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Micro-channels machining on polycrystalline diamond by nanosecond laser

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ABSTRACT

In this paper, micro-channels are fabricated on the polycrystalline diamond (PCD) surface by a nanosecond laser. The effects of laser process parameters (laser power, frequency and scanning speed) on the responses of surface quality, channel dimension, material remove rate (MRR) and surface roughness *Ra* are investigated by the single factor and multi-objective optimization tests. The mathematical models between the laser process parameters and responses are developed based on the response surface method (RSM) and the adequacy of the models for the responses is studied by the analysis of variance (ANOVA) method. Ultimately, the desired micro-channels are fabricated with the optimal process parameters: laser power of 14.29 W, frequency of 12.87 kHz and scanning speed of 11.36 mm/s. The results exhibit that the developed mathematical models are in well agreement with the experimental results.

1. Introduction

Micro-textures have proven to be an effective method to improve the tribological behavior of the interfaces, and that are widely used in bearing, mechanical seals, cutting tools and cylinder liners [1–4]. Meanwhile, the hole and channel may be the most successful application of the texture patters on the tribo-surfaces, and the main mechanisms of the micro-textures are attributed to the entrapment of wear debris, increased load carrying capacity, storage of lubricants and reduced contact area [5–7]. Presently, the fabrication and application of surface textures mainly focus on the metals [8,9], ceramics [10,11], cemented carbide [12,13] and coatings [14,15], and few studies about the fabrication of micro-textures on polycrystalline diamond (PCD) are reported [16].

PCD is an excellent material for using as bearings and cutting tools in automotive, aerospace and machining industries with its unique properties of high hardness, good thermal conductivity, high wear resistance and low friction coefficient [17,18]. However, the high hardness and brittleness of the PCD make it difficult to fabricate the micro textures on its surface with the conventional methods. At present, micro-textures can be fabricated by various methods, including electrical discharge machining (EDM) [19,20], focused ion beam etching (FIB) [21], lithography technology [22], mechanical micro-machining [23,24], laser [25,26], etc. Among these methods, EDM and laser machining technology have been attracted more attentions on the machining of PCD in most studies. For examples, Wang et al. [27] investigated the micro-hole machining performance of PCD by micro-EDM technology, and the process parameters on surface quality and material remove rate of the micro-holes are studied, ultimately, the optimal machining parameters are selected. Hashikawa [28] fabricated the micro-holes on the PCD surface by laser machining first, and then finished by EDM technology for the high surface quality. Yan et al. [29] fabricated micro-textures on the PCD surface by micro-EDM with a rotary cupronickel electrode, the effect of machining parameters (discharge energy electrode and rotation rate) on the machining characteristics were clarified, and then the micro-channels with low surface roughness as well as high form accuracy were obtained. Su et al. [16] studied the influence of laser process parameters on the formation of micro-holes and micro-channels on the PCD surface by a fiber laser, and the dimensions and topography of the micro-textures were investigated. Furthermore, the optimal process parameters were obtained for the high surface quality of micro-textures. Comparing to EDM, laser machining technology exhibits more advantages for the fabrication of micro-textures such as high efficiency, no pollution, no mechanical damage and tool wear, therefore, it is a more efficient method for fabricating micro-textures on the PCD surface.

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Comparing to femtosecond and picosecond lasers, the nanosecond laser exhibits high machining efficiency and low costs. Thus, the nanosecond laser is widely used for the micromachining [30]. Unfortunately, the nanosecond laser micromachining produces more heat-affected zone (HAZ), recast layers and debris due to the long laser-material interaction time and high energy density [31]. Therefore, the laser process parameters need to be further optimized for the high surface quality.

In this paper, a nanosecond laser is used to produce the micro-channels on the PCD surface. Single factor test and multi-objective optimization are carried out to investigate the effect of laser process parameters on the surface quality, geometric dimensions and material remove rate (MRR) of the machined channels. Meanwhile, the predictive models of the geometric dimensions, MRR and surface roughness *Ra* are founded based on the response surface method (RSM), and the optimal process parameters are obtained for the desired channels.

2. Experimental details

2.1. Materials

The commercial PCD compacts (Far-East New Materials Co., Ltd., China) are used as the test materials. The PCD layer is formed by sintered diamond grit with Co binder to WC cemented carbide substrate at high temperature and pressure. The thickness of the PCD layer is about 0.5 mm, and it is about 2.5 mm for cemented carbide substrate. The PCD layer comprises an average grain size of 5 μm, and the surface roughness *Ra* is 0.038 μm. Table 1 shows the properties of the cemented carbide substrate and PCD layer.

Fig. 1 shows the typical microstructure and composition analysis of the PCD surface. It illustrates that the surface of the sample is dense and the porosity is virtually absent; EDX analyses of points A and B confirm that the gray regions are the PCD phases and the white regions are the Co binders.

2.2. Experimental methods

2.2.1. Experimental setup

An Nd:YAG laser (DP-H20, China) is used to produce the micro-channels on PCD sample surface that is fixed on a three dimensional stage. The wavelength of the laser is 1064 nm, pulse duration is 10 ns, maximum power is 20 W and the maximum frequency is 20 kHz. A single laser beam is focused on the sample surface with an incident angle of 90°, meanwhile, the preparation process is monitored by a digital microscope. All experiments are performed in air condition at room temperature.

2.2.2. Single factor test

Single factor tests are used to investigate the effect of laser process parameters (laser power, scanning speed and frequency) on the surface morphology, channel width (horizontal distance at the top surface of the channel) and depth (vertical distance between the top and bottom surface of the channel), the material remove rate (MRR) and surface roughness (*Ra*) of the machined surface. The laser power ranges from 5 to 20 W, the frequency ranges from 2 to 20 kHz, and the scanning speed ranges from 1 to 30 mm/s.

After laser irradiation, the samples are cleaned twice for 30 min in an ultrasonic bath by alcohol and then dried. The surface morphologies of the channels are observed by scanning electron microscope (SEM, QUANTA FEG250, USA) and three dimensional microscope (VHX-600E, Japan), and the surface compositions are detected by an energy dispersive X-ray spectroscope (EDX, X-MAX50, UK). The channel profile with a certain width (horizontal distance at the top surface of the channel) and depth (vertical distance between the top and bottom surface of the channel) are measured by a three dimensional microscope (VHX-600E, Japan). The cross-sectional area of the channel is also measured based on the section profile and then the material remove rate (MRR) is calculated by taking into account of the scanning speed. The surface roughness (*Ra*) of the machined surface, which represents the surface quality of the channels at a certain extent, is measured with the same area (including four channels in the area) by the white light interferometer (Wyko NT9300, USA). For reducing the measurement error, each test is repeated three times and the average values are recorded as the output.

2.2.3. Multi-objective optimization

To further investigate the effect of the process parameters and find the optimal values for getting the higher MRR and lower surface roughness *Ra*. An L_{20} array according to the CCD (central

Table 1
Properties of cemented carbide substrate and polycrystalline diamond layer.

Materials	Density (g·cm^{-3})	Elastic modulus (GPa)	Thermal conductivity (MPa)	Thermal expansion coefficient (10^{-6}/K)
WC + 8 wt.%Co	14.5–14.9	590–610	79.5	4.5–4.6
PCD	3.6–3.8	860–900	720.0	1.0–1.18

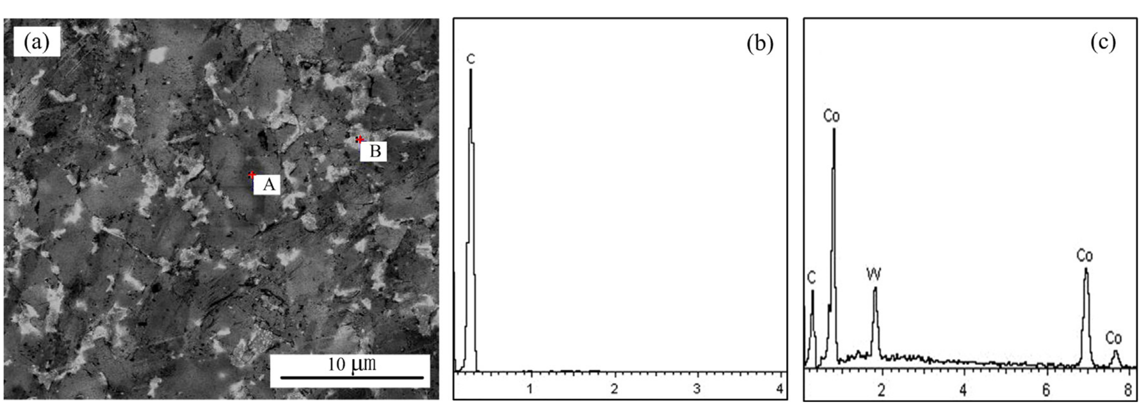

Fig. 1. SEM micrograph and EDX analysis of the PCD surface, (a) SEM micrograph of the polished surface, (b) and (c) EDX composition analyses marked in points A and B, respectively.