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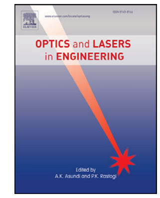

The influence of the focus position on laser machining and laser micro-structuring monocrystalline diamond surface

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ABSTRACT

Micro-structured surface on diamond is widely used in microelectronics, optical elements, MEMS and NEMS components, ultra-precision machining tools, etc. The efficient micro-structuring of diamond material is still a challenging task. In this article, the influence of the focus position on laser machining and laser micro-structuring monocrystalline diamond surface were researched. At the beginning, the ablation threshold and its incubation effect of monocrystalline diamond were determined and discussed. As the accumulated laser pulses ranged from 40 to 5000, the laser ablation threshold decreased from 1.48 J/cm^2 to 0.97 J/cm^2. Subsequently, the variation of the ablation width and ablation depth in laser machining were studied. With enough pulse energy, the ablation width mainly depended on the laser propagation attributes while the ablation depth was a complex function of the focus position. Raman analysis was used to detect the variation of the laser machined diamond surface after the laser machining experiments. Graphite formation was discovered on the machined diamond surface and graphitization was enhanced after the defocusing quantity exceeded 45 µm. At last, several micro-structured surfaces were successfully fabricated on diamond surface with the defined micro-structure patterns and structuring ratios just by adjusting the defocusing quantity. The experimental structuring ratio was consistent with the theoretical analysis.

1. Introduction

Diamond is widely used in many industrial and scientific applications, such as electronic devices [1], medical products [2], optical elements [3], MEMS and NEMS components [4], ultra-precision machining tools [5], etc. Its excellent properties, like the extremely high mechanical hardness and high elastic modulus [6], also make diamond very difficult to process. However, the extensive applications of diamond issued an urgent demand of high precision and high accuracy micro-structuring diamond, especially in the emerging micro-structured diamond tool researches [7–12]. Laser micro-structured diamond tools have been proved effective for improving the machining performance in turning or grinding difficult-to-machine materials.

Pulsed laser beam machining is widely used to prepare micro-structured diamond tools owing to its great advantages such as non-contact machining, no sample geometry restriction, no tool wear, cost reduction and small heat affected zone [13]. By means of laser beam micro-machining, Axinte et al. [8–10] developed a novel diamond grinding tool, which featured ordered micro-structure arrays, and reported a significant improvement of the grinding performance, comparing with traditional tools. With laser micro-structured coarse-grained diamond grinding wheel, Guo et al. [7] achieved a significant reduction of the subsurface damage depth of ground optical glass surface. Laser micro-structuring also considerably improved the machining performance of polycrystalline diamond tool and reduced the cutting force and the tool-chip contact length in turning titanium alloy [12]. As aforementioned discussion, laser micro-structuring is promising in improving the machining performance of diamond machining tools. For laser beam machining diamond material, many research attentions have been paid to the micro-structure pattern design and its influence on machining performance [7–10], the material removal mechanism of different pulsed lasers [14–18]. More research efforts are still needed for the efficient micro-structuring of diamond surface with the defined micro-structure geometries, especially in the applications of micro-structured diamond tools with large area micro-structured surface.

In this paper, the influence of the focus position on laser machining mono-crystalline diamond and its application in efficient micro-structuring of diamond surface were studied. The ablation threshold of monocrystalline diamond and its incubation effect were determined and discussed at first. Subsequently, the influence of the defocusing

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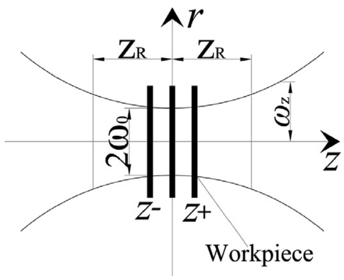

Fig. 1. Schematic of the laser beam propagation.

quantity on ablation width and depth was studied and presented. After that, Raman analysis was used to probe the alteration of diamond surfaces machined at different defocusing quantities. At last, some different micro-structure surfaces were successfully fabricated on diamond surface with the deserved parameters by adjusting the focus position.

2. Theory analysis

2.1. Laser ablation threshold

In pulsed laser machining, material removal occurred only when the incident laser fluence was greater than the ablation threshold of the sample surface. For the laser with a Gaussian profile, the ablation threshold could be determined by the method introduced by Liu [19]. The laser fluence along with the spot radius can be written as [20]:

$$I(r) = I_0 \cdot \exp(-2r^2/\omega_0^2) \tag{1}$$

where, I(r) is the laser fluence at radius r, ω_0 is the focus radius, I_0 is the maximum laser fluence at the spot center and can be calculated by Eq. (2),

$$I_0 = 2P/\pi\omega_0^2 f_p \tag{2}$$

where, P is the average laser power, f_p is the laser repetition frequency.

Laser pulses would remove material within a diameter D at which the laser fluence equaled to the ablation threshold I_{th}. Replacing the I(r) in Eq. (1) with I_{th} and integrating Eq. (2) into Eq. (1), the theoretical ablation diameter D ($D = 2$r) obtained with the laser power P could be determined by

$$D^2 = 2\omega_0^2 \ln(P/P_{th}) \tag{3}$$

P_{th} is the critical laser power at which material removal only occurs at the spot center. By fitting Eq. (3) with the ablation diameters machined with different laser powers, the laser ablation threshold I_{th} and the focus radius ω_0 could be obtained. Due to the well-known incubation effect [21,22], the ablation threshold nonlinearly decreases along the accumulated laser pulse number N. Several nonlinear functions have been used to describe the incubation effect in multi-pulse laser machining [22]. In this paper, the incubation effect is described by Eq. (4) which has been proved a well description of the incubation effect of dielectric material [23].

$$I_{th}(N) = I_{th,\infty} + \left[I_{th,1} - I_{th,\infty}\right]e^{-k(N-1)} \tag{4}$$

where, $I_{\rm th}$(N) is the ablation threshold for an arbitrary number of pulses, $I_{\rm th,\infty}$ is the multi-pulse ablation threshold for infinite pulses, $I_{\rm th,1}$ is the single pulse ablation threshold, J/cm^2, k is the incubation coefficient.

2.2. The influence of defocusing position on ablation depth

As shown in Fig. 1, in a focused Gaussian laser beam, the laser spot radius at a defocusing position z is determined by Eq. (5) [24]

$$\omega_z = \omega_0 \cdot \left[1 + \left(z/Z_R\right)^2\right]^{1/2} \tag{5}$$

where, Z_R is the Rayleigh length [25].

Not only in ultra-short laser machining [26], but also in nanosecond laser machining, the ablation rate of laser pulse has been proved logarithmically depending on the laser fluence [27,28]. The ablation rate h can be described by Eq. (6),

$$h = \delta \ln\left[I/I_{th}(N)\right] \tag{6}$$

where, I is the laser fluence, I_{th}(N) is the laser ablation threshold, δ is the coefficient related to the optical penetration depth or the electron heat diffusion depth. With the increasing of the defocusing quantity, the maximum laser fluence at the laser spot center is expressed as

$$I_z = I_0 \cdot \omega_0^2/\omega_z^2 \tag{7}$$

In laser scanning, the equivalent laser pulses, which is the accumulated pulse number at a point on the scanning path, could be determined by

$$N = 2\omega_z f_p/v \tag{8}$$

where, N is the equivalent laser pulses, and v is the scanning velocity [29]. Thus, the equivalent laser pulse number N_z in laser scanning at a defocusing position z is

$$N_z = 2\omega_0 \cdot \left[1 + \left(z/z_R\right)^2\right]^{1/2} \cdot f_p/v \tag{9}$$

Owing to the Gaussian profile of the laser beam, the ablation depth would smoothly decrease with spot radius and the maximum ablation depth would be achieved at the laser spot center. In this paper, the maximum depth is defined as the ablation depth in laser machining. After determining the equivalent laser pulses, the ablation depth in laser micro-structuring at a defocusing position z could be obtained by integrating the Eqs. (5) and (9) into (10).

$$H_z = N \cdot h_z = N_z \cdot \delta \cdot \ln\left[I_z/I_{th}(N)\right] \tag{10}$$

Basing on the calculation of Eq. (10), the ablation depth could be determined.

2.3. The calculation of the structuring ratio

As the actual contact area directly influenced the functional performance of different micro-structured surfaces, the structuring ratio was used to describe micro-structured surfaces in this paper. The structuring ratio was defined as the ratio of the unaffected surface area to the total surface area. Here, in percent is adopted to describe the micro-structured surface. The structuring ratio can be calculated as:

$$\eta = \left(A_{total} - A_{struc}\right)/A_{total} \tag{11}$$

As the laser beam spot size can continuously change with the defocusing quantity z, a larger ablation area is possible to be achieved at a defocusing position by laser machining with enough pulse energy. In other words, micro-structured surfaces with designed specific structuring ratio could be fabricated just by adjusting the defocusing quantity and without any change of the laser machining system.

In this paper, the typical micro-structured surfaces included the wave line micro-structure, the parallel line micro-structure and the cross line micro-structure were researched and fabricated, as shown in Fig. 2. The angle of the wave line micro-structure is 45°. For simplifying the experiments, the groove pitch a is set as 50 µm. The focus radius and the Rayleigh length of the laser beam is about 10.7 µm and 23.7 µm, respectively. The structuring ratios of the three typical surfaces could be calculated by

$$\eta_1 = 1 - \sqrt{2}w/a,\ \eta_2 = 1 - w_z/a,\ \eta_3 = \left(a - w_z\right)^2/a^2 \tag{12}$$

3. Experimental details

The laser micro-machining system is shown in Fig. 3. The translation stage had a moving accuracy of 0.1 µm in the $X/Y/Z$ direction. The sub-nanosecond pulse laser worked at the wavelength 532 nm, the