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Micro-dimple array fabricated on surface of Ti6Al4V with a masked laser ablation method in air and water

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A B S T R A C T

A method called masked laser ablation (MLA) was proposed to fabricate a micro-dimple array on a substrate surface with a pulsed Nd:YAG laser. Micro-dimple arrays were successfully fabricated on the surface of Ti6Al4V samples both in air and water. The aim of this paper was to investigate the influence of processing parameters on the morphology of micro-dimples, spatter deposition, micro-dimple depth and ablation rate. Contrast experiments were conducted to evaluate the effects of masks. Results showed that the shape of micro-dimples in air could be affected by the overlapping of spatter between the adjacent micro-dimples, while in water it is nearly copied from the mask. The bottom of the micro-dimple fabricated in water was coarse but the periphery was clean. The spatter deposition extremely depended on the laser intensity, pulse numbers and surroundings. Discussions about the existence of masks were carried on.

1. Introduction

The fabrication of micro-texturing has aroused considerable interest in recent years due to its wide industrial applications, such as the amelioration of wear performance [1,2], improvement of fuel efficiency [3], manufacturing superhydrophobic surfaces [4] and serving as a mold for micro-lens fabrication [5].

In general, the present manufacturing approaches of micro-dimples can be classified into mechanical methods [6,7], etching technologies [8,9] and laser based methods [10–13]. Compared with the other two methods, laser based methods have unique advantages such as absence of tool wear, friendly environment, ease of operation, and the ability to produce micro-dimples in a wide variety of material. Laser based methods include laser shock processing (LSP) [10,11] and laser ablation [12,13]. LSP is a new processing technique, which generates plastic deformation on the surface of metal sample using a laser-induced shockwave with high pressure [14]. However, LSP is still limited in the laboratory due to its low productivity and inability to produce deep micro-dimples [11]. The laser ablation method with nanosecond pulse laser is the most reported technique for the fabrication of micro-dimples. Segu [13] fabricates multi-scale texture dimples with specific formula arrays on AISI 52100 steel with a pulsed Nd:YAG laser. Vilhena [15] fabricates well-defined micro-dimples on 100Cr6 steel samples with laser ablation method. However, during laser ablation processing, micro-dimples are inherently associated with spatter deposition due to the expulsion of ejected material, which subsequently recondenses and adheres on the surface around the micro-dimple periphery [15,16]. Moreover, an overlapping of adjacent spatter will lead to the increase of spatter bonding strengths when fabricating closely spaced array structures [17].

Spatter deposition must be removed subsequently in practice. Numerous techniques based on chemical and physical anti-spatter mechanisms have been presented to either reduce or prevent spatter. Demir [18] used a $H_2SO_4 + HF$ aqueous solution to etch the generated spatter on titanium sample. Their work shows that chemical techniques can effectively clear the spatter but the sample surface is also inevitably affected. Mishra [19] attempted to manually polish the spatter from the textured surface. However, such a physical based method would bring about additional damage such as a slight curvature change of the surface. Besides, the more the spatter deposits, the more production time and costs are created with these methods. Therefore, it is important to fabricate micro-dimple arrays with as little spatter deposition as possible.

Ti6Al4V titanium alloy has various applications such as in aerospace and medical equipment due to its combination of high strength-to-weight ratio, excellent corrosion resistance and biocompatibility [20]. In this paper, a method called masked laser ablation (MLA) is developed to produce a micro-dimple array on the surface of a Ti6Al4V sample in air and in running water. Technological parameters on the morphology of micro-dimples, spatter deposition and ablation rate in air and

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running water are studied. The possible mechanisms in these two surroundings are also discussed. The results of this work can provide an effective way to reduce the spatter deposition in the laser ablation method.

2. Experimental procedures

2.1. Principle of MLA

The principle of MLA is illustrated in Fig. 1(a). A mask with holes is fixed on the surface of the workpiece with a clamp system. A laser beam is passed through an attenuator and a homogenizer, and then it is focused by a long focal length lens. The homogenizer used here is to modulate the spatial distribution of the laser beam to be a homogeneous intensity profile. When the focused laser pulse passes through the mask, it is divided into several micro-scale laser beams with intended shape. Finally, these micro-scale laser beams arrive at the workpiece. They ablate the surface of workpiece, and then micro-dimple arrays form.

2.2. Material preparation and MLA parameters

Ti6Al4V samples were sectioned into rectangular-shape samples with dimensions of 15 mm × 50 mm × 3 mm (width × length × thickness) for micro-dimple fabrication. The chemical composition of the Ti6Al4V samples is listed in Table 1. In order to improve surface finish before micro-dimple fabrication, each sample was ground with different grades of SiC paper (150# to 1200#), followed by cleaning with 97% ethanol in an ultrasonic bath for 30 min.

A 304 stainless steel sheet with a thickness of 250 μm was used as a mask. A 3 × 3 hole array with 680 μm hole pitch was drilled on the mask, and each of the holes was a rounded square hole with a width of about 500 μm and a fillet radius of about 50 μm as shown in Fig. 1(b). The mask hole is fabricated with a laser cutting system.

MLA experiments were performed using a Q-switched Nd:YAG laser with a wavelength of 1064 nm, and the full width at half maximum (FWHM) of the pulses were about 10 ns. The laser spot diameter was about 3 mm when it arrived at the workpiece. Laser energy of 2 J, 5 J, and 8 J pulse were used in MLA experiments, and the calculated laser power density was 2.83 GW/cm^2, 7.07 GW/cm^2, and 11.32 GW/cm^2 respectively. MLA experiments were conducted both in air and water. Running water with a thickness of about 1.5 mm was used when MLA

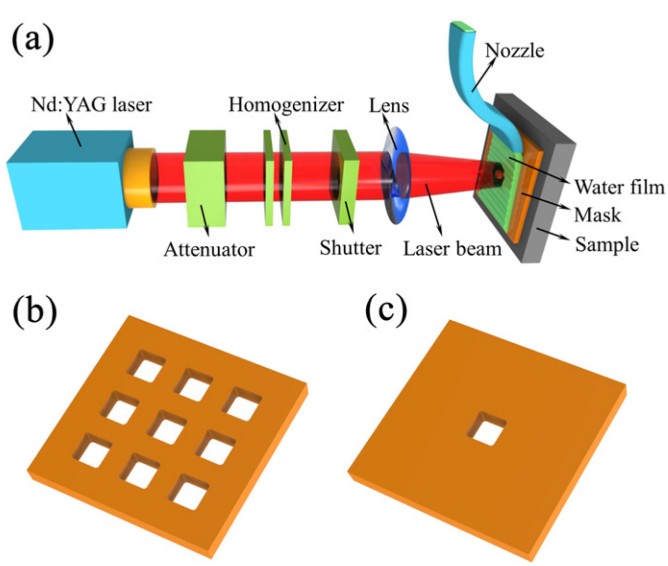

Fig. 1. (a) Schematic of experiment setup used for micro-dimple fabrication; (b) mask with hole array; (c) mask with single hole.

Table 1
Chemical composition of Ti6Al4V.

Composition	Al	V	Fe	Si	C	N	H	O	Ti
Percent (wt.%)	5.5–6.8	3.5–4.5	0.3	0.15	0.1	0.04	0.015	0.2	Other

was conducted in water, with the speed of about 2 cm/s. MLA in air was performed under atmospheric pressure.

As the spatter would overlap between adjacent micro-dimples, a single micro-dimple was fabricated with the single-hole mask, used to evaluate the effect of MLA, as shown in Fig. 1(c). The dimension of the single hole was the same as the holes of the array.

2.3. Measurement methods

The morphology of micro-dimples before post processing was characterized by a scanning electron microscopy (JEOL-JSM-7001F).

The spatter deposition area was measured in the original captured SEM image. Considering the irregular shape of spatter deposition, it was hard and inaccurate to calculate its area by manual work, so a professional photograph processing software, called ImageJ, was used to measure the area automatically [21].

The depth of the micro-dimple was measured with the help of a contactless image measuring system of true color confocal microscope with a scanning stage (Axio-CSM-700). For each process parameter, five samples were fabricated and the average value was used.

3. Results and discussion

3.1. Morphology of a micro-dimple

Fig. 2 shows a micro-dimple array fabricated on the surface of a Ti6Al4V sample at the same laser parameters by MLA in air and water. As shown in Fig. 2(a), the peripheries of micro-dimples in air are encircled with spatter deposited onto the sample surface. It is found that the micro-dimples are likely to be circular other than square, even though the hole of the mask is a rounded square. This may be due to the significant overlapping of spatter between the adjacent micro-dimples. Therefore, we cannot obtain the intended shape of micro-dimples by MLA in air. Traces of spatter deposition around the micro-dimple periphery are not seen in water, as shown in Fig. 2(b). It is obvious that the micro-dimples have a rounded square shape and almost the same as the shape of the hole drilled on the mask, unlike the phenomenon in air.

To exclude the overlapping effects of neighboring micro-dimples, a single micro-dimple fabricated with a single-hole mask is used to investigate the MLA technology in more detail.

Fig. 3 shows a single micro-dimple fabricated in air and water by 9 laser pulses with a laser intensity of 11.32 GW/cm^2. Fig. 3(a) and (b) show the general view of micro-dimple, Fig. 3(c) and (d) show the enlarged depiction of the micro-dimple's bottom, and Fig. 3(e) and (f) show the enlarged depiction of the micro-dimple's periphery. Dramatically different morphologies in the microstructures at the bottom of micro-dimple, rim of micro-dimple, and spatter deposition around the micro-dimple periphery can be observed clearly from these pictures. In air, it can be seen that the micro-dimple bottom is smooth characterized with some periodic ripples, as shown in Fig. 3(a) and (c), which may be due to the interaction between the molten material and the laser induced surface plasma wave [22]. A large amount of spatter deposition radially piles up on the periphery of the micro-dimple, as shown in Fig. 3(e). The trace of molten material ejection is obviously away from the micro-dimple, and the border of the micro-dimple almost cannot be identified where the spatter deposition sticks together in clumps by the mask. To some extent, the mask can prevent the molten material from splashing along the radial direction. A rather chiseled rim of micro-dimple can be found between the smooth