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ORIGINAL ARTICLE

A mold-free laser shock micro-drawing forming process using Plasticine as the flexible support

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Abstract In this paper, a laser-generated shock wave was used to induce plastic deformation of metallic foils using Plasticine as a flexible support. In this new micro-drawing process, the laser-generated shock wave and the Plasticine are used to replace the conventional metal punch and mold. By undergoing large plastic deformation under the laser-generated shock wave, Plasticine accurately keeps the shape of the deformed workpiece, thereby improving the forming quality. Moreover, this is a damage-free forming process because the Plasticine is softer than metal foils. The feasibility of this new drawing process was conducted experimentally on aluminum, cooper, and titanium foils. The thickness distribution at the cross-section of the work piece was studied to evaluate the risk of crack. Meanwhile, the arrays of craters were fabricated on titanium foils. The results show that mold-free laser shock micro-drawing forming is an effective method to fabricate controlled micro-craters on metallic foils.

Keywords Metal forming · Plasticine · Mold-free · Laser shock micro-drawing · Material thinning

1 Introduction

The increasing demand for miniaturization in electronics and other devices has led to new manufacturing requirements [1–4]. As mass production manufacturing techniques and micro- and meso-forming have recently attracted the attention of both manufacturers and researchers [5–8]. Micro-sheet forming is the main process used to produce micro-sheet parts because of its low cost, small space requirement, and low-energy consumption.

The laser shock forming process is a new process based on laser-induced shock waves [9–11]. In contrast to traditional laser forming of metal sheets, where thermal mechanisms cause bending of the sheets, the shock process is based on a nonthermal forming process. The laser-induced shock wave can be used, in principle, for all metal sheet forming processes as long as the parts are within micro- or mesoscopic size ranges [8].

Laser shock forming technology for micro-sheet forming has been the subject of numerous investigations. Application of laser shock wave for metal sheet was attempted by Zhou et al. [12]. Zhou et al. [13, 14] deformed 0.3–0.9-mm-thick austenitic and ferritic stainless steel sheets using laser-induced shock waves. Subsequently, the forming behavior in the laser stretch-forming process was studied by Vollertsen et al. [8]. Recently, laser dynamic forming to deform metallic foils into micro-mold with widths ranging from 200 to 300 μm was achieved by Cheng et al. [15]; the geometries of the formed features on the foils conformed to those of the micro molds. More recently, Vollertsen et al. [16] utilized the laser deep drawing technique to deform plastically 20-μm-thick copper, aluminum, and stainless steel sheets into spherical cups of 1 mm height using a TEA-CO2 laser. Very recently, micro-channels with dimensions of 260 μm × 59 μm have been generated on 10-μm-thick copper foils by laser shock embossing technology [17]. Despite the differences in the above reported processes, all of these require the use of micro-molds to create micro-features on metal sheets or foils. However, it is difficult and expensive to fabricate the micro-molds using common methods such as micro-electrical discharge machining; ultra-precision micromachining; lithography, electroplating, and

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molding (LIGA); and laser ablation [18, 19]. In addition, mold fabrication is typically limited to specific composite micro-structures. Therefore, it is desirable to develop a mold-free manufacturing process that can produce micro-features on metal sheets or foils.

Nagarajan et al. [20] reported a new mold-free forming technology; they investigated the metal sheet deformation behavior under laser shock pressure using a flexible pad instead of a micro-mold. This work demonstrated that the micro mold is not essential for creating micro-features on the metal sheet. However, at present, the mold-free forming method still has a major shortcoming: The shape of the deformed workpiece cannot be accurately kept because of the tendency of the elastic material to release the elastic deformation and retract to its original shape once the load is removed.

To overcome this drawback, a plastic material should be used as the flexible support. Plasticine, the most widely used soft modeling material, which shows elastic plastic flow behavior, has been successfully used as a convenient model material to simulate the plastic deformation of metals in metal-forming processes for the last 40–50 years [21–24]. Because of its suitable material properties, there has been a high degree of interest in the applications of Plasticine in the mold-free process.

In this study, the Plasticine is used as the flexible support to replace other micro-mold. The physics of the mold-free laser shock micro-drawing forming process of metal foils is studied along with the influence of the laser energy and material type on deformation. The change in material thickness after forming is studied to investigate the risk of cracking. In addition, a 3×4 array of craters is fabricated to demonstrate the repeatability of this technique.

2 Forming mechanism

As illustrated in Fig. 1, the typical application of the mold-free laser shock micro-drawing forming process is carried out under a confined regime configuration. The target surface is locally coated with an ablative medium and then covered by a confining medium (such as K9 glass). When the surface of the work piece is irradiated by a high-energy focused and pulsed laser beam, the ablative medium is instantaneously vaporized into a high-temperature and high-pressure plasma. This ablated plasma expands from the workpiece surface and, in turn, exerts mechanical pressure on the surface, which would induce compressive waves in the workpiece. Plastic deformation of the workpiece would be induced by the shock wave. The ablative medium acts as the sacrificial material to avoid the thermal effect from heating the surface; the confining medium delays thermal expansion and confines the plasma against the surface of the target material, thus generating a higher pressure [25]. As shown in Fig. 1, the metal foil is placed over the surface of Plasticine which is expected to play the role of rigid mold. The Plasticine which can undergo large plastic deformation under loading is used as the flexible support. When the laser beam irradiates the metal foil surface, the downward shock loading would impart a downward inertia to the shocked region of the metal foil, and both the metal foil and the Plasticine would begin to deform. After the laser shock is stopped, this downward movement continues to make the shocked region plastically deformed because of the effect of inertia. Finally, the local plastic deformation in the action zone of the shock pressure would lead to the generation of micro-crater.

In this mold-free laser shock micro-drawing forming process, the laser beam is employed as the variable convex mold and the Plasticine is used as the flexible support to replace the micro-mold. The plasma induced by the circular spot is axisymmetric and spreads to the surrounding regions. Therefore, the formed metal foil is also axisymmetric. The Plasticine undergoes large plastic deformation along with the plastic deformation of the metal foil. In this way, the micro-features can be obtained without the assistance of a rigid micro-mold.

3 Experimental setup

For experiments, a short pulse Nd-YAG laser with a Gaussian distribution beam was used. The laser was operated at the repetition frequency of 10 Hz, and a pulse duration is approximately 8 ns. A wavelength of 1064 nm was selected to enable the laser beam to propagate further through water, owing to lower absorption of beam energy. The laser pulse was focused on the interaction area using a reflecting mirror and a focusing lens (f=100 mm), as shown in Fig. 2. To get the desired spot size, the workpiece was placed away from the focal point at an appropriate distance.

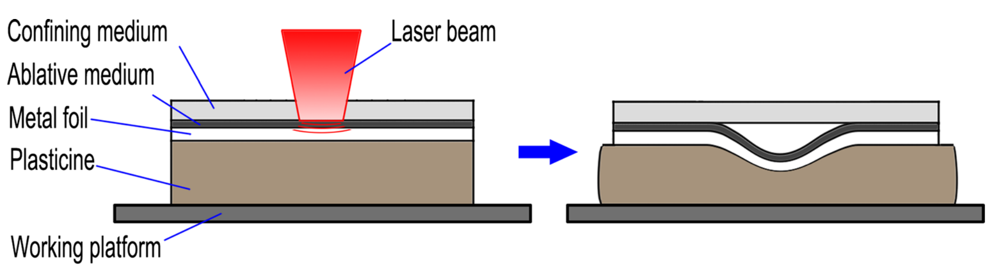
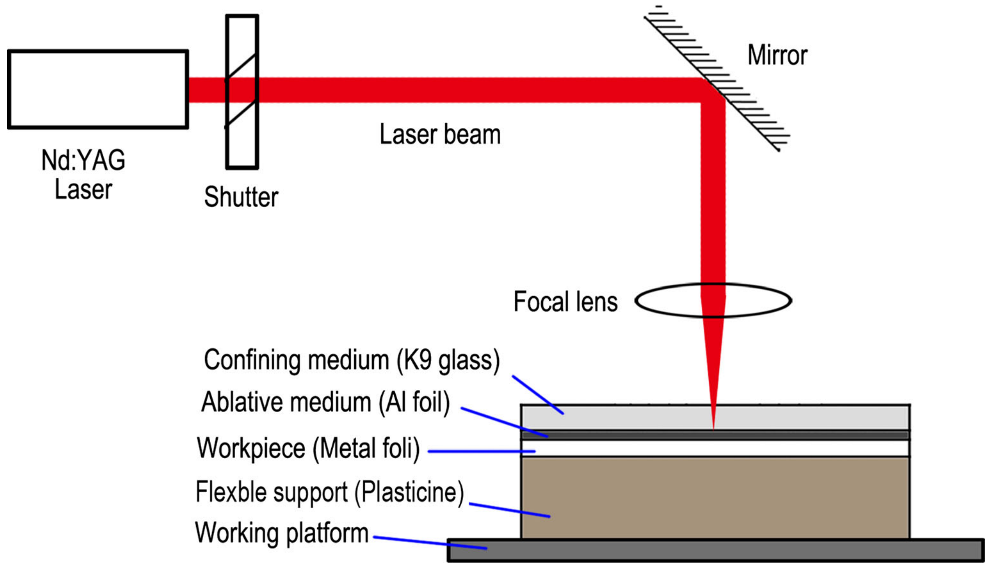


Fig. 1 Schematic of the mold-free laser shock micro-drawing forming

Fig. 2 The layout of experiment



To investigate the influence of the type of material on deformation, the mold-free laser shock micro-drawing forming process was conducted on aluminum, titanium, and copper foils. The samples were cut into squares from commercially supplied metal sheets. For the ablative medium, 17-μm-thick aluminum (99.9 % purity) was used, which has low vaporization energy and excellent laser absorption characteristics. Anhydrous alcohol was adopted to clean the surface of the workpiece. The flatness of workpiece and the ablative medium should be guaranteed. The confining medium (K9 glass) was firmly clamped to the ablative medium with a holder.

In this study, orange Plasticine (made by CYMO) was chosen as the flexible support. Because commercially available Plasticine contains a considerable number of air pockets, these air pockets should be removed from the material to establish a reasonable degree of homogeneity. After removing the air pockets by working the material through repeated rolling and folding operations, the Plasticine was made into a cylindrical shape and placed on the surface of the working platform, which was used as the flexible support. The experimental conditions and specimen parameters are summarized in Tables 1 and 2.

A digital microscope (Keyence VHX-1000) was employed to analyze the three-dimensional morphologies of the micro-craters on the metal foil surfaces, as well as the ablation state of the ablative medium.

Table 1 The detailed experimental conditions

Parameters	Value
Laser energy, E (mJ)	1020, 1380, 1690, 1900
Beam diameter, ΦD (mm)	1.6

4 Experimental results

4.1 Ablation states of ablative medium

Figure 3 shows the different ablation states of the ablative mediums (aluminum foil) under different laser energies. As shown in Fig. 3a–d, it can be seen that the ablation states of ablative mediums would be more serious with the increasing laser pulse energies (from 1020 to 1900 mJ). Besides, some serious ablation states can be obtained with 1690 and 1900 mJ laser energies. However, the ablative mediums still remain intact with no cracks apparent after forming. This shows that the existence of the serious ablation state would not exert unfavorable influence on workpiece quality.

4.2 3D micro-topography of the workpiece

Figure 4a, b shows the measured surface 3D micro-topography of the aluminum sample in the laser shock region. It can be seen that a smooth crater was formed with no signs of melting, burning, or ablation, meaning that the forming process is non-thermal. As seen, the sample generates plastic deformation and the workpiece has a high spatial resolution at the micron-level. The ablative medium can protect the workpiece from thermal effects such that the purely mechanical effects are induced.

Table 2 The detailed data about the metal foils (used as workpiece) in the experiments

The type of material	Thickness (μm)
Aluminum	17
Cooper	18
	30
Titanium alloys	35

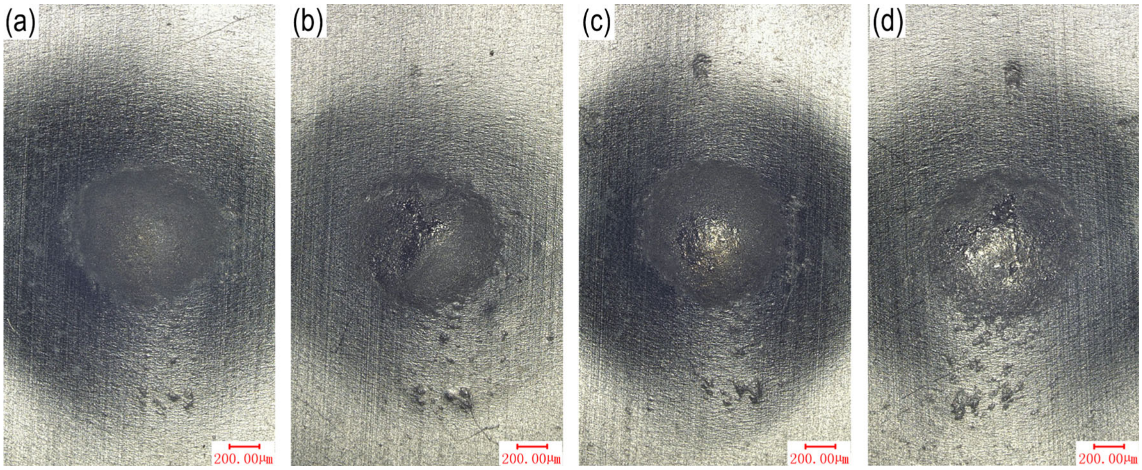


Fig. 3 The ablation states of ablative mediums (aluminum foil) with 17-μm-thick aluminum foils as workpieces: **a** with 1020 mJ energy, **b** with 1380 mJ energy, **c** with 1690 mJ energy, and **d** with 1900 mJ energy

Figure 4c shows the surface profile curve of the sample surface crater. It is noteworthy that the deformation depth reaches 321.1 μm with the maximum deformation depth occurring at the center of the crater. The deformation force exerted on the metal foil depends on the laser-induced shock loading. In addition, the formed micro-crater can increase the fatigue resistance of the workpiece.

4.3 Influence of laser energy and type of material

In the mold-free laser shock micro-drawing forming process, a laser beam is employed as the variable convex mold; the properties of which will have influences on the crater profile. Therefore, it is necessary to conduct experiments to analyze the influence of the laser energy on the deformation of thin metal foils.

The mold-free laser shock micro-drawing forming process was performed on aluminum, cooper, and titanium foils. The experiments were repeated three times, and the average values were adopted to draw Fig. 5.

The results obtained for a 17-μm-thick aluminum foil workpiece are shown in Fig. 5a; the crater depths and widths increase with increasing laser energy from 1020 to 1900 mJ. It is understandable that the increase of the micro-crater depth

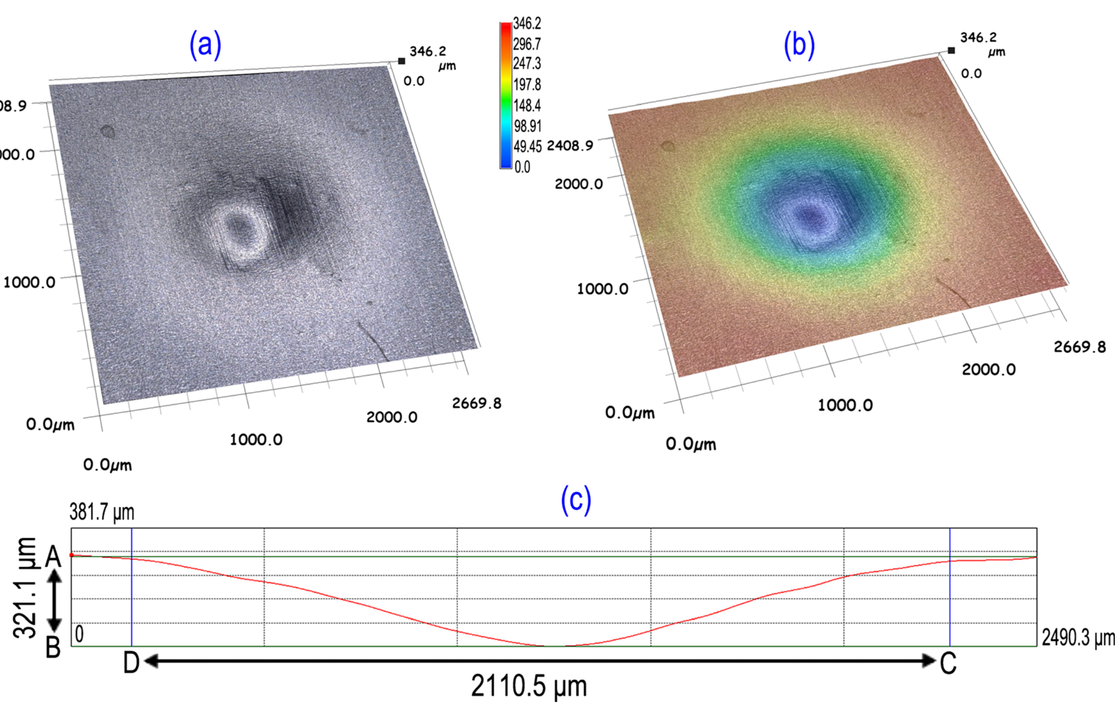


Fig. 4 Micro-crater in the shock region (a laser of 1020 mJ energy on a 17-μm-thick Al sample). **a** The magnification micro-topography of micro-crater; **b** 3D plot of the formed crater; **c** surface profile curve of the crater

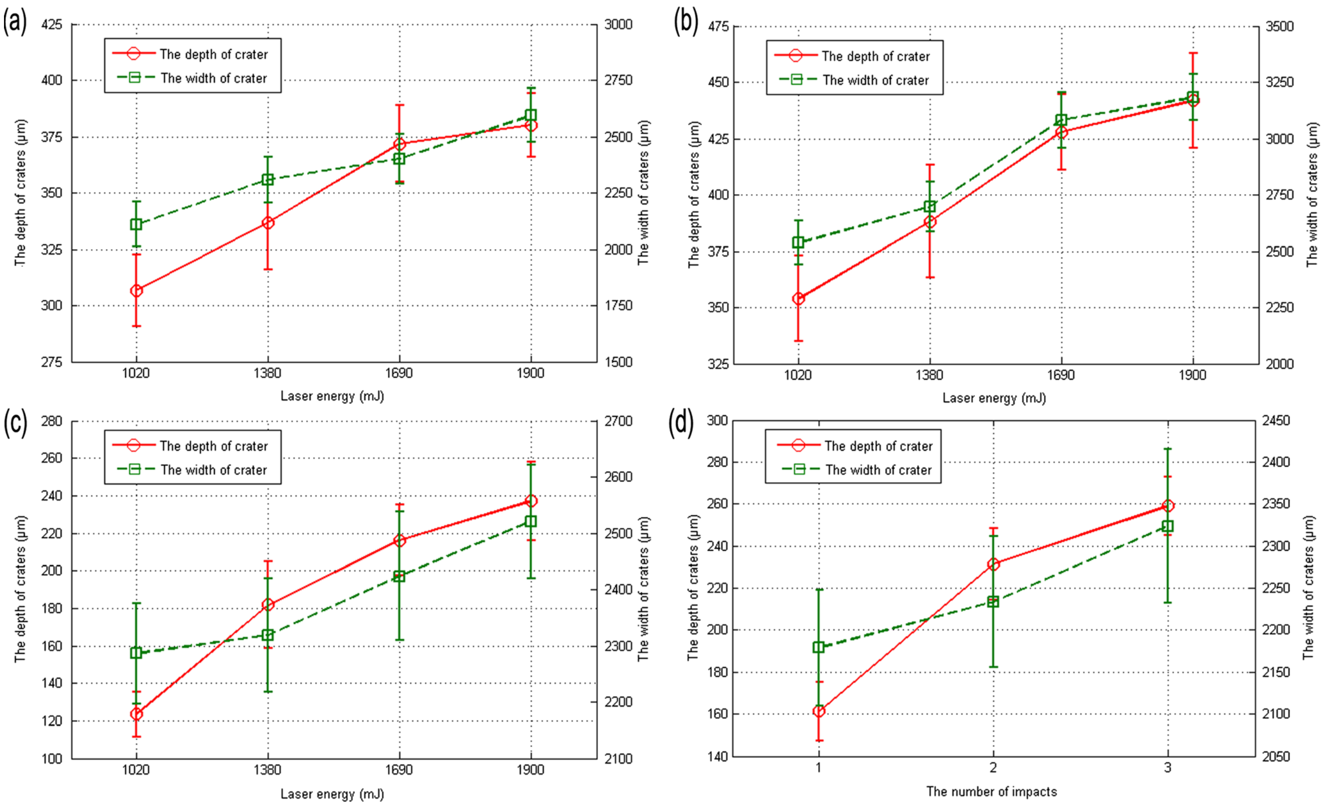


Fig. 5 **a** The crater depth and crater width variation with increasing energies (1020, 1380, 1690, and 1900 mJ) for a laser on a 17-μm-thick aluminum foil. **b** The crater depth and crater width variation with increasing energies (1020, 1380, 1690, and 1900 mJ) for a laser on a 18-μm-thick cooper foil. **c** The crater depth and crater width variation with increasing energies (1020, 1380, 1690, and 1900 mJ) for a laser on a 30-μm-thick cooper foil. **d** The crater depth and crater width variation with increasing impact numbers (*1*, *2*, and *3*) for a laser on a 35-μm-thick titanium foil

can be explained by the increased pressure. It is worth noting that there is only a relatively small change in the width of the crater which appears to reach a limit. One reason for this could be that the width of the crater is related to laser spot. When the surface of the ablative medium is irradiated by the laser, a shock wave is caused by the expansion of the plasma generated. Despite the plasma being confined by the confining medium, outward expansion of the plasma is inevitable. This becomes more significant as affected area increases. Therefore, the crater width reaches itself a limit.

Figure 5b displays the changes in the crater depth and width shown in 18-μm-thick cooper foils. It can be seen that the trends in the changes of depth and width are the same as those for the aluminum foils. The crater depth in the copper foils is greater than that in the aluminum foils under the same laser energy. It is assumed that the differences in material properties of the two metals are responsible for this difference. The cooper foils are more easily deformed than aluminum foils.

To investigate the influence of foil thickness on the deformation, 30-μm-thick cooper foils were also used. As shown in Fig. 5c, a smaller crater was obtained when the 30-μm-thick cooper foils were used in the experiments. This is because metal foils become harder to deform with increasing thickness.

Titanium displays poor wear resistance, and its fatigue performance depends to a large extent on its surface properties [26]. Nevertheless, titanium is widely used in the aerospace field (jet-engine blades and gas turbine parts) as well as for tools and sport products because of its favorable properties such as high specific strength and excellent corrosion resistance [27]. It would therefore be useful and interesting to study the formation of micro-crater in titanium using the mold-free laser shock micro-drawing forming process. We used 35-μm-thick titanium foils as the workpiece. Multiple impacts were applied to the titanium foil to obtain suitable craters, as shown in Fig. 5d. The 2D and 3D morphologies of the titanium workpiece after one impact are shown in Fig. 6, revealing the high-surface quality of the workpiece. The depth of the crater reached near 160 μm and the width was about 2325 μm. It can be assumed that various deformations and crater profiles in different metal foils can be achieved by using the method of mold-free laser shock micro-drawing forming simply by adjustment of the laser processing parameters.

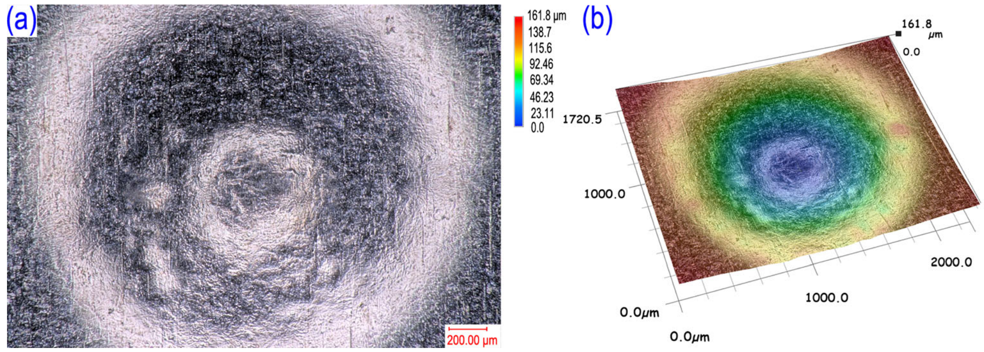


Fig. 6 The surface of titanium workpiece after one impact: **a** The magnification micro-topography of micro-crater; **b** 3D plot of the formed crater

4.4 Thickness distribution

Because the thinning of the material introduces the risk of cracking, it is reasonable to investigate the foil thickness distribution to evaluate the risk of cracking. Figure 7a, b shows the 3D micro-topographies of the craters formed on the titanium foil with three impacts measured from the top and the bottom surfaces. A comparison of the crater profiles measured from the top and the bottom surfaces is provided in Fig. 7c to evaluate the thinning trend. The two curves were drawn into one figure with 35-μm offsets in the horizontal direction. It is evident that there was a change in thickness, especially in the bell zone of the crater. The thickness in the bell zone of the crater reached 25.67 μm, which is thinner than the original material (35 μm). The center zone of the crater was 30.33 μm thick, which means there was only a small reduction in the thickness of the crater in the center zone. This can be explained as follows: In the mold-free laser shock micro-drawing forming process, the workpiece would generate material flow to form the micro-crater under the action of laser-induced wave. The Plasticine undergoes large plastic deformation along with the plastic deformation of the metal foil. The outer material of the laser-irradiated zone would be bent and then drawn downward. The inner material is also pushed downwards to form the crater, and a tension force is applied at the bell of the crater. Because of the downward material flow, the thickness at the bell of the crater is reduced. It can be inferred that there is a risk of cracking in the thinned zone if the laser energy is too large.

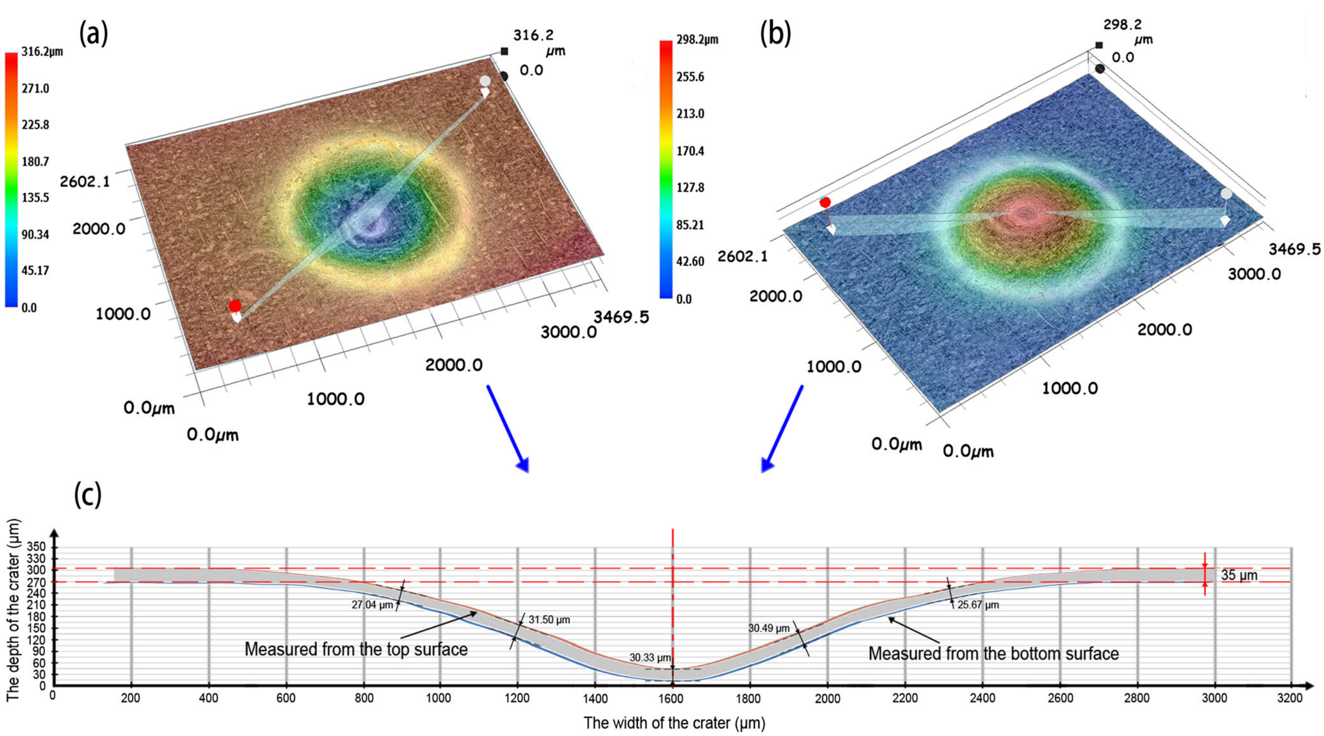


Fig. 7 **a** 3D micro-topography of the formed crater measured from the top surface (three impacts on the 35-μm-thick titanium foil). **b** 3D micro-topography of the formed crater measured from the bottom surface (three impacts on the 35-μm-thick titanium foil). **c** Comparison of two crater profiles to evaluate the thinning trend: One curve was measured from the top surface and another curve was measured from the bottom surface (three impacts on the 35-μm-thick titanium foil)

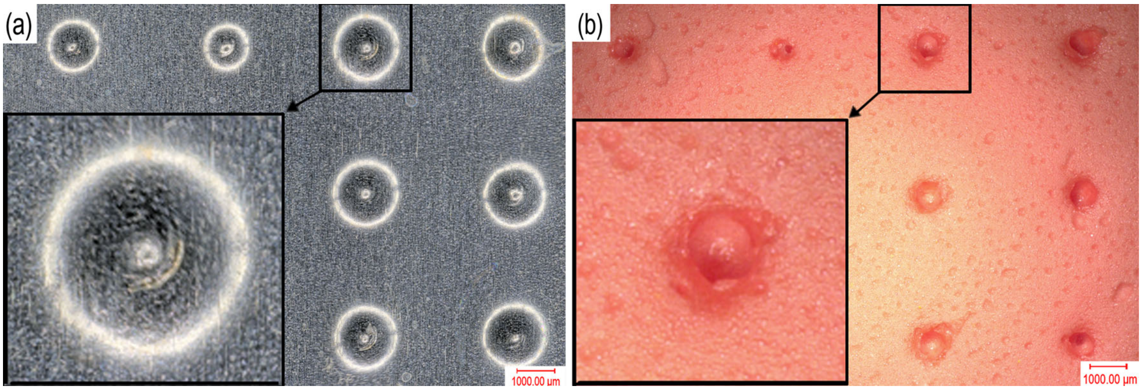


Fig. 8 **a** The photograph of an array of craters fabricated on the surface of Plasticine. **b** The photograph of an array of craters fabricated on the surface of titanium foil

4.5 Fabrication of crater arrays

Figure 8a shows the photograph of an array of craters fabricated on the surface of titanium foil. As the crater diameter was greater than 1 mm, a pitch length of 3 mm was used to avoid interference of shock waves propagating from adjacent irradiation spots. Each column of craters was fabricated under the same laser energy to evaluate the repeatability of the process. It can be seen that the micro-craters on each column are uniform repeatability, indicating that mold-free laser shock micro-drawing forming is an effective method to fabricate controlled micro-cater arrays. Besides, from left to right, the workpieces were loaded with laser energies from 1020 to 1900 mJ to fabricate the craters. Craters of different sizes were formed, indicating that the deformation of the workpiece and the shape of the crater can be adjusted simply by changing laser energy. Figure 8b shows the photograph of an array of craters fabricated on the surface of Plasticine. The micro-crater over the Plasticine surface is gradually formed along with increasing laser energy. That is, to say, the final shape of the thin metal foil is determined by the combined effects of the laser beam properties and the surface topography of the Plasticine.

As described above, it is important to highlight the obvious advantages of replacing of rigid mold with Plasticine. On one hand, it is convenient to use Plasticine as the flexible support because it is easy to handle and shape. This process can be regarded as damage-free forming process because of the low hardness value of Plasticine compared with that of the metal workpiece. In addition, the presence of a compressive stress state after processing can reduce the springback deformation of the workpiece, and the shape of the deformed work piece can be accurately retained because the plastic material used as the flexible support can retains its shape even when the load is removed. The contribution of these factors enables precis forming. On the other hand, it was reported by Li et al. [28] that material fracture would take place once the forming velocity of the metal foil exceeds a critical velocity. However, in our mold-free process, the Plasticine is placed under and supports the workpiece. Therefore, the forming velocity of the metal foil can be controlled, and the occurrence of fractures can be reduced because the deformation of the metal foil is controlled by Plasticine.

5 Conclusions

A mold-free laser shock micro-drawing forming process using Plasticine as the flexible support was developed to fabricate micro-features on metallic foils. Micro-craters were obtained on both the metal foils and the Plasticine. The crater profiles on Plasticine surface, which underwent a large plastic deformation, changed with the deformation of the metal foils and laser energy, and a compressive stress was induced in the workpiece. Therefore, the shapes of the deformed workpieces could be accurately retained and springback deformations could be reduced. Moreover, this is a damage-free forming process because the Plasticine used as the flexible support is softer than the metal foils.

The influence of laser energy and the type of material in the process were also studied. With the increasing laser energy, the depth and width of the formed micro-craters increased, with the width reaching a limiting value at high energy. Moreover, the change of material thickness was studied to evaluate the risk of cracking. After mold-free laser shock forming, the material at the bell zone of the crater was thinned. It can be inferred that there is a risk of cracking in the thinned zone if the laser energy is too large. In addition, an array of craters was successfully fabricated on titanium foil, demonstrating that the mold-free laser shock micro-drawing forming is effective in fabricating controlled micro-cater arrays in metallic foils.

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