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Experimental investigation on: Laser shock micro-forming process using the mask and flexible pad

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ABSTRACT

A forming process called the mask and flexible pad laser shock forming was proposed to fabricate the micro-features on the copper foil. In this process, the mask and laser beam were used as rigid punches. Shock waves induced by plasma were used as the source of loading and plasticine was used as a flexible pad. This was a micro scale and high strain rate forming process and the traditional forming method with micro-mold was changed. In the experiment, surface morphology of formed parts was represented and it was found that the mask played a significant role in the forming process. In order to understand the forming process in the experiment, process parameters, including laser pulse energy, numbers of laser pulse and grain size, were analyzed. The experimental results showed that different parameters had different effects on formed parts. The surface quality and the thickness distribution of formed parts were investigated. It was found that formed parts could keep good surface quality after laser shocking and the reasons were explored. The thickness distribution was measured and the thickness thinning rate was calculated. There was no local tightening or rupture in the forming area. In this paper, the micro-features could be obtained on metallic foils and the method of mold-free was proved to be feasible.

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1. Introduction

In recent years, laser application technology is widely studied and becoming increasingly mature and it has been applied to many processes, such as laser shock peening, laser welding, and laser shock forming [1–3]. The formed parts are gradually used in the fields of communications, electronics and micro-electro-mechanical systems.

The technology of laser shock micro-forming is a kind of high-speed loading process. Deformation of the metal foil occurred at a high-strain rate [4] and this is a new forming process. Hackle et al. [5] proposed the method of laser shock forming based on the laser shock peening. He revealed the principle of laser shock forming, based on the study of the plastic deformation of the material. In the same year, Zhou et al. [6] showed that the deformation of the material was the function of mechanical effect other than thermal effect and also calculated the strain rate of the material up to 10^{-7}/s. Chen et al. [7] conducted the experiment of laser shock forming and studied the forming parameters, including laser pulse energy and the thickness of the material. He also studied the thickness of the deformation area and measured the hardness of forming area through the nano-indentation experiment. Recently, Liu et al. [8,9] produced the micro-gears with clear profile and high precision by laser shock punching process.

As the development of laser application technology, some researchers have carried out the research on the mold-free forming process. Nagarajan et al. [10,11] manufactured micro-features on metallic foils using the technology of laser-induced shock forming without the assistance of micro-mold. Ye et al. [12] produced micro pits on the pure aluminum foil using fs laser and investigated the effects of important factors, including pulse widths, impacting times and clamping modes. Zhang et al. [13] used plasticine as a flexible support to form micro-craters on the surface of aluminum, cooper, and titanium foils. Through the summary of the above cases, a forming process called the mask and flexible laser shock forming (MFLSF) were proposed to manufacture micro-features. Dai et al. [14] fabricated a micro-dent by a novel net mask shock processing on the surface of LY2 aluminum alloy. The results showed that mold-free laser shock micro-forming was an effective method to make micro-craters on metallic foils and worthy of further study.

In this investigation, the mask and the laser beam were employed as the variable convex mold and the plasticine was used as the flexible support. Two kinds of different thickness of the copper foil were used in the experiment. The materials were annealed with different temperatures to get different grain sizes. The

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morphology of the formed parts was analyzed. The influence of impacting times and the grain sizes on the forming process was also investigated. In order to observe the quality of the formed parts, the surface roughness of the forming area and the thinning rate of the cross-section were measured. The results from the experiment were expected to promote the understanding and application of the technology of the MFLSF.

2. Experiment

2.1. Experiment preparation

In the investigation, 99.9% pure copper foil was selected to be a target. In order to reduce the original microstructure defect density and research the grain size effects on deformation behavior, 40 μm and 60 μm thickness of copper foil were annealed in a vacuum furnace to obtain a wide range of grain sizes. The copper foil was put into mold with epoxy and then were polished and chemically etched by a mixture of 10 g $FeCl_3$, 30 mm HCL, and 120 mL H_2O. The grain size in the thickness direction was measured by the optical microscopy based on the ASTEM-E112-10 standard and the result could be seen from the Fig. 1. The average grain diameter was 7.9 μm, 10.2 μm, 16.9 μm, 30.6 μm respectively at the annealing temperature of 350 °C, 450 °C, 550 °C, 650 °C. The material of the mask was 304 stainless steel and it was cut into rectangular shape with the dimension of 500 μm × 1000 μm (width × length) by wire-electrode cutting, shown in Fig. 2(a). A thin layer of black paint (10 μm) was sprayed on the specimen to act as an ablative layer to protect the surface from thermal effect. Polymethyl methacrylate (PMMA) was used as confinement layer, which could limit the movement of the plasma, shown in Fig. 3. The plasticine was used as the flexible support. Due to commercially available plasticine contained a considerable number of air pockets, these air pockets should be removed to ensure a reasonable degree of homogeneity. The plasticine was put into a container with a hole at the bottom and the flatness should also be guaranteed.

In the experiment, a short pulse Nd-YAG laser beam with Gaussian distribution [15] was used. It was operated at the repetition frequency of 10 Hz, and the pulse duration was about 8 ns. The wavelength of 1064 nm was selected to enable laser beam to propagate the PMMA. In order to get the proper laser spot (2 mm), which could cover the whole mask, the working platform was placed away from the focus lens with the right distance. After the laser shock forming, the Keyence VHX-1000 digital microscope was used to observe the morphology, ablative layer and confinement layer. The Zeiss Axio CSM 700 true color confocal microscope was used to test the surface roughness of the workpiece. Scanning Electron Microscope (SEM) and Stemi 2000-C were also used in our experiment.

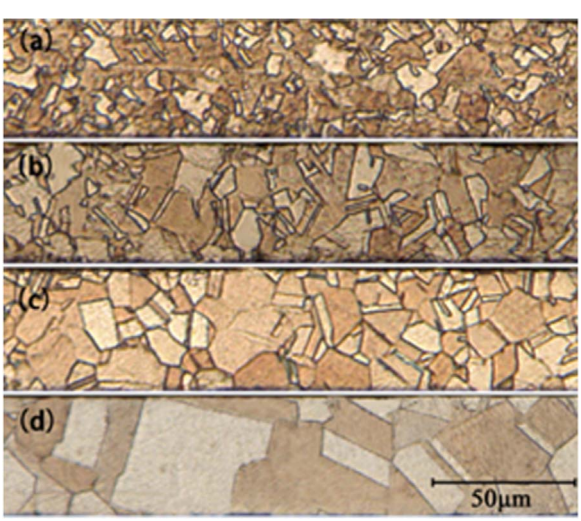

Fig. 1. Optical images of the microstructures of the copper foils after annealing at different temperatures: (a) 350 °C, (b) 450 °C, (c) 550 °C and (d) 650 °C.

2.2. Forming mechanism

Schematic of laser shock forming is shown in Fig. 4. It can be clearly seen that the mask is on the top and a confinement layer covers the surface of the workpiece with the ablative layer. Plasticine is at the bottom of the workpiece, acting as a flexible pad. It was ensured that the laser spot was larger than the mask, so the mask could play a role in the experiment, shown in the Fig. 2(b). When the laser beam passes through the mask, the shape of the laser spot becomes a rectangle. The corresponding ablative layer is instantaneously vaporized into a high-temperature and high-pressure plasma, and the plasma expands from the workpiece surface. Because of the existence of confinement layer, the ablated plasma moves downward to the surface of the workpiece, as shown in the Fig. 3(b). The plasma expands rapidly in a small space and induces shock waves on the surface of the workpiece. Plastic deformation of the workpiece would happen due to the effect of shock waves. The ablative layer covering workpiece acts as the sacrificial material to protect the surface from the thermal effect and the confinement layer can prolong the duration time of plasmas. There is some damage on the mask surface noticed after laser irradiation, shown in Fig. 5. In the MFLSF, the laser beam and the mask are employed as the variable convex mold and the plasticine is used as the flexible pad to replace the micro-mold. When the plasma acts on the workpiece, the plasticine undergoes larger plastic deformation along with the plastic deformation of the copper foil. Then, the micro-features can be obtained without the assistance of a rigid micro-mold.

2.3. The typical morphology of the formed part

Fig. 6 showed the micro-feature of formed worpiece at the following condition: laser energy = 1200mJ; number of pulses = 1. There was a rectangular shape at the bottom in the dotted line, shown in Fig. 6(a) obtained by Stemi 2000-C. Fig. 6(b) was the spatial dimensions of the micro-feature obtained by the Keyence VHX-1000 digital microscope.

From the Fig. 6(a), it could be found that the rectangle was on the surface of the workpiece. But there was still a bump at the edge of the region. The cross-section morphology of the formed features was shown in Fig. 6(b). Its total forming size was larger than the size of the mask and the rectangular area was less than the mask size in the center region. It could be analyzed that the formed part was composed of two parts: directly forming area and indirectly forming area. The directly forming area located at the center of the workpiece was directly impacted by the laser pulse energy. The indirectly forming area is the result of plastic bending around the directly forming area. Fig. 7 shows that the forming area is composed of three parts: elastically forming area, plastically forming area and directly forming area at the beginning of the forming process. When the laser shock was over, elastically forming area recovered to its original state, leaving only the remaining two areas, directly forming area and indirectly forming area. The result was the same with the research of Ye et al. [12].

2.4. Influence of number of the laser pulse

In order to study the influence of the number of the laser pulse, each workpiece was impacted with different impacting times (1,

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