



Friction and wear behavior of microwave sintered $\text{Al}_2\text{O}_3/\text{TiC}/\text{GPLs}$ ceramic sliding against bearing steel and their cutting performance in dry turning of hardened steel

Jiaao Wang^{a,b}, Yu Cheng^{a,b,*}, Yong Zhang^{a,b}, Zengbin Yin^{a,b}, Xiao Hu^{a,b}, Qin Yuan^{a,b}

^a Nanjing University of Science & Technology, School of Mechanical Engineering, Nanjing 210094, PR China

^b Collaborative Innovation Center of High-End Equipment Manufacturing Technology (Nanjing University of Science & Technology), Ministry of Industry and Information Technology, PR China

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ABSTRACT

An $\text{Al}_2\text{O}_3/\text{TiC}/\text{GPLs}$ (ATG) composite ceramic tool material was fabricated by microwave sintering. The tribological properties of ATG during sliding against GCr15 bearing steel were studied, to investigate the effects of sliding speed and normal load on the friction coefficient and wear rate. In addition, the cutting performance of ATG tools for machining of hardened alloy 40Cr steel was experimentally studied and compared with those of commercial tools. The results showed that the added graphene platelets enhanced the wear resistance and reduced the friction coefficient of the tool material. Furthermore, upon adding graphene platelets, the ability of the tools to resist breakage and their cutting depth improved. The cutting length of the microwave-sintered ATG ceramic tools was approximately 125% higher than that of hot-pressed ceramic tools and 174% higher than that of cemented carbide tools.

1. Introduction

The cutting materials with high hardness and strength, such as hardened steel, has become an important topic in industry and academic research; furthermore, grinding, the traditional machining method for hardened steel, leads to high cost, low efficiency, and environmental pollution [1,2]. High-speed hard turning is one of the most effective ways to solve the problems created by grinding, but may cause varying degrees of tool wear [3]. In the high-speed machining field, in comparison with traditional cutting tools, Al_2O_3 -based ceramic tools have superior wear resistance and hardness, as well as good chemical stability and humidity resistance [4,5]. Therefore, they are regarded as one of the most appropriate tools for cutting hardened steel. However, the high brittleness of Al_2O_3 seriously restricts its application [6,7].

In the last few years, many studies have suggested that the addition of a second particulate phase is an effective way to strengthen and toughen alumina matrix ceramic cutting tools. Furthermore, some studies reported methods to increase the wear resistance and reduce the friction coefficient of ceramic materials. Heuer et al. [8] first applied ZrO_2 transformation toughening to structural ceramics; 15 vol % m- ZrO_2 was dispersed in Al_2O_3 composites, which resulted in composites that exhibited high fracture toughness ($11 \text{ MPa m}^{1/2}$) at

room temperature. The phase transformation of ZrO_2 (from t- ZrO_2 to m- ZrO_2) at 950°C caused volume expansion of the ZrO_2 particles, and the expanded particles generated both shear stress and dilatation, which could prevent crack propagation. Than et al. [9] used a pressureless sintering (PS) method to prepare $\text{Al}_2\text{O}_3/\text{ZrO}_2$ composites; both t- ZrO_2 and m- ZrO_2 were added to Al_2O_3 , and the strength of the $\text{Al}_2\text{O}_3/(\text{t-ZrO}_2 + \text{m-ZrO}_2)$ composites was increased by threefold to 940 MPa compared to Al_2O_3 alone, while the toughness was twice as high. The incorporation of submicron particles or nano-particles, such as TiN, SiC, TiC and MgO is another effective method to fabricate toughened Al_2O_3 -based composites [10–13]. Yin et al. [14] fabricated $\text{Al}_2\text{O}_3/\text{TiC}$ micro-nano-composite ceramic tool materials using a hot-pressed (HP) sintering method, and reported a fracture toughness of $8.3 \text{ MPa m}^{1/2}$ for composites with 6 vol% nano-TiC.

With the emergence of many new materials since the beginning of the 21st century, there has been a great enrichment of possible compositions for composite materials. Graphene in particular has attracted great attention due to its excellent electrical, optical, and mechanical properties, as well as its two-dimensional structure [15–17]. Lee et al. [17] used nano-indentation with an atomic force microscope to study the intrinsic breaking strength and elastic properties of free-standing monolayer graphene membranes, and found a breaking strength of 42 N m^{-1} and intrinsic strength of 130 Pa for bulk

* Corresponding author at: Nanjing University of Science & Technology, School of Mechanical Engineering, Nanjing 210094, PR China.
E-mail address: chengyu106@mail.njust.edu.cn (Y. Cheng).

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graphite. Hod and Scuseria [18] reported a very high Young's modulus of ~ 7 TPa for ultranarrow graphene strips and concluded that graphene nanoribbons (GNRs) are one of the strongest materials in existence. Graphene platelets (GPLs), also called graphene nanoplatelets (GNPs), multilayer graphene nanosheets (MGN) or graphene nanosheets (GNS), consist of multilayer graphene. These GPLs have been used as a competitive nanofiller in composite materials due to their remarkable mechanical properties and large specific surface area [19,20]. In addition, Rutkowski et al. [21] studied the effect of GNPs on the wear and friction properties, as well as cutting performance, of Si_3N_4 ceramic tool materials. Their results showed that increasing the graphene phase to more than 2 wt% caused a noticeable increase in the wear rate of the composites, while the addition of 0.5 wt% GNP resulted in the lowest friction coefficient; when NC6 steel was cut at a 75 m/min cutting speed, the roughness of the workpiece was much lower when compared to a commercial Al_2O_3 -based material (TACN). Chen et al. [22] fabricated Al_2O_3 /GNS composites using a hot-pressed (HP) sintering method, and reported a 43.5% increase in fracture toughness upon incorporating 0.2 wt% GNS; the main toughening mechanisms of these Al_2O_3 /GNS composites were reported to be crack branching, bridging, deflection, and pull-out of GPLs. Jaroslaw et al. [23] used a spark plasma sintering (SPS) method to add graphene oxide (GO) to an alumina matrix and discussed its influence on the cutting performance and mechanical properties of obtained composites. Their results showed that the fabricated cutting tools performed better in terms of cutting performance than the commercial cutting tool TACN ($\text{Al}_2\text{O}_3 + \text{ZrO}_2 + \text{Ti(C,N)}$).

HP sintering and SPS are the main methods for the fabrication of alumina-based ceramic tool materials [19]. HP sintering is a time consuming process and has the additional disadvantage of abnormal grain growth. Although SPS is a novel-fast heating technology that is characterized by a short sintering period and high heating rate, its high energy consumption makes it challenging to prepare ceramic tools with economic viability [24]. Microwave sintering, however, is a process of volumetric heating. Compared with traditional heating methods, microwave sintering has a series of advantages including shorter processing periods, lower sintering temperatures, and higher heating rates. In addition, its characteristics of automatic control and a pollution-free environment make it relatively easy to be used in industrial processes [25,26].

The preparation and cutting performance of Al_2O_3 -based ceramic tool materials using microwave heating have been the subject of several studies [6,27–29]. However, few studies have concentrated on the tribological properties and cutting performance of microwave-sintered Al_2O_3 -based ceramic tools reinforced with GPLs for dry machining of hardened steels. In our previous study [30], we succeeded in sintering Al_2O_3 /TiC/GPLs (ATG) ceramic tools by microwave heating and discussed their properties in detail. Thus, in the present study, we experimentally investigate the tribological properties and cutting performance of these ATG ceramic tool materials during sliding against GCr15 bearing steel and machining of hardened alloy 40Cr steel.

2. Experimental procedures

2.1. Preparation of Al_2O_3 /TiC/GPLs (ATG) composite ceramic tools

The Al_2O_3 /TiC/GPLs composite ceramic tool materials (ATG) were prepared using commercial powders: $\alpha\text{-Al}_2\text{O}_3$ (0.5 μm , 99.9% purity), TiC (1 μm , 99.9% purity), Mo (1 μm , 99% purity), Ni (99.5% purity, 1 μm), MgO (99.9% purity, 1 μm) and Y_2O_3 (99.5% purity, 1 μm), as well as graphene platelets (GPLs, Nanjing, China). The optimal mechanical properties were achieved with 0.2 wt% GPLs in our previous study, and the relative density, Vickers hardness and fracture toughness were 97.70 ± 0.20 , 18.47 ± 0.45 GPa and 8.73 ± 0.35 $\text{MPa m}^{1/2}$ [30]. The compositions of ATG composites ceramic are listed in Table 1. The prepared GPLs suspension was diluted to a

Table 1

Compositions (wt%) of Al_2O_3 /TiC/GPLs composites.

Materials	GPLs	$\alpha\text{-Al}_2\text{O}_3$	TiC	Mo	Ni	MgO	Y_2O_3
wt%	0.2	62.8	30	3	3	0.5	0.5

concentration of 2 mg/ml using N-Methyl-2-pyrrolidone (NMP) and sonicated using a sonication bath (DSA200-JY₁-9.0 L) for one hour. Then the mixed powders above were put into corundum grinding media and were ball milled for 48 h at 200 rpm in a QM-3SP2 planetary ball grinder (Nanjing, China). After that, the mixed powders were put into a vacuum drying oven (Model DZF-1, Shanghai) and were dried at 100 °C, then the dried powders were sifted through a 100-mesh for later use. A certain weight of dried powders above were then put in a cold steel die, and pressed at about 200 MPa using a bench press (Model LDJ400, Taiyuan, China) for 2 min. Square specimens of 13.1 mm in length and about 6.8 mm in height were prepared for further sintering and performance study.

The green samples were embedded in a crucible filled with silicon carbide powder, which could prevented samples from oxidation and heat samples effectively in low temperature. The green samples were sintered in the NJZ-1 microwave furnace (2.45 GHz, Nanjing, China) under an argon atmosphere with power output within the limits of 0–6 kW. The temperature of the sample was measured by an infrared pyrometer (Model ST-2, Taiyuan, China), and it was installed above the chamber of the furnace with the minimum detectable temperature 350 °C. The sample sintering was performed at 1700 °C, holding for 10 min at the heating rate of about 35 °C/min. Afterwards the sintered samples were unaffectedly cooled down to the room temperature and then polished for further experiments.

2.2. Wear experiments

Wear behavior of the ATG ceramic tool materials was studied in dry sliding against bearing steel. The surfaces of the tools were carefully polished until the roughness below 0.1 μm by PG-2 metallographic polisher (Shanghai, China). The wear experiment was performed on the tribometer UMT-2 by CETR Instruments (USA) using the ball-on-plate configuration at the room temperature (20 °C) and under air humidity 30%, with a highly polished GCr15 bearing steel ball (hardness 63HRC, diameter 4 mm). All the experiments were performed in dry conditions. The applied normal loads in the wear process were 20–50 N, the sliding distances were 90–180 m and the sliding speeds were 15–30 cm/s.

The friction coefficients were calculated and tangential forces in the experiments were measured. The worn surface of the friction material was examined by scanning electron microscope (Quant 250FEG); the chemical elements in the wear zone were analyzed by energy dispersive spectroscopy of Quant 250FEG, and the wear mechanism, failure modes and microstructure were studied. The tool material losses (volume of the wear traces) when sliding against bearing steel were measured by a Profilometer Dektak XT, by BRUKER. The value of wear rates (W) were calculated according to the volume loss (V) of the tools per distance (L) and the normal load (Fp):

$$W = \frac{V}{L \cdot F_p} (\text{mm}^3/\text{mN})$$

The microstructure and the wear traces engendered at the surfaces of the ceramic tool materials were viewed by scanning electron microscopy (SEM, Quant250FEG, USA).

2.3. Cutting experiments

The cutting experiments of the prepared ATG ceramic tools were accomplished on a CNC lathe (Model CK6140) under dry conditions.

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