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Review

A processing technology of grooves by picosecond ultrashort pulse laser in Ni alloy: Enhancing efficiency and quality

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HIGHLIGHTS

- Multi-scan processing could increase the depths of grooves.
- Multi-scan processing optimizes sidewall and bottom morphology of grooves.
- Multi-scan processing could enhance the efficiency and quality of grooves.
- Temporary saturation and the bending for deep groove processing are presented.
- The related reasons and the solutions on the deep groove bending are discussed.

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ABSTRACT

The comparative study is presented of grooves ablation for the single- and multi-scan processing technology in Ni alloy using a 10 ps pulse laser with the wavelength of 532 nm and the repetition rate of 1 kHz. Results show, when the *N* (the effective ablation pulse number per unit area), for the single-scan processing of grooves, have been divided into multiple groups and combined with multiple times ablation, namely the multi-scan processing, the groove depth and morphology quality could be enhanced effectively. In addition, the temporary saturation of the groove depth and the bending on the deep groove bottom are reported. Especially for the bending phenomenon which hinders the further deepening of the groove, the related reasons and the solutions are discussed.

1. Introduction

Ultrashort pulse laser micromachining, with the pulse duration less than 10 ps, has some advantages, including the "cold" and contactless processing, the materials independence, beyond the diffraction limit, high precision and automation, etc [1–3]. Meanwhile, there is a very wide range of applications for ultrashort pulse laser micromachining. For example, Zang et al. reported that microholes had been fabricated on roughened ZnO through the femtosecond laser direct writing for the output power enhancement of InGaN light-emitting diodes [4]. Romoli et al. presented the microholes drilling for gasoline direct injection nozzles by ultrashort pulse laser in martensitic stainless steels [5]. Borowiec et al. reported the microgroove ablation in the indium phosphide, a compound semiconductor material used in optoelectronic and high-speed electronic field, by femtosecond pulse laser at a center wavelength of 800 nm [6]. Wang et al. studied the femtosecond laser rear-side ablation of Cr film for the applications in the fields of semiconductor manufacturing and photoelectrical devices [7]. Furthermore, for the new composite materials and multilayer composite materials, the high-quality processing could be gotten through ultrashort pulse laser. Such as, Salama et al. demonstrated the ablation of the carbon fibre-reinforced polymer(CFRP) composites by picosecond ultrashort pulse laser, the characteristics of CFRP include the inhomogeneity properties, the heat sensitivity and the great abrasive etc. The research showed that there is the small heat affected zones(HAZs) for the holes and non HAZ on the cutting surfaces [8]. Morán-Ruiz et al. studied the femtosecond laser micromachining of metallic/ceramic composite material and obtained high quality holes for the solid oxide fuel cell devices through single processing [9].

It is worth to note that there are two well-known challenges for ultrashort pulse laser micro hole/groove machining, including the depth saturation and the molten spatters around the periphery of the microstructure. First, the depth of micro hole/groove would reach a saturation state when the laser energy or pulses is up to the value,

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defined as the saturation energy or pulses [10,11]. The potential reasons are the plasma shielding effects, the variation of the material thresholds based on the multiple pulses accumulation effect, the trouble on the ablated materials ejecting along with the formation of the micro hole/groove and so on [12–14]. Besides, the bending phenomenon on the deep hole/groove bottom also hinders the increase in the processing depth. For the molten spatters around the periphery of the microstructure, minimizing the heat and boundary effects is one of the most considerable advantages for ultrashort pulse laser micromachining, which could make the high precision fabrication achieved. However, the studies of both experiment and theory show that the heat and boundary effects couldn't be avoided completely, the molten layer couldn't be zero even for ultrashort pulse laser with the pulse duration of low femtosecond scale [15–17]. One of the specific phenomena is that there are always the molten spatters around the periphery of the microstructure, resulting in the poor morphology quality.

Due to the pulsed irradiation of laser, the grooves have been ablated depending on the number of overlapping pulses. Therefore, there are two processing methods for the grooves ablation, namely the single- and multi-scan processing. Specifically, the effective ablation pulse number per unit area based on the single-scan processing of groove has been divided into multiple groups and then been combined with multiple times ablating, namely the multi-scan processing. However, the total processing time of groove is almost identical for the single- and multi-scan processing with the same effective ablation pulse number per unit area. In this paper, the contrast study is presented of grooves ablation with the single- and multi-scan processing technology in Ni alloy using picosecond ultrashort pulse laser. The characteristic dimensions and morphology of grooves are explored in order to obtain the optimal processing technology. In addition, some interesting phenomena are reported, such as the temporary saturation of the groove depth and the bending on the deep groove bottom.

2. Experiments

2.1. Experimental setup

The laser source was a neodymium-vanadate (picoREGEN IC-1500 ps Nd:VAN; Austria) laser delivering pulses of 10 ps duration with the wavelength of 532 nm and the repetition rate of 1 kHz. The laser was directly focused onto the sample surface by an objective lens with a focal length of 100 mm, and the laser beam spot radius at the focal plane is ~15 μm. The Ni alloy(GH4169) samples were placed on a 3D precision motion stage to allow the position control with a high precision accuracy. An accurate imaging system including a CCD camera allowed a high-resolution visualization of the ablated zone on the sample surface. The experiments were performed in air. Fig. 1 illustrates the setup of picosecond ultrashort pulse laser micromachining system. After the experiments, the grooves were split through the sandpapers and the polishing agents, and then, they were cleaned through the ultrasonic cleaner in acetone. At last, through the scanning electron microscopy(SEM), the comparatively authentic dimensions, the longitudinal sections and the morphology of grooves could be gotten. Moreover, every groove would be measured on three sections in order to calculate the average groove width and depth.

2.2. Groove processing upon the pulsed laser

For pulsed laser processing, the grooves would be ablated depending on the effective ablation pulse number per unit area, denoted N. And the N has the relationship with the scan speed ν as shown in Eq. (1) [18]:

$$N = \frac{2\omega f}{\nu} \tag{1}$$

where ω is the laser beam spot radius, f is the repetition rate of laser. Based on the Eq. (1), there is the inverse proportion between the effective ablation pulse number per unit area N and the scan speed ν. For the groove processing, if the scan speed ν has been increased to $S * \nu$, correspondingly, the effective ablation pulse number per unit area N would be reduced toN/S. At this time, increasing the scan times to S times simultaneously, both the effective ablation pulse number per unit area and the machining time keep constant. In a word, within the same machining time, for the same effective ablation pulse number per unit area N, there are several choices for groove processing upon pulsed laser shown in Fig. 2. First, it is called the single-scan processing. Second, the multi- or S-scan processing (S is the scan times, and $S \geq 2$), now, the scan speed is increased S times correspondingly based on the Eq. (1). However, there are many differences in the characteristic dimensions and morphology of grooves for the single- and multi-scan processing. In this paper, the researches on the single- and multi-scan processing of grooves with the same machining time are presented using a 10 ps ultrashort pulse laser, in order to obtain the high quality and efficiency processing technology.

3. Results and discussions

3.1. Width of groove based on the single-and multi-scan processing

Fig. 3(A) shows the grooves widths for the single-scan processing with the scan speed 0.025 mm/s, and the multi-scan processing including 2-scan combined with the scan speed 0.05 mm/s, 4-scan with 0.1 mm/s and 8-scan with 0.2 mm/s. Furthermore, based on the Eq. (1), the effective ablation pulse number per unit area N is 1200. It can be seen from the Fig. 3(A), with the increase in both the scan speed and the scan times, the grooves widths increase gradually firstly for the laser energies of 0.002 mJ, 0.007 mJ and 0.022 mJ, and displays a saturation state only for the energy of 0.022 mJ. Nevertheless, it is different in the change trends of the grooves widths between Fig. 3(A) and (B). For the Fig. 3(B), the effective ablation pulse number per unit area N is equal to

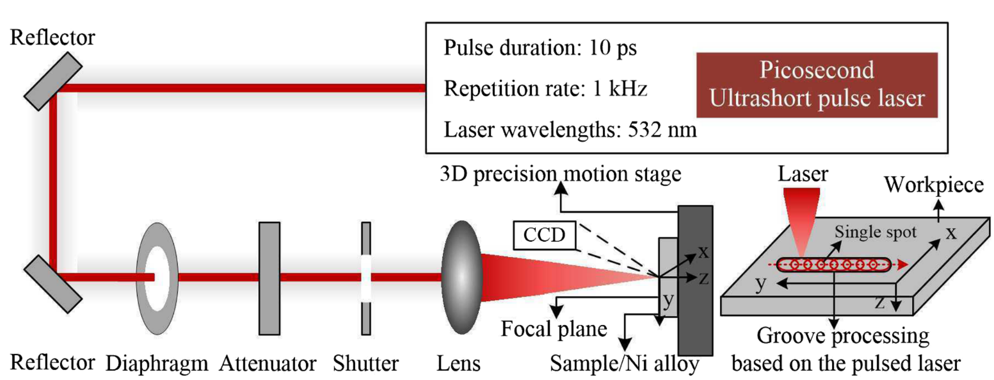

Fig. 1. Schematic of the picosecond ultrashort pulse laser micromachining system.