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Influence of plasma shock wave on the morphology of laser drilling in different environments

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ABSTRACT

Nanosecond pulse laser was used to study nickel-based alloy drilling and compare processing results of microholes in air environment and water environment. Through analysis and comparison, it's found that environmental medium had obvious influence on morphology of laser drilling. High-speed camera was used to shoot plasma morphology during laser drilling process, theoretical formula was used to calculate boundary dimension of plasma and shock wave velocity, and finally parameters were substituted into computational fluid dynamics simulation software to obtain solutions. Obtained analysis results could intuitively explain different morphological features and forming reasons between laser drilling in air environment and water environment in the experiment from angle of plasma shock waves. By comparing simulation results and experimental results, it could help to get an understanding of formation mechanism of microhole morphology, thus providing basis for further improving process optimization of laser drilling quality.

1. Introduction

Since its birth, laser has been applied to microhole processing, while with progress of laser technology and laser processing technology over the half of a century, laser microhole processing technology has obtained considerable development. Laser processing technology for aero turbine blade gas film hole has also gone through different phases and is continuously developing with elevated requirements for aero-engine design. At present, the requirement of the latest turbine blade gas film hole processing is to process gas film holes being 0.1 mm or so on blade surface with ceramic thermal barrier coating so as to ensure the optimal blade cooling effect. In order to satisfy this requirement, researchers have carried out theoretical and experimental researches of various laser processing.

In order to further improve laser processing quality, researchers have tried all kinds of out-field auxiliary methods [1]. Ho et al. applied electrostatic field [2] to reduce plasma and accelerate granular movement, which improved material removing rate of ultrashort pulse laser when drilling on copper metal. Lu et al. studied nanosecond and millisecond laser ablation under simultaneous effect of external electric and magnetic fields [3], results indicated that electromagnetic field could influence movement of plasma and improve drilling quality. Okamoto et al. investigated the influence of the surrounding gas conditions on the surface integrity in the micro-drilling of silicon carbide. They found appearance of plasma generation [4] affected the surface integrity at the circumference. Nath et al. used nanosecond laser to conduct drilling experiment respectively in air environment and water environment and then explained the influence of environment [5] on hole morphology in laser drilling from aspects of plasma and cavitation effect. Luo et al. stated the improvement of laser ablation efficiency in the liquid [6] is attributed to the strong confinement of plasma plume accompanying with shockwave and cavitations bubbles. Xia et al. used features of vacuum environment [7,8] which could reduce heat-affected zone of laser drilling and reduce plasma shielding effect, and processed holes with high ratio of pit-depth to pit-diameter on non-metal material through femtosecond laser. Moghaddam proposed a theory [9] of using double-pulse laser ablation to amplify plasma which could be used to process microholes with variable diameters. Above researches indicate that auxiliary environment can significantly influence plasma state, but plasma morphology and space-time distribution [10] in micro-deep holes are quite complicated. Plasma not only influences laser drilling efficiency and quality, monitoring plasma can also be used to optimize drilling technology. Ho et al. used high-speed camera to shoot plasma in laser drilling process [11], determined mask diameter above workpiece by analyzing plasma size and finally improved processing efficiency and quality. Acquisition and analysis of plasma image can also be used to control defocusing amount [12] of laser drilling and improve drilling

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efficiency by 47%.

Although literatures have verified that applying auxiliary physical environments in pulse laser processing can reduce plasma agglomeration and increase material removing rate, etc, relevant literatures are still in exploratory phase with a shortage of systematic theoretical researches. The effect of plasma on morphology of laser processing is lack of quantitative analysis based on calculation and simulation. During laser processing process, characteristics of plasma and laser transmission exert great influence on energy absorption and transfer. Hence, there is an urgent need of establishing trans-scale model with organic combination of laser transmission, plasma effect, energy absorption and transfer, material removal and interface effect to study material removing process [13] under multi-pulse effect.

In this paper, theoretical formula was used to calculate boundary dimension of plasma and shock wave velocity, and finally parameters were substituted into computational fluid dynamics simulation software to obtain solutions. Obtained analysis results could intuitively explain different morphological features and forming reasons between laser drilling in air environment and water environment in the experiment from angle of plasma shock waves.

2. Experimental method

The experiment used Inno1316 model Nd: YAG diode-pumped laser designed and produced by German INNOLAS LASER GMBH. Processing parameters were as shown in Table 1. HITACHI S-3000N scanning electron microscope (SEM) was selected to observe microhole morphology. OLS4000 laser scanning confocal microscope produced by Olympus company was used to measure specific dimension of microhole. High-speed digital camera was Phantom v1212 promoted by American Vision Research Corporation.

This paper mainly studied direct processing of microholes on nickel-based alloy 718 as the substrate, and chemical components of experimental material were as shown in Table 2.

Optical path of laser drilling experiment was shown in Fig. 1, light beam sent from laser successively passed diaphragm, shutter and dichroic mirror, dichroic mirror divided light beam into two paths, and one path reached power meter and the other reached experimental material through focus lens. The experiment was divided into two types according to difference in environment: the first type was laser drilling in air environment. Experimental material and motion stage were directly fixed, and laser directly acted on material surface as shown in Fig. 2a; the second type was laser drilling in water environment. Experimental material was put into organic glass container filled with aqueous solution, container and motion stage were fixed, and laser acted on material surface through quartz glass window at side wall of the container as shown in Fig. 2b; high-speed camera was used to shoot morphology of laser plasma. Parameter setting of laser and position settling of moving stage in the experiment were controlled by computer.

Table 1
Table of processing parameters.

Parameter	Value
Wavelength (nm)	532
Pulse width (ns)	10
Repetition frequency(Hz)	100
Laser mode	$TEM_{00}(M^2 < 1.3)$
Focal length(mm)	150
Power (W)	0.4, 1.03, 2.45
Pulse number	500, 2000

Table 2
Table of chemical components.

Material	Composition (wt%)						
	Ni	Cr	Al	Fe	Nb	Mo	Ti
Inconel 718	55	21	0.8	14	5	2.8	1.15

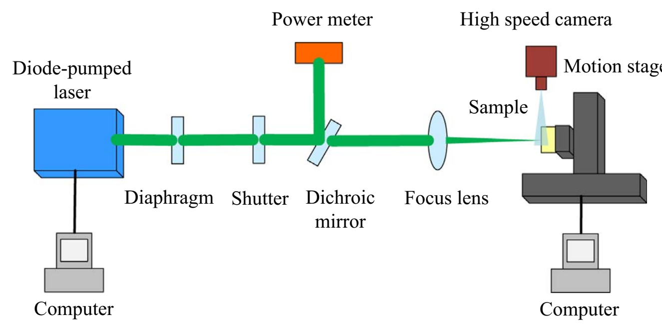

Fig. 1. Schematic diagram of experimental Optical path.

3. Results and discussion

3.1. 1 Experimental results

Fig. 3 shows plasmas shot by high-speed camera during nanosecond pulse laser nickel-based alloy drilling in air environment, we could see from the figure that as laser drilling time lengthened, heights of plasmas gradually decreased, but diameter change was not obvious. This was because as drilling depth increased, laser beams were gradually out of focus, light intensity gradually weakened, and formed plasmas reduced. By comparing plasma morphologies formed by lasers of different powers, we could find that the higher the power, the higher the plasmas, but diameter different was minor.

We observed shallow-hole morphologies of laser ablation in different environments through electron microscope and confocal microscope as shown in Fig. 4. Fig. 4a shows extrance morphology of nanosecond pulse nickel-based alloy lasing in air environment, Fig. 4a1 and Fig. 4a2 shows that a large quantity of splashes deposited around the extrance, and materials stacked at hole edge and were in protuberance like an annular volcanic vent. Analysis believed that in laser processing process, as absorption of laser energy in a large quantity, laser plasma had high-temperature and high-pressure effect, outward expansion process would generate laser plasma shock waves [14], and this shock would make materials experiencing fusion, gasification and ionization splash outward, and then pit points would form more effectively. Fig. 4b shows extrance morphology nanosecond pulse nickel-based alloy lasing in water environment, we could see from Fig. 4b1 and Fig. 4b2 that both extrance and profile morphology were improved, and materials stacking didn't occur at extrance. This was because underwater laser plasma of high temperature and high pressure made outward expansion movement at supersonic speed, and continuously compressed surrounding aqueous medium to form laser-induced plasma shock waves. When laser was interacting with target material in liquid environment, it would generate specific cavitation phenomenon. During pulsation and collapse of laser vacuole, both jet flow and shock waves generated nearby target material surface would bring shock effect to target material, and this shock had secondary processing effect on material.

In order to make detailed comparison of drilling effects in air environment and water environment, this paper conducted a series of laser drilling experiments of different energies. Fig. 5a shows a group of extrance morphologies of nanosecond pulse laser nickel-based alloy drilling in air environment, we could see from the figure that hole