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Effect of femtosecond laser pretreatment on wear resistance of Al_2O_3/TiC ceramic tools in dry cutting

Youqiang Xing, Jianxin Deng *, Kedong Zhang, Guodong Zhang, Huanhuan Gao

Key Laboratory of High Efficiency and Clean Mechanical Manufacture of MOE, School of Mechanical Engineering, Shandong University, Jinan 250061, PR China

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ABSTRACT

A femtosecond pulsed laser (pulse width: 120 fs, wavelength: 800 nm and repetition rate: 500 Hz) was used for the pretreatment on the rake face of Al_2O_3/TiC ceramic cutting tools. The evolution of surface morphology of pretreated cutting tools irradiated with different pulse energies was measured by scanning electron microscope (SEM) and atomic force microscope (AFM). Dry cutting tests were carried out with these pretreated tools and conventional tools on hardened steel. The effect of pulse energy on the wear resistance of these pretreated tools was investigated. Results show that the cutting forces have no significant difference between laser pretreated tools and the conventional tool; the cutting temperatures of laser pretreated tools were slightly reduced compared with the conventional tool. Meanwhile, we found that the laser pretreated tools increased the adhesions of chips on the rake face, but they can significantly improve the wear resistance of the rake face; and laser pulse energy was found to have a profound effect on the wear resistance of the laser pretreated tools.

1. Introduction

Al_2O_3 based ceramic has excellent properties, such as: low density, high melting point, high hardness, good chemical inertness and high wear resistance. They are generally the most suitable materials for dry cutting and high-speed machining of high hardness workpiece materials compared with high-speed steel and carbide tools due to these advantages. In dry cutting, friction and wear tend to be high between the tool and workpiece since they will be subjected to a higher temperature caused by severe friction between tool and workpiece during machining processes. This will result in increasing tool wear and hence a reduction in tool life. Therefore, the wear resistance of cutting tools is constantly and strongly required to improve for increasing the tool life.

In recent decades, surface modification of cutting tools by laser treatment is an attractive technology. It has been introduced to improve the surface hardness and fracture toughness, modify the chemical composition and the structure of the surfaces, reduce the friction, improve adhesive strength between coating and substrates, improve the anti-adhesive properties and wear resistance and then increase the tool life [1–8]. For example, D'yachenko et al. [9] studied the performance of high-speed steel tools treated with pulsed laser in cutting of 4Kh4VMFS steel. Results showed that the life of high-speed steel tools may be increased significantly as a result of laser treatment with a pulse power density. Darmawan et al. [10] reported that the wear resistance and wear pattern of the laser-treated AISI-M2 cutting tools in peeling beech were improved than those of the conventional cutting tool. Deng et al. [11] used a laser-texturing technique to treat the cemented carbide cutting tools. Results showed that the laser pretreated cutting tools resulted in a reduced cutting force and friction coefficient at the tool–chip interface compared with the conventional tool, and then reduced the tool wear and increased the tool life. Sugihara and Enomoto [12–14] developed a series of textured tools irradiated with a femtosecond laser. Results showed that cutting tools with textured surface significantly decreased the contact area and promoted anti-adhesive properties at the tool–chip interface in wet and dry face milling aluminum. The interaction between lasers and ceramics has been studied for many years. Shukla and Lawrence [15,16] used fiber and Nd:YAG lasers to study the effect of the surface treatment of a silicon nitride (Si_3N_4) based engineering ceramic. Results showed that the laser radiated surface of the Si_3N_4 based engineering ceramic had more resistance to crack propagation. Wang et al. [17] used a CO_2 laser to treat an Al_2O_3-based ceramic aiming at modifying its microstructure and improving its erosion resistance. Wu et al. [18] and Schubert et al. [19]

* Corresponding author at: Department of Mechanical Engineering, Shandong University, No. 17923 Jingshi Road, 250061 Jinan, Shandong Province, PR China. Tel.: +86 531 88399769.
E-mail address: jxdeng@sdu.edu.cn (J. Deng).

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Table 1
Properties of Al_2O_3/TiC ceramic.

Composition/wt.%	Density/ g cm^{-3}	Hardness/ HV	Flexural strength/ MPa	Fracture toughness/ MPa $m^{1/2}$
Al_2O_3/55%TiC	4.76	2400	900	5.04

used an excimer laser to improve the toughness and bending strength of Al_2O_3-based ceramic materials.

In this paper, the rake face of Al_2O_3/TiC ceramic tool was irradiated by a femtosecond laser with different pulse energies; the aim of the research was to develop a possibility for the use of a laser to improve the wear resistance of cutting tools. The performance of these tools was investigated in dry cutting of hardened steel compared with the conventional tool. Based on the results, the relationship between laser pulse energy and wear resistance of cutting tools was studied.

2. Experimental details

2.1. Preparation of Al_2O_3/TiC ceramic tool materials

The commercial hot-pressed Al_2O_3/TiC ceramic (Zibo Dongtai Co., Ltd., China) was selected as the test material in this study. The main components and mechanical properties of the samples were listed in Table 1. The dimensions of cutting tools were 12 × 12 × 7.94 mm^3 with a 0.1 mm at 5° edge chamfer and nose radius of 0.1 mm. The rake faces of these tools were finished by grinding and polishing to the roughness less than Ra 0.02 μm. After that they were cleaned with 30 min ultrasonic bath in alcohol and acetone, respectively.

2.2. Laser pretreatment processes

A regenerative amplified Ti: sapphire femtosecond laser system (Legend Elite-USP, Coherent Inc., USA) with a wavelength of 800 nm, pulse duration of 120 fs and the repetition rate of 500 Hz was used for surface irradiation on the rake face of cutting tools. A single femtosecond laser pulse with a beam diameter of 6 mm was selected and the beam was focused on the sample surfaces by a lens with focal length of 20 cm to give a spot diameter of about 5 μm at the focal plane. An attenuator was used to obtain the proper pulse energy. The Al_2O_3/TiC ceramic sample was placed on a three-dimensional XYZ stage with a precision of 100 nm, the incident angle of the laser beam with respect to the sample surface was near normal. All experiments were performed in air condition under atmospheric pressure. The photos of the femtosecond laser processing equipment are shown in Fig. 1.

Table 2
Experimental parameters of the femtosecond laser used during irradiation of Al_2O_3/TiC ceramic.

Laser wavelength (λ)	800 nm
Pulse width	120 fs
Laser spot diameter	5 μm
Scanning spacing	5 μm
Laser pulse energy (E_p)	$E_p1 = 1$ μJ
	$E_p2 = 2$ μJ
	$E_p3 = 3$ μJ
Laser fluence (Φ)	Φ1 = 5.09 J/cm^2
	Φ2 = 10.19 J/cm^2
	Φ3 = 15.28 J/cm^2
Laser pulse repetition rate	500 Hz
Scanning speed	250 μm/s
Number of overscan	1 overscan

The Al_2O_3/TiC ceramic inserts were irradiated by a femtosecond laser on the rake face and chamfer with 0.7 × 0.7 mm^2, and the processing parameters of the femtosecond laser were given in Table 2. The ceramic inserts irradiated with pulse energy of 1, 2 and 3 μJ were named AT-1, AT-2 and AT-3, respectively. Fig. 2 shows the schematic diagram of laser irradiation dynamics utilized on samples.

2.3. Cutting tests

Dry cutting tests were carried out on a CA6140 lathe equipped with a commercial tool holder having the following geometry: rake angle $\gamma_o = -5°$, clearance angle $\alpha_o = 5°$, inclination angle $\lambda_s = -5°$ and side cutting edge angle $K_r = 45°$. The workpiece material used was AISI 1045 hardened steel with a hardness of HRC 40–50 in the form of a round bar with an external diameter of 120 mm. All tests were carried out with the following parameters: cutting speed $v = 80$–260 m/min, depth of cut $a_p = 0.2$ mm, feed rate $f = 0.2$ mm/r. For comparison, a conventional Al_2O_3/TiC ceramic tool with the same composition and geometry was also used, and it was named AS. Cutting force was obtained with a KISTLER 9275A piezoelectric quartz dynamometer linked via change amplifiers to a chart recorder. The cutting temperature of the tool rake face was measured by an infrared thermography (TH5104R, Japan). The schematic diagram of the cutting test apparatus is shown in Fig. 3.

The worn morphology of the cutting tool was examined by scanning electron microscope (SEM, QUANTA FEG 250, USA) and white light interferometer (Wyko NT9300, USA). The chemical composition on the wear surface was identified by energy dispersive X-ray spectroscope (EDX, X-MAX50, UK).

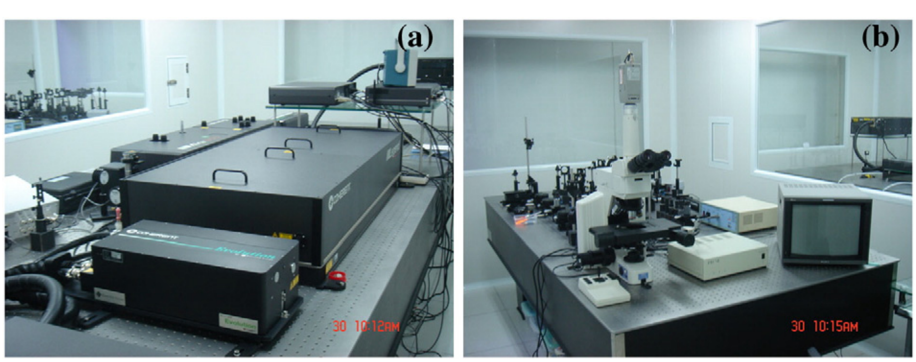

Fig. 1. Photos of femtosecond laser processing equipment: (a) femtosecond laser system, (b) 3D micromachining platform.