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# Mold-free fs laser shock micro forming and its plastic deformation mechanism

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ABSTRACT

Mold-free micro forming using a fs laser was investigated by producing micro pits on pure aluminum foil. The characteristics of the pit profiles, their forming mechanisms, and the influences of some important parameters on the pit profiles were investigated by measuring the profiles and the surface morphologies of the pits. The microstructures of the shocked aluminum foil were observed through transmission electron microscopy (TEM). Pits obtained through fs laser shock forming are composed of two regions: the directly impacted region and the plastically bending region. Diameters of the former strongly depend on laser beam sizes. The plastically bending region has a negative effect on forming precision. Shorter laser pulse width is beneficial for narrowing the range of the plastically bending region and enhancing the forming precision. Using a single-side clamping mode can also narrow the plastically bending region through buffering the local bending. Fs laser-induced microstructures are characteristic of fragmentary short dislocation lines and parallel slip lines, which are the results of the ultrafast and ultrahigh pressure loading. The localization of the fs laser shock forming induced by ultrafast loading can enhance the precision of mold-free forming.



## 1. Introduction

With the advancement of micro devices, there is an increasing demand for the development of production technology for micro parts. Cold plastic deformation is a type of near-net-shape forming technology that has sparked many researchers' interests for its potential application in the fabrication of micro parts. For example, thin-walled parts may be obtained through micro deep drawing or micro punching [1]. Micro gears and other solid parts have been fabricated using micro bulk forming [2]. However, traditional plastic forming methods have many disadvantages hindering their application in micro manufacturing. It is difficult to make a micro mold or die, and, even if that effort is successful, demolding becomes the problem. The spring-back phenomenon is yet another problem that seriously decreases manufacturing accuracy [3,4].

Laser shock forming—a non-thermal laser forming method that has the advantages of non-contact, tool-free, high efficiency, and high precision—has been successfully introduced into micro manufacturing and has been reported as having great importance [5–10]. Generally, there are two categories of laser shock forming: with mold [5–8] and without mold [4,9–10]. For the former, the maximal horizontal size of the formed microstructure is determined by the mold, and the laser parameters are the main influence on the vertical size. For the latter, the forming process is performed without a mold, so the sizes of the shocked zones are mainly determined by the laser parameters. Laser shock forming without mold is free of all problems resulting from micro molds. In addition, advances in laser technology enables restricting the energy to a small, localized area and inducing highly localized plastic deformations, which may increase the forming precision of the mold-free laser shock forming method. So, mold-free forming technology has great potential as an application in micro manufacturing.

Until now, ns lasers have been widely used in laser shock microforming [5–9] .In fact, fs lasers with shorter pulses can induce shock waves with much higher pressure than ns lasers. For direct ablation by fs laser, strong shock wave with a peak pressure of tens to hundreds of GPa can easily be obtained [11–14]. We also quantitatively evaluated the peak pressure of a fs laser-induced shock wave when it was used for confined ablation (where a transparent confining layer is used to confine the expansion of the ablated plasma) and we found that, even with a very low laser fluence, the peak pressure could reach several tens of GPa [15], which is much higher than the dynamic yield strengths of most metals. So, fs laser-induced shock waves have been used in processing materials and fabricating parts [10,15–20]. Compared to a ns laser, a fs laser has unique advantages when

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performing micromachining and micro manufacturing, including higher precision and the lack of a heat-affected zone [21,22]. Besides, due to the ultrashort loading time, the total shock effect induced by a fs laser is not large enough to blow away microparts or burst thin metal targets [19,20]. All these properties make fs lasers very suitable for microforming. In our previous work [10,15], we conducted experiments involving fs laser shock forming. A new confining layer has been used in the fs laser shock process and three-dimensional (3D) microstructures have been produced successfully on metal foil. We have investigated the effects of the pulse width, the impacting times, and the confining layer on the deformation depth. The destroying mechanisms of the confining layer during fs laser shocking also were analyzed. The plastic deformation mechanisms of polycrystalline copper foil that has been shocked using a fs laser were characterized too.

This article is a continuation of our previous work. The mold-free fabrication of 3D pits on aluminum foil using fs laser has been investigated. The profile characteristics of the pits and the forming mechanisms were analyzed. We also investigated the effects of important factors, including pulse widths, impacting times, and clamping modes, on these pit profiles. We expect that the results we have found will help promote the use of mold-free fs laser shock forming and enhance the controllability of the forming process. In addition, transmission electron microscopy (TEM) observation has been used to analyze the plastic deformation mechanisms of the aluminum under ultrahigh strain rate and pressure induced by the fs laser.

## 2. Experiment

Rolled pure aluminum foil with a thickness of 20 μm was used as the target. The aluminum foil was annealed at 550 °C for 60 min and then exposed to furnace cooling in a vacuum, so as to decrease the original microstructure defect density in preparation for TEM observation. The hardness of the annealed aluminum foil was measured to be about $44HV_{0.025}$. Before performing laser shock, a thin layer of black paint (15 μm) was sprayed on the specimens to act as an absorbent layer. Then, gum water (30 μm) or adhesive tape (30 μm) was coated on top of the absorbent layer to act as a confining layer. The main component of the gum water is polyvinyl alcohol, and its acoustic impedance is $0.16 \times 10^6$ g•cm$^{-2}$ s$^{-1}$[23]. This kind of confining layer has been used in Ref[10]. Adhesive tape, the main component of which is polypropylene, was another new confining layer used in our experiments[15], because of its higher acoustic impedance ($0.19 \times 10^6$ g•cm$^{-2}$ s$^{-1}$) [24].

An experimental setup similar to Ref [10] was used in our experiments, as shown in Fig. 1 A fs laser with a 800 nm wavelength was used. Its repetition rate can be set for between 1 Hz and 1 kHz; its pulse width between 80fs and 800fs; and its maximum energy can reach 500 μJ. 1 Hz was used to produce the 3D pitting on the metal foil. The laser was focused onto the specimens using a focusing lens with a 1000 mm focal length. By changing the distances between the specimens and the focal point, different laser spot sizes could be obtained on the specimens. The specimens were clamped on one support seat. Rubber gaskets were applied to help clamp the thin foil tightly. In order to investigate the influence of the clamping method on the mold-free shock process, fully clamping and single-side clamping modes were used, as is shown in Fig. 1. Furthermore, on the condition of single-side clamping, we changed the distances *d* between clamping end and laser impacting point, to obtain more clamping conditions. In this article, the laser spot sizes on the metal targets are about hundreds of micrometers. The hole diameter on the supporting seat is 15 mm, which is much greater than the laser spot sizes, and the hole edge has almost no effect on forming macro plastic deformation. Thus, the technique is actually an application of mold-free plastic forming technology.

During our experiment, to avoid directly ablating the target surface, we ensured that the absorbent layer was not completely ablated by choosing the appropriate experiment parameters. So, the shock wave launched on the absorbent surface, first transmitted through the remaining absorbent material and then reached the absorbent-target interface. A mismatch between the acoustic impedance of the two materials caused only part of the shock wave energy to penetrate through the interface into the target. This phenomenon would certainly weaken the final shock effect. However, in this article, we will not discuss the influence of this weakening effect, because it exists in all experiments. We do not believe that it will change the relevant common regularities.

After the laser shock experiment, the morphologies of the shocked specimens, along with any of the remaining absorbent and confining layers, were observed through a 3D profiler, a Keyence VHX-1000. Then, the specimens were cleaned with acetone to clear away the absorbent and confining layers. The profiles of the laser shocked pits were also observed through the Keyence VHX-1000. TEM was used to observe the microstructures in order to analyze the plastic deformation mechanism of the pure aluminum subjected to fs laser shock. Because the laser spot was only hundreds of micrometers, it was necessary to improve the convenience of conducting TEM by shock scanning some of the specimens through moving the specimens along the x and y axis to obtain the continuously shocked area, as is shown in Fig. 2. The laser repetition rate was tuned to 1 kHz. The moving parameters (speed or feeding distance) along the x and y axis were carefully adjusted to guarantee an overlapping rate of the laser beam. During laser scanning, the laser diameter was about 210 μm. So, the laser scanning speed along the x axis was set to about 100 mm/s and the feeding distance per step along the y axis was set to a laser diameter about 210 μm. Then, disks with the diameter 3 mm were directly cut from these shocked areas on the foil, and thinned to perforating from the specimen back surface, opposite to laser irradiated surface. So most of the laser shocked materials remained. Then, the perforated disks were observed on JEM-2100 operating at 200 kV. The procedure used to prepare the TEM specimen is shown in Fig. 2.

## 3. Results and discussions

### 3.1. The typical profiles of the pits obtained through mold-free FS laser shock

Fig. 3 presents the typical 3D profiles of the pits. The main process parameters were: laser energy 500 μJ per pulse, beam diameter 400 μm, and pulse duration 340fs. Gum water was used as the confining layer in this experiment. During the experiment, specimens were fully clamped as shown in Fig. 1 and specimens were impacted two times on the same point to increase the pit depths. In this experiment, the energy density was set to about 0.4 J/cm$^2$. Due to ultrashort pulse duration, the power density can still reach about $1.17 \times 10^{12}$ W/cm$^2$. So, following the procedures in Ref [15], the peak pressure is evaluated about 35.2 GPa (the acoustic impedance of the aluminum is about $1.5 \times 10^6$ g cm$^{-2}$ s$^{-1}$ [25]). With such a strong shock wave, obvious plastic deformations have been observed in our experiment.

Fig. 3(a) is a typical central profile line of the pits. It is found that the entrance diameter of the pit is much bigger than the laser beam size after mold-free laser shock process. We analyze that the pit is composed of two regions. One is directly produced by fs laser induced shock wave, which is located at the central of pit. Around the pit edge, there is the plastically bending region because shock pressure induces the bending moment. These two regions can be