time

kept constant increased after the molten plastics had just solidified or after some time, the replication degree was not affected seriously, but amount of time needed to form the workpiece was extended and the forming efficiency decreased. Thus, the maintaining pressure time should be approximately the solidification time of the molten plastics.

The solidification time of the molten plastics after stopping the ultrasonic action was measured by a thermocouple (OMEGA TC-TT-K-36-36, USA), which was placed in the EVA powder. Figure 8 shows the temperature of the EVA powder over time.

Upon stopping the ultrasonic action after 1.46 s, the EVA powder decreased in temperature to the melting temperature and solidified. Considering that the maintaining pressure time must be greater than the solidification time, we preliminarily determined the maintaining pressure time to be 1.5 s.

Table 3 Replication degrees R of specimens at various ultrasonic action duration times t_u

t_u (s)	R (%)
0	38.9 (+3.9, −2.8)
0.1	61.2 (+4.4, −4.9)
0.2	79.5 (+2.8, −2.3)
0.3	91.8 (+1.7, −1.4)
0.4	94.5 (+2.1, −1.8)
0.5	97.1 (+1.6, −1.9)
0.6	96.9 (+1.8, −1.6)

Based on these analyses and experiments, we determined a preliminary set of optimum time parameters: an ultrasonic action duration time of 0.5 s and a maintaining pressure time of 1.5 s. However, whether micro-USF could produce good forming replication degree and whether these time parameters were the optimal combination needed to be verified through a forming experiment under real working conditions.

5 Forming experiment and results

To study how the ultrasonic action duration time and maintaining pressure time affected the forming replication degree, many experiments are needed to study the relation between the replication degree and the various combinations of time parameters.

An additional method was adopted in this paper. We fixed a parameter (t_1) and studied the changes of the replication degree when another parameter (t_2) varied with time parameters, which were preliminarily determined by measuring the molten degree and the solidification time of the plastic powder, and, thus, we determined the optimal t_{2o}. Then, we fixed the t_{2o} and

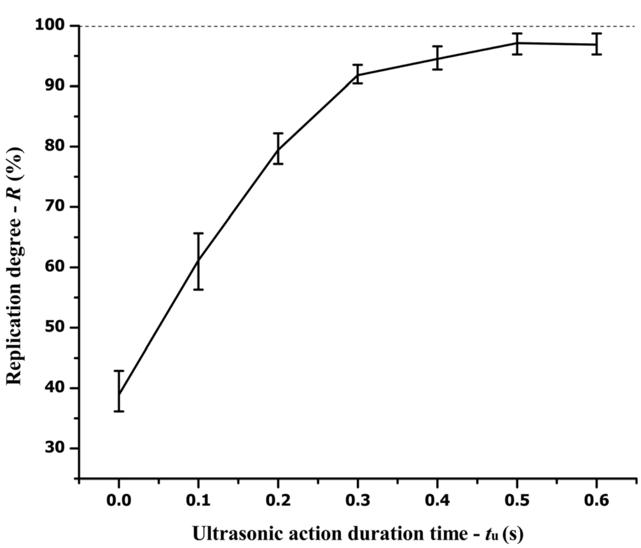


Fig. 9 Replication degree as a function of ultrasonic action duration time

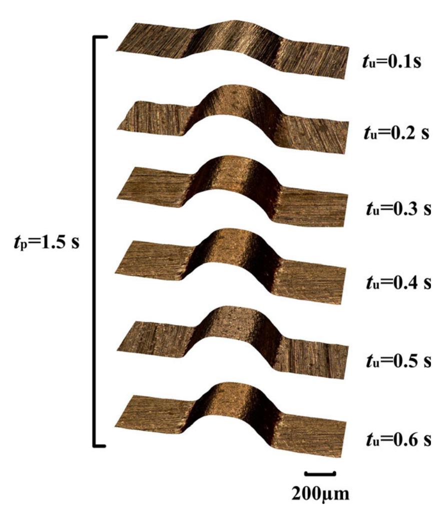


Fig. 10 The local photo of sample microchannels formed with 1.5 s maintaining pressure time and different ultrasonic action duration time

Table 4 Replication degrees R of specimens formed at various maintaining pressure times t_p

t_p (s)	R (%)
0	82.3 (+2.3, −1.2)
0.5	91.6 (+1.1, −2.5)
1.0	94.6 (+0.9, −1.1)
1.5	97.1 (+1.6, −1.0)
2.0	96.5 (+1.0, −1.1)
2.5	96.3 (+0.8, −0.5)
3.0	96.3 (+1.6, −0.7)

studied how changing t_1 influenced the replication degree and determined the optimal t_{1o}. The combination of time parameters (t_{1o}, t_{2o}) should thus be the optimal combination of time parameters under actual working conditions.

(1) Influence of ultrasonic action duration time upon replication degree

Using a preliminary maintaining pressure time of 1.5 s, we performed experiments with ultrasonic action times of 0, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 s, and we calculated the replication degree R of the specimens by using the aforementioned method. The experimental data is shown in Table 3, and the replication degree as a function of action time is shown in Fig. 9. Figure 10 is the local photo of sample microchannels formed with 1.5 s maintaining pressure time and different ultrasonic action duration time.

Figure 9 shows that the specimen replication degree increased as the ultrasonic action duration time increased with a fixed pressure time (1.5 s). Without ultrasonic action (ultrasonic action duration time of 0 s), the forming replication ability was low and there were large differences among specimens, even though the main pressure was applied for 1.5 s. It is difficult to form microparts by transmitting the main pressure only through the plastic powder without ultrasonic action.

When the ultrasonic action duration time was 0.5 s, the replication degree, averaged from five specimens, was 97.1 % and its maximum was 98.7 %, indicating that the replication degree approached the limit. When the ultrasonic action duration time increased further, the replication degree did not rise sharply. Further, the repeated collisions and friction between the specimen and die caused defects such as scorching and fractures. Thus, the optimal ultrasonic action duration time was 0.5 s when the maintaining pressure time was 1.5 s.

(2) Influence of maintaining pressure time upon replication degree

When the maintaining pressure time is 1.5 s under actual working conditions, the optimal forming replication degree can be obtained from the ultrasonic action time of 0.5 s. The experiment below examines whether this maintaining pressure time is optimal.

Given an ultrasonic action duration time of 0.5 s, we performed experiments with maintaining pressure times of 0, 0.5, 1.0, 1.5, 2.0, and 2.5 s to measure the section profile curve of the specimen and calculate the replication degree R. These experimental data are shown in Table 4, and the corresponding curve is shown in Fig. 11. Figure 12 is the local photo of sample microchannels formed with 0.5 s ultrasonic action duration time and different maintaining pressure time.

Figure 11 shows that, at a fixed ultrasonic action duration time, the replication degree increased rapidly as the maintaining pressure time increased up to 1.5 s. Further, the replication

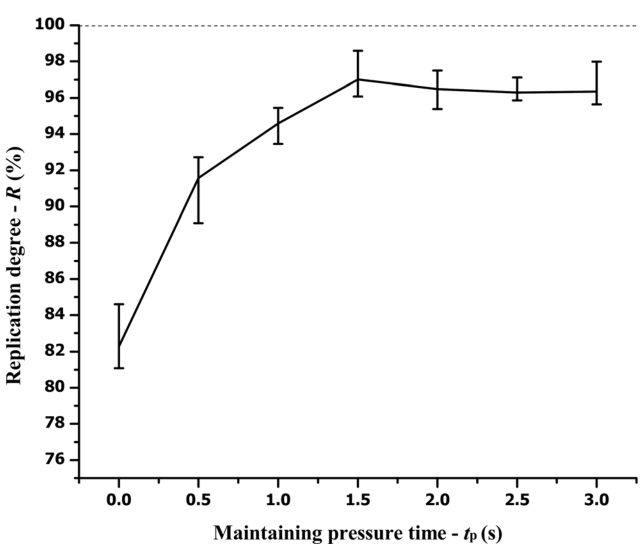


Fig. 11 Replication degree as a function of maintaining pressure time

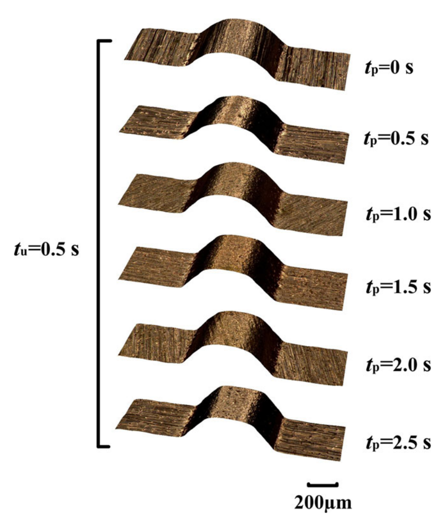


Fig. 12 The local photo of sample microchannels formed with 0.5 s ultrasonic action duration time and different maintaining pressure time

Table 5 Combined influences of ultrasonic action duration time t_u and maintaining pressure time t_p upon replication ability R

R (%)		t_u (s)						
		0	0.1	0.2	0.3	0.4	0.5	0.6
t_p (s)	0						82.3	
	0.5						91.6	
	1.0						94.6	
	1.5	38.9	61.2	79.5	91.8	94.5	97.1 97.0	96.9
	2.0						96.5	
	2.5						96.3	
	3.0						96.3	

degree fluctuated around 97 % when the maintaining pressure time exceeded 1.5 s, because the mean of the replication degree of five specimens was 97.0 %. The maximum replication degree reached 98.6 % when the maintaining pressure time was 1.5 s. After 1.5 s, the replication degree fluctuated slightly because of measurement errors. Moreover, the molten plastics solidified after 1.5 s, and the replication degree could not be improved by holding the pressure constant. Thus, the optimal forming efficiency was obtained at a maintaining pressure time of 1.5 s, and the optimal maintaining pressure time was 1.5 s.

When the main pressure was removed without the maintaining pressure time (maintaining pressure time of 0 s) when the ultrasonic action was stopped, the replication degree was lower (82.3 %), which demonstrated that the blank was incompletely deformed within the ultrasonic action duration time (0.5 s). When the main pressure was driven by the molten plastics to come into play, and the thin sheet metal blank was fully deformed by extending the ultrasonic action duration time, defects occurred such as scorching and fracture. However, when the main pressure continued acting upon the blank under a holding pressure after the ultrasonic action was stopped and before the molten plastics was solidified, we were able to avoid defects in the parts caused by overlong ultrasonic action. This guaranteed that the blank was fully deformed and obtained good forming effects. When manufacturing high-quality parts, it is very important to select the appropriate combination of ultrasonic action time and maintaining pressure time.

Table 6 Optimal process parameter combination of ultrasonic microchannel forming

<table>
<tr><td rowspan="8">Experiment condition</td><td rowspan="3">Die</td><td rowspan="2">Shape</td><td colspan="4">Size</td><td rowspan="2">Processing method</td></tr>
<tr><td>Opening width</td><td>Bottom width</td><td>Depth</td><td>Tilt angle of side wall</td></tr>
<tr><td>Microchannel of trapezoid cross section</td><td>689 μm</td><td>400 μm</td><td>250 μm</td><td>60 º</td><td>WEDM</td></tr>
<tr><td rowspan="2">Forming material</td><td>Material</td><td>Annealing temperature</td><td>Thickness</td><td>Grain size</td><td colspan="2">Ratio of thickness to grain size</td></tr>
<tr><td>T2 copper</td><td>300 ºC</td><td>50 μm</td><td>5.3 μm</td><td colspan="2">9.4</td></tr>
<tr><td rowspan="2">Punch material</td><td>Material</td><td>Form</td><td colspan="2">Mean grain size</td><td colspan="2">Melting temperature</td></tr>
<tr><td>EVA plastics</td><td>Grain</td><td colspan="2">350 μm</td><td colspan="2">90 ºC</td></tr>
<tr></tr>
<tr><td colspan="2" rowspan="2">Optimal process parameters of microchannel forming</td><td>Ultrasonic frequency</td><td>Ultrasonic power</td><td>Ultrasonic amplitude</td><td>Main pressure</td><td>Ultrasonic action duration time</td><td>Maintaining pressure time</td></tr>
<tr><td>20 kHz</td><td>2080 W</td><td>3.4 μm</td><td>0.6 MPa</td><td>0.5 s</td><td>1.5 s</td></tr>
</table>

(3) Optimal combination of ultrasonic action duration time and maintaining pressure time

The data of Tables 3 and 4 are collated in Table 5. For the sake of brevity, Table 5 does not show the error range but shows the mean of the replication degree.

Table 5 shows that the replication degree at the optimal ultrasonic action duration time (0.5 s) was 97.1 %, and at the optimal maintaining pressure time (1.5 s) was 97.0 %. Considering the possibility of errors in measurements, these values could be equal. The same replication degree was obtained by changing the ultrasonic action duration time with a fixed maintaining pressure time or changing the maintaining pressure time with a fixed ultrasonic action duration time when the ultrasonic action duration time was 0.5 s and the maintaining pressure time was 1.5 s, which was the optimal value. Thus, these values (ultrasonic action duration time (0.5 s) and the maintaining pressure time (1.5 s)) were the optimal combination for manufacturing microchannel parts under real working conditions.

We verified the optimal ultrasonic action duration time and maintaining pressure time by assessing the melted condition of the plastic powder and the solidification time of the molten plastics in the previous forming experiment. Thus, we determined the optimal combination of time through simple measurements of the plastic powders' performance.

6 Optimal process parameters

From our experimental results, we determined the optimal combination of process parameters for microchannel forming and processing with micro-USF applied to 50 μm T2 copper sheets, as shown in Table 6.

Our results show that micro-USF had strong forming ability. With the optimal process parameters, the forming replication degree of micro-USF reached 97 % for T2 copper sheets with microchannels that were hundreds of micrometers wide. Accounting for the dimensional errors in the measurements, this replication degree approached its limit.

7 Conclusions

(1) A method for determining the optimal time parameters was introduced when the micro-USF method was used. The optimal ultrasonic action duration time could be determined by the plastic powder melting time, and the optimal maintaining pressure time could be determined by the molten plastics solidification time.
(2) The forming experiment verified the correctness of the above method for determining the optimal time parameters and confirmed that under the experimental conditions used, a 0.5 s ultrasonic action duration time and 1.5 s maintaining pressure time is an optimal time parameter combination.
(3) Use of the optimal time parameter combination yields microchannel parts with a replication degree of 97 % and without surface defect formation.

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