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Material removal effect of microchannel processing by femtosecond laser

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A R T I C L E   I N F O

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A B S T R A C T

Material processing using ultra-short-pulse laser is widely used in the field of micromachining, especially for the precision processing of hard and brittle materials. This paper reports a theoretical and experimental study of the ablation characteristics of a silicon wafer under micromachining using a femtosecond laser. The ablation morphology of the silicon wafer surface is surveyed by a detection test with an optical microscope. First, according to the relationship between the diameter of the ablation holes and the incident laser power, the ablation threshold of the silicon wafer is found to be 0.227 J/cm^2. Second, the influence of various laser parameters on the size of the ablation microstructure is studied and the ablation morphology is analyzed. Furthermore, a mathematical model is proposed that can calculate the ablation depth per time for a given laser fluence and scanning velocity. Finally, a microchannel milling test is carried out on the micromachining center. The effectiveness and accuracy of the proposed models are verified by comparing the estimated depth to the actual measured results.

1. Introduction

In recent years, femtosecond lasers have been shown to offer unique advantages in material processing because of their extremely short pulse time and ultra-high peak power [1]. Femtosecond lasers can process both hard, brittle, and transparent materials with high precision. As a result, such materials can be used in the field of precision machining. Research on ultrashort pulse lasers acting on materials has mainly focused on the damage threshold of typical materials and the material removal mechanism [2–3]. Because the damage threshold is an important factor in the mechanism of material removal, the relationship between the laser and the threshold power plays a significant role in the shape, size, and quality of the microstructure during processing [4].

Many academics and researchers have studied the damage threshold and discussed how it affects the material removal mechanism and processing efficiency. Huang [5] performed an ablation test on the Cr12 metal. Based on the test conditions, the area push algorithm was applied to calculate the damage threshold of metal materials. The results show that the monopulse damage threshold of Cr12 using a laser with a 10-ns pulse width and a beam waist radius of 54.5 μm is 0.20 J/cm^2. Tan et al. [6] analyzed different ways of drilling holes using a femtosecond laser. Based on Cooper's experiments on multipulse femtosecond lasers, they acquired the ablation threshold value of copper according to threshold theory. This experiment demonstrates that laser parameters such as the monopulse power, pulse number, and defocusing position affect the radius, roundness, taper, and ablation rate of microholes. The research group led by Zoppel [7] studied the ablation properties of SiC using an excimer laser with 34-ns pulse width and 248-nm wavelength and a femtosecond laser with 300-fs pulse width and 248 nm wave length. The ablation results indicate thresholds of 0.85 J/cm^2 and 0.13 J/cm^2, respectively. The authors concluded that the reduction in threshold value might be caused by the multi-photon absorption effect. In addition, some theories on the material removal mechanism have been proposed. Liu et al. [8] used the multiphoton absorption effect to explain the energy absorption process when a femtosecond laser acts on a dielectric material. They also confirmed that a strong threshold effect would, theoretically, appear as ablating on the dielectric material. Longtin [9] combined the saturated absorption and multiphoton absorption effects to develop a new model of heat absorption.

Many researchers have studied the ablation properties of a femtosecond laser, and numerous reasonable explanations for the experimental results have been presented. However, the conclusions drawn in each study are quite different, such as inconsistent ablation threshold values, various explanations for the material removal mechanism, and complicated influence factors. Therefore, it is meaningful to continue studying the damage threshold, material removal mechanism, and efficiency in order to provide more theoretical and experimental support for the femtosecond laser ablation mechanism. Here, we discuss the damage thresh-

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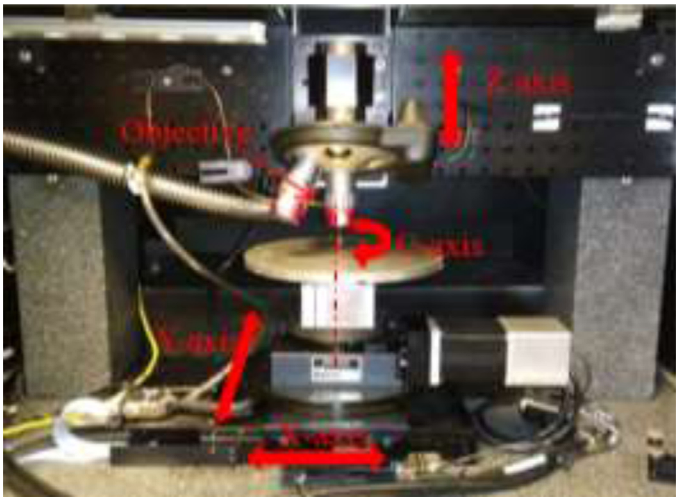

Fig. 1. Micromachining center involving a rotary table.

old, material removal mechanism, and material removal rate based on ablation of a silicon wafer subjected to a femtosecond laser.

2. Femtosecond laser experimental platform

The femtosecond laser experimental platform consists of a motion control processing platform and a femtosecond laser source. The laser source is a Ti: sapphire femtosecond laser system based on the chirped-pulse-amplification principle. The laser system is designed along the following technical parameters: pulse wavelength of 800 nm; pulse width of 100 fs; repetition frequency of 1 kHz. The objective lens used to deliver and focus the laser beam is Mitutoyo Ltd's Apo NiR Series (NA = 0.1, 5X). The beam focuses on the motion control platform vertically after being focused by the lens. As shown in Fig. 1, the platform is driven by a 4-axis system (X, Y, Z, axes and rotation axis C). The X-axis and Y-axis are used to control the movement of the platform; the Z-axis adjusts the height of the focus point, and the C-axis is used to adjust the position of the workpiece. By default, the material processed in this paper is 100-oriented, phosphorus-doped Si with a resistivity of 5–10 Ω-cm.

3. Analysis of ablation threshold and material removal effect

3.1. Ablation threshold

The ablation mechanism of the femtosecond laser is complex, and the threshold theory is widely accepted in various theories. The ablation threshold is the lowest laser energy density that can be damaged when the laser ablates on the material. Popular methods of determining the threshold are online observation, morphology detection, and numerical calculation [10]. In this study, the ablation threshold will be derived from the functional relation between ablation diameter and pulse intensity after observing the ablation material through a microscope. This method not only has a theoretical basis, but also avoids the errors that can be introduced in calculating the ablation volume. Moreover, the beam waist radius value can be obtained through the experiment.

The actual beam waist radius values are different from those given by the theoretical calculations, because the laser focus is affected by many factors such as the strong nonlinear effect of focusing. The modified calculation for the beam waist radius is

$$w_0 = M^2 \frac{f\lambda}{\pi r} \tag{1}$$

where λ is the laser wavelength; r is the laser beam spot radius before focusing; and f is the focal length of the focusing lens. M is the quality correction coefficient between the real laser beam and the standard Gaussian beam.

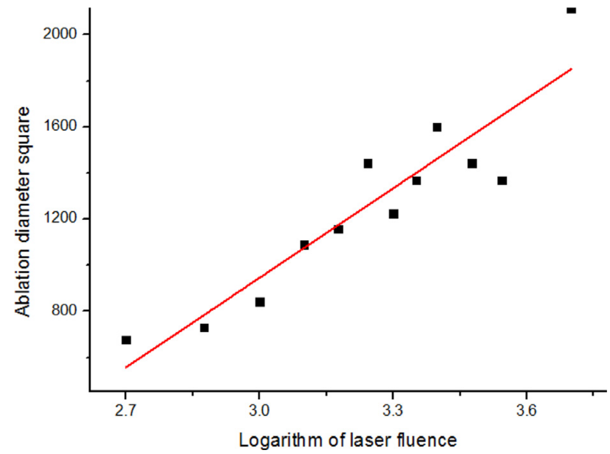

Fig. 2. Relationship between the square of the ablation diameter and the logarithm of laser fluence.

The correction coefficient is calculated as

$$M^2 = \pi D_0^2 \left[\frac{\sqrt{(D_z/D_0)^2 - 1}}{4\lambda\pi} \right] \tag{2}$$

where D_0 is the diameter of the beam spot at a focus point and D_z is the diameter of the beam spot at a distance z from a focus point along the beam.

The relationship between the femtosecond laser fluence and the diameter of the ablation zone D is known to be [11]:

$$D^2 = 2w_0^2 \ln\left(\frac{2E_p}{\pi w_0^2 E_{th}}\right) \tag{3}$$

In this equation, E_{th} is the ablation threshold of the material and E_p is the monopulse energy intensity.

When ablating with a multipulse laser, the threshold relationship between the monopulse and multipulse scenarios can be represented as [12]

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

where $F_{th}(1)$ is the monopulse ablation threshold; $F_{th}(\infty)$ is the multipulse ablation threshold; and k is an accumulation coefficient.

From this equation, we know that the increased number of pulses in the femtosecond laser ablation leads to a slight decrease in the ablation threshold. This means that the multipulse femtosecond laser can remove material more easily than the monopulse laser, even with the same energy fluence.

Fig. 2 illustrates the relationship between the microhole sizes and the incident laser power (mW) as some microholes on the surface of the silicon wafer are ablated by the femtosecond laser with 1 kHz repetition frequency over 1 s. The experimental results were fitted to a linear relationship. The slope of this straight line is 1295 for a beam waist radius of 8 μm. Assuming D = 0, we can calculate the ablation threshold of the silicon wafer to be 0.227 J/cm^2 for a laser with a 1-kHz repetition frequency, 800-nm wavelength, and 1000 pulses. We conclude from this experiment that the diameter of the ablation hole on the silicon wafer surface would enlarge with an increase in the incident laser power until reaching some saturated size. This result means that the square of the ablation diameter is linear with respect to the logarithm of laser fluence, which agrees with Eq. (3). However, the ablation threshold of the silicon wafer in this test is different than the results in [13] and [14]. The reasons are as follows: (1) The shorter the pulse width, the greater the peak energy density, and so the higher the material removal rate