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Cutting performance and wear characteristics of Al_2O_3/TiC ceramic cutting tools with WS_2/Zr soft-coatings and nano-textures in dry cutting

Youqiang Xing, Jianxin Deng*, Shipeng Li, Hongzhi Yue, Rong Meng, Peng 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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To improve the cutting performance and reduce the tool wear, novel Al_2O_3/TiC cutting tools were developed with coating and laser technologies: first, the WS_2/Zr coated Al_2O_3/TiC ceramic cutting tool; second, nano-textured Al_2O_3/TiC ceramic cutting tools deposited with WS_2/Zr composite soft-coatings. Dry cutting tests were carried out on hardened steel with the conventional and developed tools. The cutting force, cutting temperature, friction coefficient, and tool wear were measured. Results show that the WS_2/Zr coated Al_2O_3/TiC cutting tools with and without nano-textures significantly improve the lubricity at the tool-chip interface; the cutting force, cutting temperature, friction coefficient and tool wear are reduced compared with the conventional tools; the nano-textured tools deposited with WS_2/Zr composite soft-coatings are the most effective. In addition, the geometry of nano-textures has a profound effect on the lubricity, the WS_2/Zr coated cutting tool with areal nano-textures is the most effective in improving the cutting performance and reducing the tool wear. The abrasive wear, chipping and adhesions are the predominant wear characteristics of conventional tools, the abrasive wear and coating flaking is for coated tools, and the adhesions at the tool tip is mainly for the coated tools with nano-textures.

1. Introduction

Al_2O_3 based ceramic cutting tools are applied widely for dry cutting and high-speed machining of high hardness workpiece materials in the industry due to their unique intrinsic properties: high melting point, high hardness, good chemical inertness and high wear resistance [1,2]. However, the friction coefficient of Al_2O_3 based ceramic cutting tool under dry cutting condition of hard materials is relatively high [3,4], and this will result in increased tool wear and reduced tool life. Therefore, considerable efforts had been made to reduce friction and wear and extend the tool life. Deng et al. [5] reported a ceramic cutting tool with the additions of CaF_2 solid lubricants. The results showed that the friction coefficient at the tool–chip interface in dry cutting with this ceramic tool can be reduced compared with the tool without solid lubricants. Broniszewski [6] developed the Al_2O_3 ceramic tool with the additions of Mo to improve its tribological properties by forming MoO_3 and MoO_2 oxides. Zhao [7,8] developed the Al_2O_3 based functionally gradient ceramic tool and it exhibited high thermal shock resistance and long tool life.

Surface coating is also an effective way to improve the tribological performance and wear resistance of materials, including hard-coatings (TiN, TiCN, TiAlN, etc.) and soft-coatings (MoS_2, WS_2, CaF_2, etc.), and the coating technology had been used in cutting tools [9–15]. For ceramics, a few researches about coating technology were reported. Soković et al. [16,17] deposited different hard-coatings (TiN, Ti(C, N), (Ti, Al)N, etc.) on the Al_2O_3 ceramic tools surface by PVD and CVD technologies. Results showed that the Al_2O_3 ceramic tools with hard-coatings reduced the tool wear and increased the tool life. Dobrzański and Mikuła [18] investigated the mechanical and functional properties of $Al_2O_3+ZrO_2$ ceramic deposited with multi-layer hard-coatings (TiAlSiN+TiN, TiN+TiAlSiN+AlSiTiN, TiCN+TiN, etc.). Results showed that the $Al_2O_3+ZrO_2$ ceramic deposited with hard-coatings resulted in an increasing microhardness, a high wear resistance and a significant increase of the tool life in cutting of grey cast iron. Aslantas et al. [19] deposited TiN coating on the surface of Al_2O_3 based ceramic tool to improve its wear resistance and increased tool life. However, hard-coatings may be not the most suitable for the ceramic substrates due to the high hardness of ceramic itself; soft-coatings may be expected to be more suitable for ceramic and a few

* 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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researches were reported. For example, Wang et al. [20] reported an Al_2O_3 ceramic with CaF_2/Al_2O_3 composite soft-coatings by laser cladding technology. Results showed that the developed ceramic had much superior wear resistance and noticeable lower friction coefficient under dry sliding wear test conditions. Liu [21] deposited MoS_2 soft-coatings on the ceramic tools by magnetron sputtering. Results showed that the flank wear of the coated cutting tools was reduced, and their wear life was extended markedly in dry cutting 1045 and 302 steels.

Recently, surface texturing as a way for improving tribological properties of contact surfaces had received a great deal of attention and it had already been used in some fields such as bearings, engine cylinder liners and seal rings [22–24]. For cutting tools, the experimental observations and theoretical calculations showed that the tool surface topography had a significant impact on the tribological performance during machining [25–27]; meanwhile, due to the advantages of surface texturing, it applied to the cutting tools for decreasing the friction and wear was studied for many years. For example, Xie et al. [28,29] reported that the micro-grooves patterned on the tool rake face by micro-grinding method contributed to reducing friction and cutting force, excluding cutting heat and then reducing tool wear in dry turning of titanium alloy. Xu et al. [30] fabricated the textures on forming tools using an Nd:YVO_4 picosecond laser system. Results showed that the textured tools reduced the friction at the tool–workpiece interface, forming forces and temperatures when machined aluminum alloy. Ling et al. [31] studied the effect of surface micro-textures on drills fabricated using a diode-pumped Nd:YVO_4 picosecond laser in machining of titanium plate. Results revealed that the textured drills reduced adhesion of titanium chips on the drills and the significantly improved the lifetime of drills. Previous studies also demonstrated that the effect of textures had a significant correlation with the geometrical characteristic of textures. Deng et al. [32] fabricated microscale textures with different geometrical characteristics on the tool rake face, and MoS_2 solid lubricants were filled into the textures. Results showed the elliptical grooves were more effective than parallel or perpendicular grooves. Koshy and Tovey [33] used sink electrical discharge machining (EDM) to generate areal and linear textures on the rake face of cutting tools. Results demonstrated a significant reduction of feed and cutting forces in cutting of steel and aluminum, and the areal textures showed more effective compared with the linear textures. Kawasegi et al. [34] reported that textures parallel to the cutting edge on the rake face were more effective in reducing friction and wear compared with other textures, which was in line with the results [35,36], but contradicted to the results obtained by Chang et al. [37]; they also reported that nanoscale textures on the tool rake face were more effective than microscale textures in decreasing friction and adhesion. Researchers also found that the combination of surface textures, lubricants and coatings on the cutting tools seemed to take a synergic effect on the cutting performance. Lei et al. [38,39] reported that the textured tools filled with liquid and soild lubricants, results showed that the micropool lubricated cutting tools improve the cutting performance and reduce the tool wear. Obikawa et al. [35] reported that the textured cemented carbide cutting tools coated with DLC or TiN coatings can improve the lubrication and cutting performance in machining aluminum alloy. Sugihara and Enomoto [36,40] developed DLC coated cutting tools with nano-/micro-textured surfaces. Face-milling experiments on aluminum alloys showed that DLC-coated cutting tool with textured surface significantly promoted the lubricity and anti-adhesive properties at the tool–chip interface. Deng et al. [41] used a femtosecond laser to fabricate nano-textures on cemented carbide cutting tools and then deposited with WS_2 lubricant coatings. Results showed that the deposition of WS_2 lubricant coatings on the textured rake face reduced the friction and wear in dry cutting, and it was an effective way to improve the cutting performance.

WS_2 is well known intrinsic low-friction materials that have been thoroughly investigated in the forms of solid lubricant powders and burnished coatings, as well as in the form of thin coatings deposited by PVD [42–44]. They have a lamellar structure of stacked S–W–S planes with strong bonding within the planes and weak interactions between the planes. Due to its extreme degree of anisotropy of the layered crystal structures, it exhibits a small positive net charge outside of the lamellas, resulting in very low shear strength [45,46]. In this paper, the authors fabricated Al_2O_3/TiC ceramic cutting tools deposited with WS_2/Zr composite soft-coatings by medium-frequency magnetron sputtering together with multi-arc ion plating, and the Al_2O_3/TiC ceramic cutting tools with different types of nano-textures on their rake face generated by femtosecond laser and then deposited with WS_2/Zr composite soft-coatings by medium-frequency magnetron sputtering together with multi-arc ion plating. Microstructural and fundamental properties of the coatings were examined. Dry cutting tests on hardened steel were carried out with untextured and nano-textured tools deposited with WS_2/Zr composite soft-coatings. The cutting force, friction coefficient, cutting temperature and tool wear were measured. The effects of WS_2/Zr composite soft-coatings and nano-textures on the cutting performance and wear characteristics of Al_2O_3/TiC ceramic tools were investigated.

2. Experimental details

2.1. Preparation of WS_2/Zr coated Al_2O_3/TiC ceramic tools

The substrate material utilized for the study was hot-pressed Al_2O_3/TiC ceramic (Zibo Dongtai Co., Ltd., China). Composition, physical, and mechanical properties of this tool material are listed in Table 1. The dimensions of cutting tools were $12 \times 12 \times 7.94\ mm^3$ with a 0.1 mm at 5° edge chamfer and nose radius of 0.1 mm. The rake face of these tools was finished by grinding and polishing to the roughness *Ra* less than 0.02 μm, and then was cleaned with 30 min ultrasonic bath in alcohol and acetone, respectively. After that, they were dried for approximately 10 min in a pre-vacuum dryer.

The physical vapor deposition (PVD) method was used to deposit the coatings with the PVD coating equipments (AS-585, China). For WS_2/Zr composite soft-coatings, two WS_2 targets (medium-frequency magnetron sputtering) and one Zr target (multi-arc ion plating) were used. Before deposition, the coating chamber was heated up to 180 °C and the vacuum in the chamber was pumped to 1.0×10^{-3} Pa. Then, the substrate was cleaned by argon ion bombardment for 10 min with a bias voltage of −600 V. Prior to synthesize WS_2/Zr coatings, a thin adhesion interlayer of Zr was deposited first with multi-arc ion plating process for 15 min to increase adhesion strength; then the substrates were rotated to pass in front of each of the WS_2 targets and Zr target in turn so that the WS_2/Zr coatings with the uniform thickness were deposited, and the deposition time was 100 min. All the PVD coating conditions are listed in Table 2.

Table 1
Properties of Al_2O_3/TiC ceramic.

Composition (wt%)	Density (g cm^{-3})	Hardness (GPa)	Flexural strength (MPa)	Fracture toughness (MPa m$^{1/2}$)
Al_2O_3/55%TiC	4.76	23.5	900	5.04