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Full Length Article

Effects of picosecond laser repetition rate on ablation of Cr12MoV cold work mold steel

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ABSTRACT

In this paper, the effects of pulse repetition rate on ablation efficiency and quality of Cr12MoV cold work mold steel have been studied using a picosecond (ps) pulse Nd:YVO_4 laser system at λ = 1064 nm. The experimental results of area ablation on target surface reveal that laser repetition rate plays a significant role in controlling ablation efficiency and quality. Increasing the laser repetition rate, while keeping a constant mean power improves the ablation efficiency and quality. For each laser mean power, there is an optimal repetition rate to achieve a higher laser ablation efficiency with low surface roughness. A high ablation efficiency of 42.29, 44.11 and 47.52 μm^3/mJ, with surface roughness of 0.476, 0.463 and 0.706 μm could be achieved at laser repetition rate of 10 MHz, for laser mean power of 15, 17 and 19 W, respectively. Scanning electron microcopy images revels that the surface morphology evolves from rough with numerous craters, to flat without pores when we increased the laser repetition rate. The effects of laser repetition rate on the heat accumulation, plasma shield and ablation threshold were analyzed by numerical simulation, spectral analysis and multi-laser shot, respectively. The synergetic effects of laser repetition rate on laser ablation rate and machining quality were analyzed and discussed systemically in this paper.

1. Introduction

Efficient and precise metal machining down to the micro scale, which is required for applications ranging from automotive industry to consumer electronics, medicine and production of microelectromechanical systems, is a nontrivial task. There are number of ablation techniques such as chemical and mechanical methods suggested to meet the stringent requirements. Each of these techniques interweaves some advantages with drawbacks. A mask must be used to remove the substrate if selective fabrication is required in the chemical method. Meanwhile, there are a number of pre- and post- preparations, which induce high capital and operating costs. In mechanical machining, a series of problems including low processing accuracy, low efficiency, tool wear, and downtime for tool replacement can make the process very time consuming and costly [1].

In contrast, laser micromachining has particular advantages, such as greater flexibility and higher efficiency, no mechanical contact or tool wear, no industrial effluents, fine machining accuracy, and the possibility to ablate different kinds of materials [2–6]. Thanks to its advantages, laser ablation in micro technology has increasingly superseded traditional manufacturing techniques. However, the material removal rate (MRR), the surface roughness and the interaction phenomena that occurs during in the ablation process depend strictly on the material properties, the laser source characteristics and the process parameters [3,7]. Since the pulse duration of conventional laser source (>1 ns) is longer than the heat diffusion time, the inevitable thermal effects on adjacent material cause a poor micromachining accuracy and quality of the geometrical structures [8]. The ultrashort pulse laser systems have been proved to be effective tools for high precision micro machining due to its pulse duration (<10 ps) less than the heat diffusion time [9]. Nevertheless, the processing efficiency is still far from economical industrial applications, which has been the main obstacle to a wide spread of laser micromachining [10].

The ablation efficiency increases with the laser fluence at multi kHz [11], however, the complex mechanisms such as concomitant pressure and shock waves occur at higher laser fluence, enhancing absorption of laser energy [12]. Due to this energy coupling effect, a much larger area characterized with rough surface deteriorates the machining quality and precision [9]. A high repetition rate of more than a few hundred kHz can lower the ablation threshold due to the ablation threshold lowered by incubation mechanism, this leads

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Table 1
Chemical composition of Cr12MoV steel (wt.%).

C	Si	Mn	P	S	Cr	Mo	V
1.45/1.70	≤0.40	≤0.40	≤0.030	≤0.030	11.00/12.50	0.40/0.60	0.15/0.30

to a higher ablation efficiency [13,14]. However, pulse to plume interactions must be taken into account to manage the laser pulse interactions with the already ablated material in form of particles, vapor or plasma which cause the laser energy be scattered, reflected or absorbed [15], resulting in a strong influence on the precision, efficency and the thermal load in materials processing [16–18]. As a result, ultrashort pulse lasers lose its competitive advantages in precision machining as compared with long pulse lasers.

In order to solve these mutual restraint relationships aforementioned, some researchers reported that good ablation efficiency and quality could be achieved by irradiating pulses in the optimum fluence range with high repetition rate [19,20]. In the case of ultrashort pulse laser with megahertz repetition rate at high average power, a very high speed (or low-pulse overlap) is used to increase the ablation efficiency due to the decrease of particle shielding and thermal damage effects [21]. However, there is almost no scientific investigation of laser repetition rate on ablation efficiency and quality when the laser mean power is kept constant.

Moreover, micro texture structures of Cr12MoV, which are considered a hard-to-machining object due to its high mechanical strength and hardness, has wide applications in the molds and dies industry. To the best of our knowledge, there is few scientific investigation of laser ablation on this grade cold work mold steel. Since there are carbides phases included in Cr12MoV, the differences in optical and physical properties between main substrate and carbides will cause different ablation rates between the substrate and carbides. Therefore, it is challenging to obtain high ablation efficiency with good surface quality on this inhomogeneous material. Recently, our group has done some researches on the effects of picosecond laser fluence and wavelength on the laser ablation efficiency and machining quality at 0.4 MHz [22]. The goal of our work is to cover this knowledge gap.

In this paper, the primary aim of this research was to present a systematic study on the effects of picosecond laser repetition rate (RR) (from 0.2 to 20 MHz) on the ablation efficiency and surface quality (Ra) of Cr12MoV cold work mold steel when the mean power is set on 15,17 or 19 W, respectively.

2. Experimental material and setup

2.1. Material

For this study, a commercial Cr12MoV steel was used and the corresponding compositions are listed in Table 1. Cr12MoV specimens were initially milled and mirror-polished to guarantee surface finishing and the flatness before conducting the experiments.

2.2. Experimental equipment

Experiment was performed using a commercial industrial grade diode-pumped solid-state (DPSS) picosecond pulse laser manufactured by EdgeWave GmbH (Laser model: PX100II-A), Germany. The laser source emits a 10 ps pulses at a wavelength of λ = 1064 nm. The picosecond laser had perfect power and beam pointing stability and the main parameters are specified in Table 2. The picosecond laser beam was expanded 3 times, and then delivered into a focused scanning field lens with 100 mm focal length through a 2D galvanometer scanner, as shown in Fig. 1. Spectrometer was used to collect the plasma light emission. The Cr12MoV specimen was fixed

Table 2
Main parameters of the picosecond laser.

Laser parameters	Picosecond laser	Units
Wavelength	1064	nm
M^2 factor	<1.3	–
Focal length	100	mm
Beam diameter	3	mm
Focus diameter	26	μm
Pulse width	10	ps
Repetition rate	0.2–20	MHz

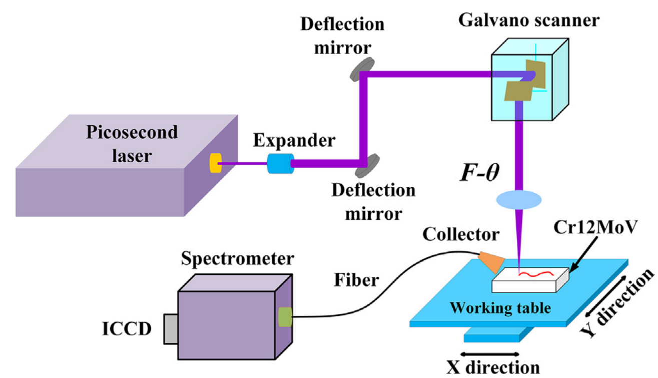

Fig. 1. Schematic diagram of experimental setup for picosecond laser ablation of Cr12MoV.

on a vacuum chuck mounted on the XY table driven by a linear motor with high accuracy of positioning. The focal plane was fixed on the surface of the samples. The laser mean power was measured by using a power meter (F150A-SH thermal head and a NOVA display from OPHIR). All experiments were conducted in ambient air without shielding gas, except for a transverse airflow to protect the focusing optics.

2.3. Experimental theory and methods

In the process of laser ablation, the sample is exposed to picosecond laser continuously scanned at speed ν. It is convenient to express the scanning speed in terms of an effective number of pulses delivered at a single point. The approximate relation derived for the effective number of pulses incident (N_{eff}) is calculated from Eq. (1) [23]:

$$N_{eff} = \frac{2\omega_0 f}{\nu} \quad (1)$$

where ω_0 is the spot radius which is equal to 13 μm, f is the laser repetition rate, and ν is the scanning speed which is constant at 5000 mm/s. It is important to note that this is an approximate relationship and not expected to be completely equivalent to stationary processing with N pulses. Nevertheless, it is instructive in the heat accumulation analysis of pulse laser ablation. All the references to the effective number of pulses delivered in the subsequent analysis are based on Eq. (1). The pulse energy (E_{pulse}) depends on the mean power ($\overline{P}$) and repetition rate (f), given by Eq. (2):

$$E_{pulse} = \frac{\overline{P}}{f} \quad (2)$$