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ORIGINAL ARTICLE

Ultrasonically driven molten resin bulge for the formation of metal micro-structures in laminated die cavity

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Abstract This paper proposes the use of ultrasonic bulge-forming process to fabricate T2 copper foil micro-structures. This approach involves the ultrasonic plasticization of powder in a laminated die cavity and the subsequent formation of a molten resin bulge. The laminated die is fabricated by micro-double-staged laminated object manufacturing and is then used as a concave micro-cavity. This technique uses ultrasonic melt polymer powder as a soft punch. Then, T2 copper foils are extruded into the concave die cavity. Consequently, the replication of the micro-bulging parts to the concave micro-cavity is achieved. This study also determined the appropriate parameters for ultrasonic bulge-forming process. Finally, the micro-two-stage gear, micro-three-stage gear and micro-cone bulge-forming parts were manufactured with good quality. The proposed technology can be applied to effectively reproduce the fine complex structure of concave micro-cavities. In contrast to traditional techniques, this method avoids issues arising from the incorrect location of the concave–convex die.

Keywords Micro-formation · Ultrasonic bulge forming · Micro-electric resistance slip welding · Femtosecond laser cutting · EVA powder

1 Introduction

The demand for the further miniaturisation of products has been consistently growing in various industries as a result of the recent developments and application of micro-electro-mechanical systems. Thus, micro-forming technique is gaining attention from researchers around the world. Vollertsen et al. fabricated micro-cups with a depth–width ratio of 1.8 by micro-extending a 20-μm-thick aluminium foil [1]. Saotome et al. developed special equipment for micro-formed micro-cups. Using this device, they studied the micro-extensile processes and extensile limits of thin steel plates [2]. Justinger et al. developed a blanking–drawing compound die device to solve the issues related to the concave–convex die location in micro-forming, and they successfully produced micro-cups with diameters ranging from 1 to 8 mm [3]. Dong et al. performed experimental and simulation studies on micro-forming process and its flow stress scale effect [4, 5]. Yu et al. determined the characteristics of material flow in a micro-dimension and the appropriate processing parameters by considering a micro-forging/extrusion process with varying sizes of copper cylinder feedstock [6]. Micro-scale laser high-speed punching, a method for efficiently fabricating micro-holes, was proposed by Liu et al. [7]. Lai et al. investigated the flexible die-forming process with metal bipolar plates and the associated sheet-forming friction effect [8, 9].

To improve the performance of the micro-forming process, Erhardt et al. proposed the micro-deep-drawing process, in which partial heating is performed with a laser, and demonstrated drawing experiments on a 0.1-mm steel plate [10]. Ji et al. developed the pulse laser shock micro-forming method for metal sheets and successfully produced micro-structures with diameters ranging from 1.2 to 2 mm [11]. Manabe et al. adopted two-step forming method to demonstrate the formation of micro-cups with a diameter of 0.45 mm [12]. Guo et al. developed a plastic micro-forming system for manufacturing good-quality micro-gears [13, 14]. Liu et al. performed systematic studies on micro-electrochemical milling by layer process, and they successfully fabricated complex 2D micro-shapes and 3D complex micro-structures with a physical dimension of several 10 μm [15].

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The abovementioned studies have contributed to promoting the development of the micro-forming process for metal sheets. The present study proposes a new technology for micro-forming metal sheets; this method involves the ultrasonic plasticization of powder in laminated die cavity and the subsequent driving of molten resin as a soft punch [16].

In contrast to traditional micro-sheet-forming processes, the ultrasonic bulge-forming process proposed in this study uses low-melting plastic powder instead of a rigid punch. In a typical process, the plastic powder in the container is first melted by the welding action of the ultrasonic welding head. Under the pressure of the welding head, the metal foils are compacted by the molten plastic, resulting in plastic deformation. Finally, as a result of the synergistic action of the abovementioned processes, the metal foils are extruded into the concave die cavity, resulting in the fabrication of small micro-bulging parts with complex structures.

2 Production process

2.1 Formation of ultrasonic plastic powder bulge

Figure 1 shows the schematic of the processes associated with the production of micro-formed parts by using the ultrasonic bulging process [17]. The steps involved are sequentially described as follows:

1. The produced micro-laminated die is installed in the lower die's square groove (Fig. 1a), and the metal foil is fixed above the concave micro-cavity (Fig. 1b).
2. The blank holder and the container having the plastic powder are connected to the lower die with screws (Fig. 1c), and the aforementioned devices are fixed on the work platform through the compact plate.
3. Plastic powder is added into the plastic powder container and is compacted through the upward–downward movement of the welding head (Fig. 1d).
4. The ultrasonic wave is launched and applied to the plastic powder container through the ultrasonic welding head (Fig. 1e).
5. Under the action of ultrasonic energy, the plastic powder particles in the container generate heat via friction, consequently melting the solid powder. Under the continuous action of the welding head pressure and the molten plastic, the metal foil undergoes plastic deformation in the concave cavity (Fig. 1f). Accordingly, the concave cavity is expected to determine the structure and size of the bulging parts produced by the ultrasonic bulge-forming process, thereby facilitating the micro-formation of small bulging parts with complex structures. Unlike in traditional processes that involve rigid punch, the proposed method is not influenced by any sensitivity issues that could arise from the incorrect location of concave–convex dies.

2.2 Micro-DLOM process

In the ultrasonic bulge-forming process, the molten plastic powder is like the convex die, whereas the concave die cavity is obtained through a special micro-double-staged laminated

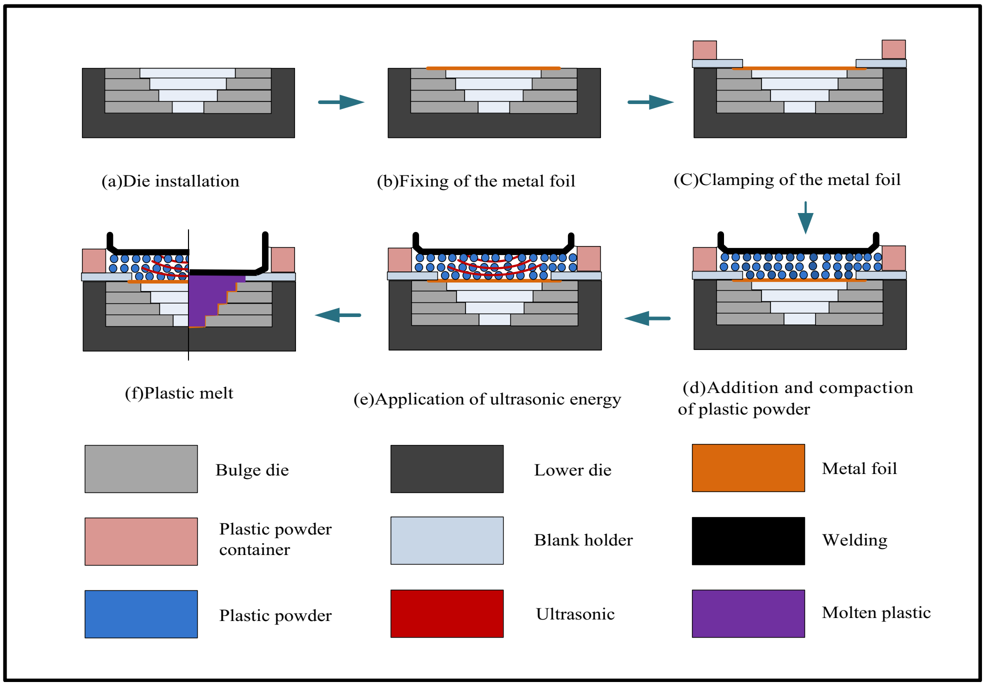

Fig. 1 Ultrasonic bulge-forming process (**a**–**f**)

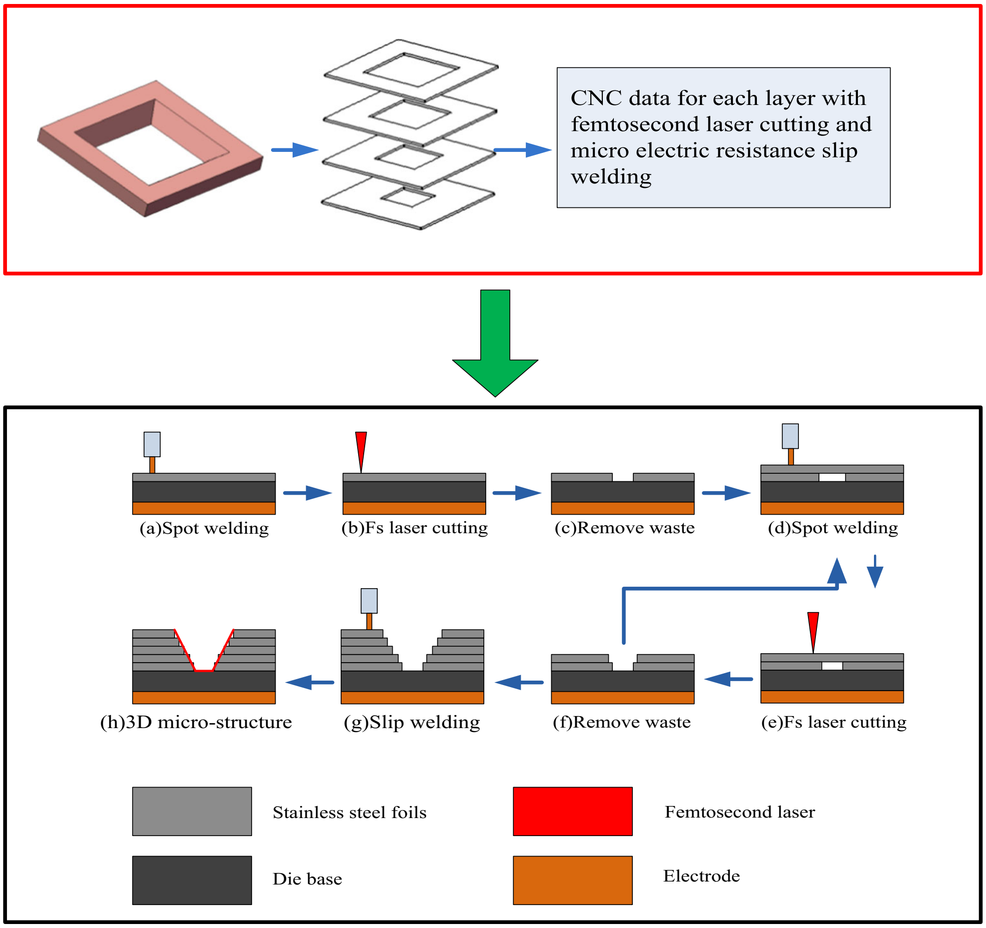

Fig. 2 Micro-DLOM process (**a**–**h**)

object manufacturing (micro-DLOM) method. This process includes the following steps (Fig. 2) [18, 19]:

1. The desired 3D micro-die is modelled by the 3D modelling software, and the 3D micro-structure model is sliced layer by layer with the slicing software, to obtain the contour data and resistance welding data associated with the 2D micro-structure at each layer.
2. The die base is installed on the workbench clamp and is moved to a resistance welder. At the resistance welder, the steel foils are fixed on the die base with welding spots. The welding spots should be placed as close as possible to the cutting edge of the femtosecond laser to prevent the horizontal movement of the steel foils and to improve the cutting precision (Fig. 2a).
3. The workbench is then moved to the femtosecond laser station. The stainless steel foils are cut by focused femtosecond laser beams according to the data obtained in step (1) to form a single 2D metal micro-structure (Fig. 2b).
4. The wastes generated by the cutting process are removed (Fig. 2c). Subsequently, the steel foils and die base are moved down by one step.
5. Then, the steel foils and die base are moved to the resistance welder, and the abovementioned processes are repeated (Fig. 2d–f). The preliminary laminated 3D micro-dies are obtained by gradually superposing and fitting the multi-layered 2D micro-structure.
6. The 2D micro-structure layers of the 3D micro-dies produced in the abovementioned processes are interconnected only by several welding points. Therefore, gaps inevitably exist between the layers of the 2D micro-structure. To eliminate these gaps, the preliminary laminated 3D micro-dies must be moved to the micro-electric resistance

Table 1 Relationship between the amplitude and power of the ultrasonic welder

Power (W)	1300	1430	1560	1690	1820	1950	2080	2210	2340	2470	2600
Amplitude (μm)	25	26	26	26	27	30	34	36	38	40	42

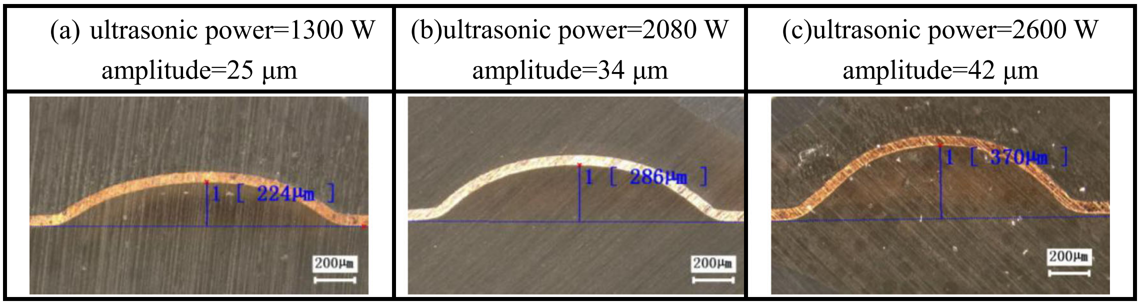

Fig. 3 Formation of micro-bulging parts under different amounts of ultrasonic power (**a**–**c**)

slip welding station for welding at multiple discharges (Fig. 2g). This step ensures the full connection between each layer of the 2D micro-structure (Fig. 2h).

2.3 Experimental setup

The ultrasonic welding machine (model: RS2026PLC) used in this study was manufactured by China Hongri Ultrasonic Equipment Co., Ltd. It has a maximum output power of 2600 W, a frequency of 20 KHz and an adjustable ultrasonic vibration time from 0.1 to 9 s. The plastic powder used in this study was ethylene–vinyl acetate copolymer (EVA) powder, with a particle size of 50 mesh and melting point of 112 °C. The experiments were performed on heat-treated T2 copper foils with a 50-μm thickness. The stereomicroscope (model: VHX-1000) manufactured by Japan KEYENCE Company was used to observe the surface morphology and measure the micro-structure size. The scanning electron microscope (model: JSM6490) manufactured by Japan JEOL Company was used to observe the surface morphology.

3 Analysis of the ultrasonic bulge-forming process

An ultrasonic welder is the main equipment used in ultrasonic bulge-forming process. Therefore, the quality of the micro-bulging parts is greatly influenced by the ultrasonic welding parameters, including ultrasonic power, ultrasonic pressure and ultrasonic work time. To obtain the more effective ultrasonic welding parameters, this study analysed different aspects of the ultrasonic bulge-forming process.

3.1 Effects of ultrasonic power on the formation of micro-bulging parts

Ultrasonic power refers to the amount of ultrasonic energy applied in the experiment. The power of the ultrasonic welder is directly related to its amplitude. The relationship between amplitude and power is shown in Table 1.

The concave square-step micro-cavity with a height of 400 μm was fabricated by micro-DLOM technique. The concave micro-cavity was formed by four square steps, and their basic dimensions are 1, 0.8, 0.6 and 0.4 mm. The height of each step is 100 μm. The bulging parts were manufactured by using T2 copper foils with a 50-μm thickness and EVA powder with a 50-mesh particle size. To investigate the effect of ultrasonic power on the bulging parts, this paper applied different amounts of ultrasonic power (1300, 2080 and 2600 W) but maintained ultrasonic pressure and ultrasonic work time at 0.6 MPa and 0.4 s, respectively. Figure 3 shows the experimental results, which reveal that a higher ultrasonic power facilitates an easier formation of bulging parts. To obtain high-quality bulging parts and to avoid excessive

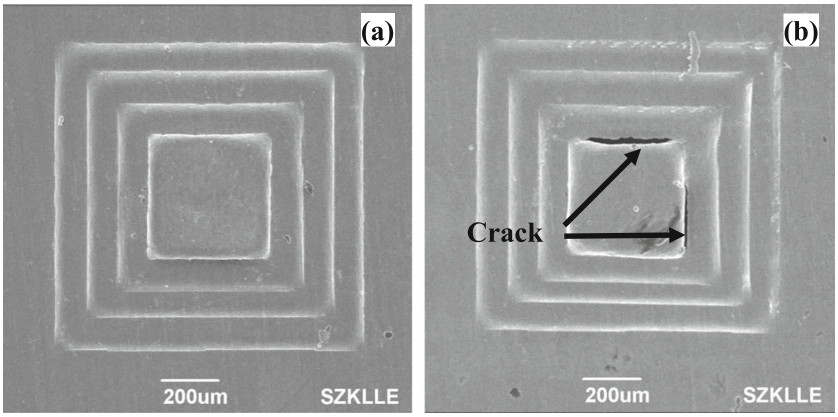

Fig. 4 Formation of micro-bulging parts with different ultrasonic pressure: **a** 0.6 MPa and **b** 0.8 MPa

parameter changes, ultrasonic power was set to 2600 W (with an amplitude of 42 μm) in this study.

3.2 Effects of ultrasonic pressure on the formation of micro-bulging parts

Ultrasonic pressure is the pressure applied by the ultrasonic welding head to the plastic powder. To obtain the appropriate ultrasonic pressure, we analysed the effects of ultrasonic pressure on the formation of micro-bulging parts. For this purpose, the bulging parts were manufactured by using T2 copper foils with a 50-μm thickness and EVA powder with a 50-mesh particle size. The ultrasonic bulge-forming process was performed under an ultrasonic power of 2600 W (with an amplitude of 42 μm) and an ultrasonic work time of 0.15 s.

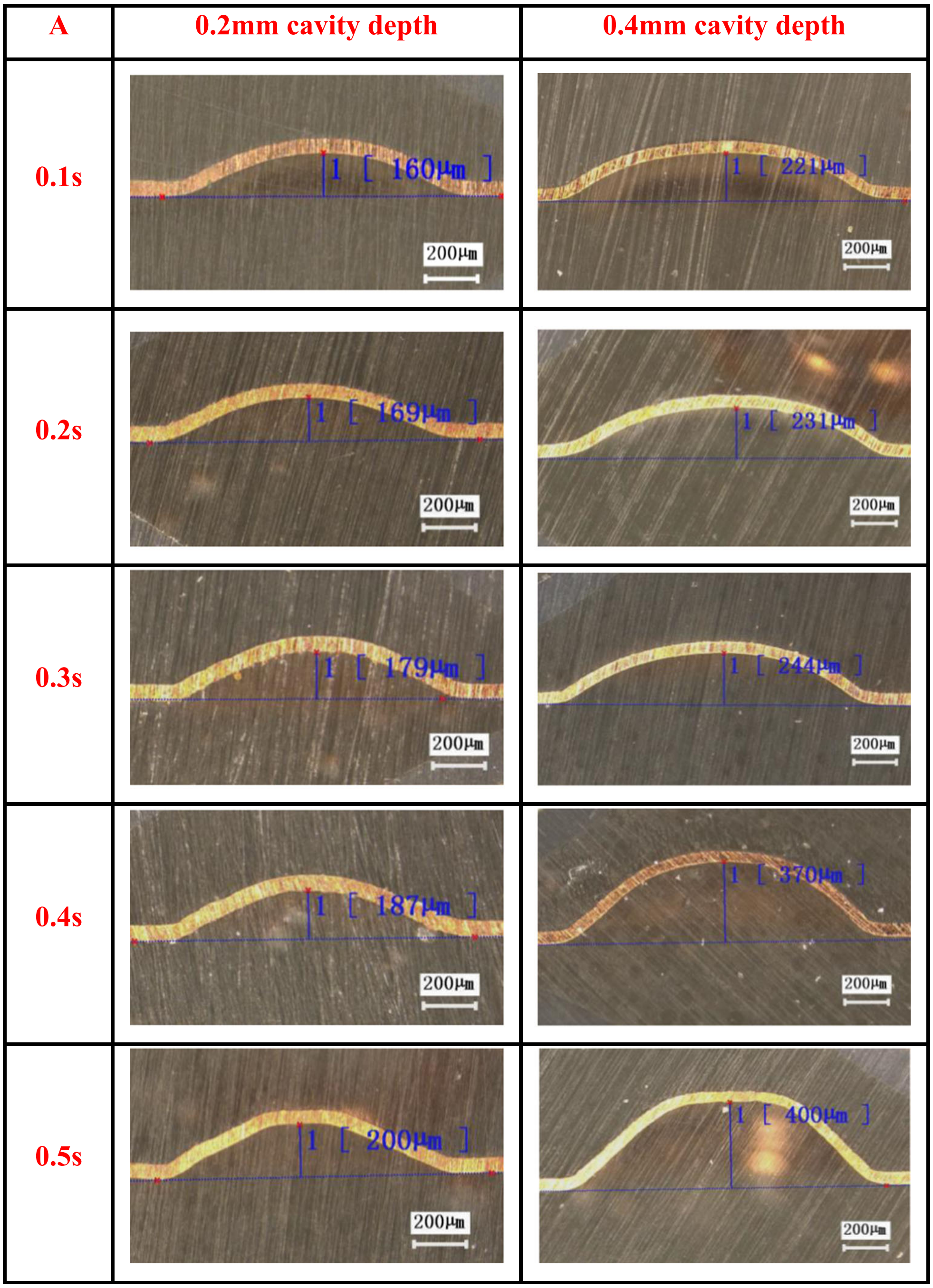

Fig. 5 Formation of micro-bulging parts at different ultrasonic work times: **a** cavity depths are 0.2 and 0.4 mm, respectively; **b** cavity depths are 0.6 and 0.8 mm, respectively

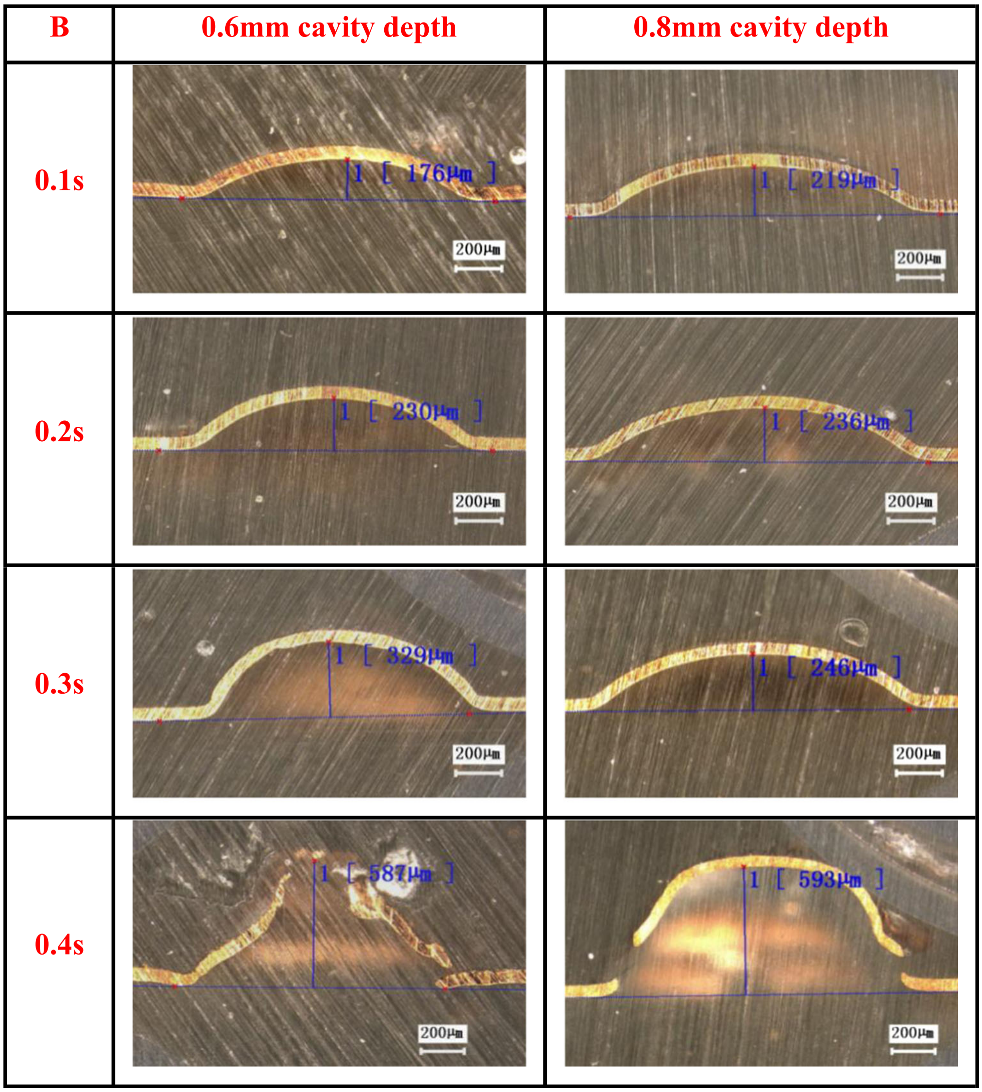

Fig. 5 continued.

The ultrasonic pressure varied from 0.1 to 0.8 MPa. By superposing 0Cr18Ni9 stainless steel foils, the concave square-step micro-cavity with 160 µm in height was obtained by micro-DLOM technique. The concave micro-cavity was formed by four square steps, and their basic dimensions are 1, 0.8, 0.6 and 0.4 mm. The height of each step was 40 µm. The micro-bulging parts were observed by scanning electron microscopy (SEM), and the results are shown in Fig. 4.

As evidenced by the SEM results, the replication of the bulging parts to the concave die cavity exhibited an improvement with increasing ultrasonic pressure from 0.1 to 0.8 MPa. When the ultrasonic pressure exceeded 0.7 MPa, we observed breakage at the edge bottom of the micro-bulging part. The reason for these results can be interpreted as follows. In case of higher ultrasonic pressure, the pressure of the EVA molten resin tends to

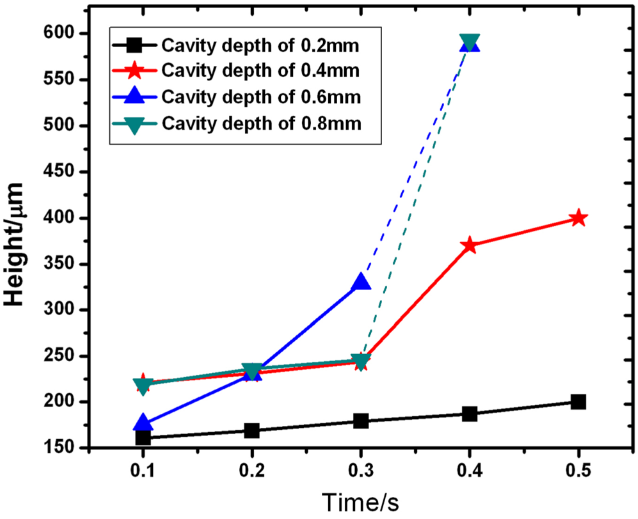

Fig. 6 Relationship between the height of the bulging parts and the ultrasonic work time at different cavity depths

be higher. Consequently, the copper foil is more intensely extruded into the concave cavity. Thus, under the gradual increase in ultrasonic pressure, we can observe an improvement in the replication of the bulging parts to the concave cavity. However, if the stress concentration brought by the laminated die step is greater than the yield limit of the copper foils, then the bulging parts will break. On basis of these findings, the ultrasonic pressure for obtaining better-quality bulging parts was set to 0.6 MPa.

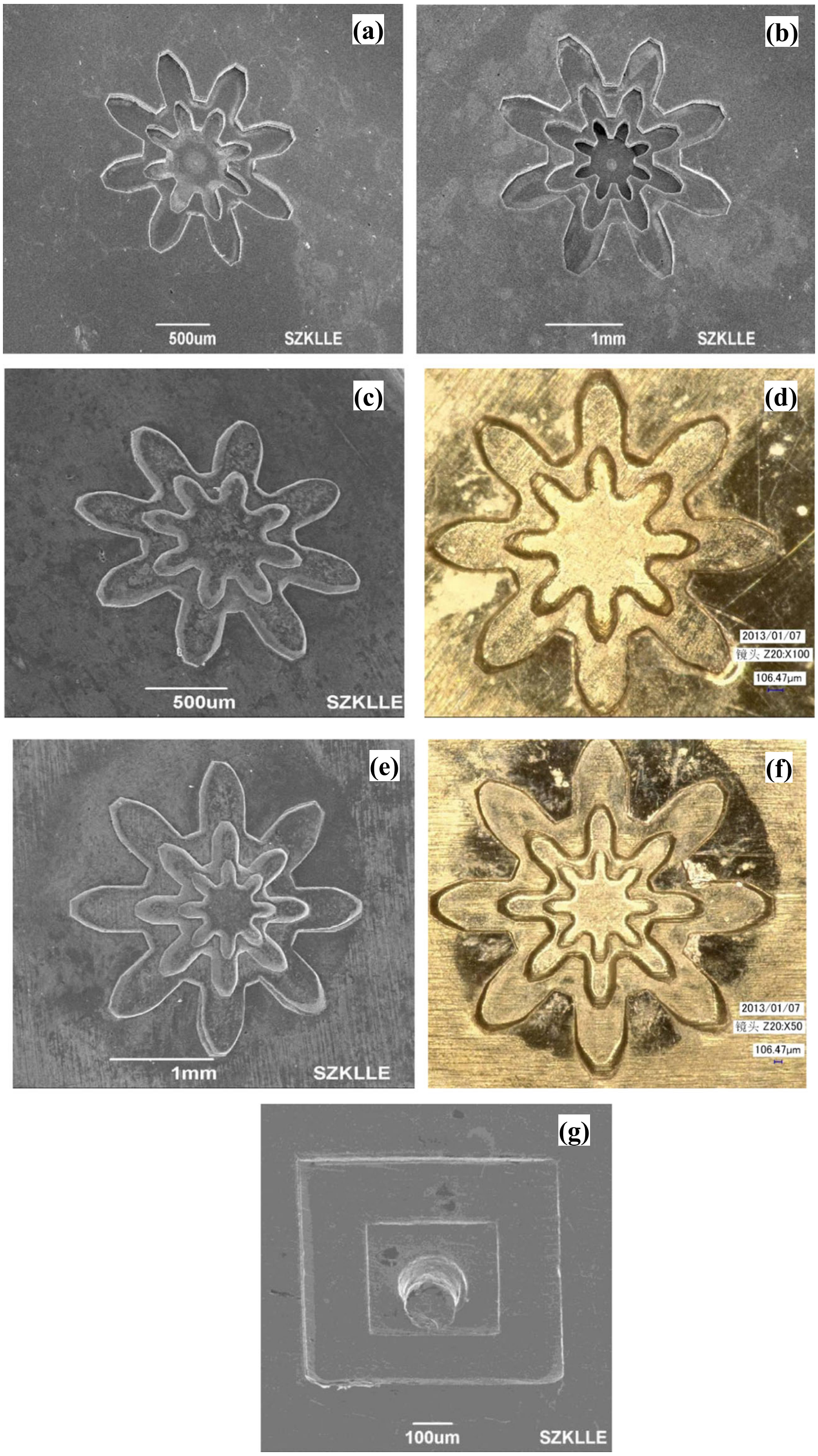

Fig. 7 SEM and stereo microscope photograph of micro-formed parts by ultrasonic bulge: **a** two-gear die cavity; **b** three-gear die cavity; **c**, **d** two-gear micro-formation; **e**, **f** three-gear micro-formation; and **g** micro-cone formation

3.3 Effects of ultrasonic work time on the formation of micro-bulging parts

Ultrasonic work time is the time for which ultrasonic energy is applied. To determine the appropriate ultrasonic work time, we adopted different ultrasonic work time, and the experimental results are shown in Fig. 5. The process parameters are described as follows: ultrasonic power was set to 2600 W, ultrasonic pressure was set to 0.6 MPa and ultrasonic work time ranged from 0.1 to 0.5 s. In this experiment, we fabricated concave micro-cavities with different depths. These concave micro-cavities include square steps with different dimensions, and the height of each step is 50 (die height 0.2 mm), 100 (die height 0.4 mm), 150 (die height 0.6 mm) and 200 μm (die height 0.8 mm). The basic dimensions of the square steps are similar to those described in Section 3.1. Figure 6 shows the relationship between the height of the micro-bulging parts and the ultrasonic work time at different cavity depths.

The experimental results indicate that cavity depth increases with increasing ultrasonic work time. Figure 6 shows that the depth of micro-bulging parts increases more quickly when the concave die is deeper. For the concave cavities with depths of 0.2 and 0.4 mm, we determine that under an ultrasonic pressure of 0.6 MPa and an ultrasonic work time of 0.5 s, the T2 copper foils can reach the bottom of the cavity, thus indicating that the formation process is completed. However, for the concave cavities with depths of 0.6 and 0.8 mm, the thickness of micro-bulging parts could decrease with an increase in the depth of the micro-bulging parts. When the ultrasonic work time is 0.4 s, the depth of the micro-bulging part is too large, making the local thickness too thin. Subsequently, under the impact of the laminated die steps and the repeated action of the ultrasonic waves, the copper foils induce the concentration of stress at the step. Upon reaching the fatigue limit of the copper foils, the bulging parts crack and burst at the end. These findings suggest that the varying forming depths of the micro-bulging parts have a one-to-one correspondence with the suitable ultrasonic time and that the micro-laminated die should be designed reasonably.

4 Formation of micro-bulging parts

To demonstrate the feasibility of this technique, we fabricated three kinds of concave micro-cavity to form the micro-bulging parts. These concave micro-cavities are the gear cavity with two-stage steps, the gear cavity with three-stage steps and the micro-cone cavity. The basic dimensions of concave micro-cavity are described as follows:

Gear cavity with two-stage steps

Parameters for the first-stage step

Modulus	0.1
Addendum circle diameter	1 mm
Addendum	60 μm
Number of teeth	8

Parameters for the second-stage step

Modulus	0.18
Addendum circle diameter	1.8 mm
Addendum	60 μm
Number of teeth	8

The gear cavity with three-stage steps was formed by increasing the third-stage step on the gear cavity with two-stage steps. The basic dimensions of the third-stage steps are described as follows:

Modulus	0.3
Addendum circle diameter	3 mm
Addendum	60 μm
Number of teeth	8

The basic dimension of the micro-cone gradually decreases along the height direction, and its basic dimensions are described as follows:

Bottom diameter	150 μm
Tip diameter	100 μm
Height	140 μm

The abovementioned micro-cavities, which were manufactured by micro-DLOM process, were applied as a concave die.

Experiments were performed with the use of EVA powder with a particle size of 50 mesh under an ultrasonic power of 2600 W, an ultrasonic pressure of 0.6 MPa and an ultrasonic work time of 0.15 s. Annealed T2 copper foils with a thickness of 50 μm were used to reproduce the abovementioned concave micro-cavities and consequently the micro-bulging parts. As shown in Fig. 7, the surface morphology of the micro-bulging parts was observed by stereomicroscope and SEM. Results indicate that the bulging parts formed by adopting the abovementioned parameters exhibited good surface quality, which is consistent with that of the concave micro-cavities.

5 Conclusions

In summary, we have proposed a new ultrasonic bulge-forming process for micro-forming metal sheets, which involves ultrasonic plasticization of the powder in a laminated die cavity and subsequent driving of the molten resin as a soft punch. The feasibility of the proposed technique was confirmed by manufacturing three types of bulging parts. The details of the investigation are described as follows:

1. By using annealed T2 copper foils with a 50-μm thickness, experiments were performed using EVA powder with a particle size of 50 mesh under an ultrasonic power of 2600 W (amplitude of 42 μm), an ultrasonic pressure of 0.6 MPa and an ultrasonic work time of 0.15 s. Micro-gear bulging parts and micro-cone bulging part were successfully fabricated.
2. Experimental results show that under an ultrasonic pressure of 0.6 MPa and an ultrasonic work time of 0.5 s, T2 copper foils can well replicate the concave die with depths of 0.2 and 0.4 mm. However, for the concave dies with depths of 0.6 and 0.8 mm, under the impact of the laminated die steps and the repeated action of the ultrasonic waves, the bulging parts crack and burst at the end when the ultrasonic work time is 0.4 s. Therefore, the different forming depths of the micro-bulging parts have a one-to-one correspondence with the suitable ultrasonic work time.
3. The structure and dimensions of the micro-bulging parts manufactured by the ultrasonic bulge-forming technique are mainly determined by the concave micro-cavity. Therefore, the proposed technique can be used for fabricating micro-bulging parts with smaller size and complex structures. Moreover, this method avoids the incorrect location of the concave–convex dies, which is common in traditional techniques.

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