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Wear mechanisms of several cutting tool materials in hard turning of high carbon–chromium tool steel

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A B S T R A C T

The present study illustrates the performance of three different cutting tool materials, namely: PCBN, TiN coated PCBN, and mixed aluminum ceramic (Al_2O_3+TiC) in the turning of medium hardened D2 tool steel (52 HRC). Formation of Cr–O tribofilms on the ceramic tool surface as a result of interaction with the workpiece material and environment (identified by X-ray Photoelectron Spectroscopy) leads to improvement of lubricating properties at the tool/chip interface. Obtained results revealed that the mixed alumina ceramic tool can outperform both types of PCBN under different machinability criteria.

1. Introduction

Hard turning is a process of single point cutting of workpieces that have hardness levels in the range of 45–65 HRC. An example is AISI D2 steel, which is a high carbon and chromium tool steel alloyed with a smaller amount of molybdenum and vanadium.

This steel is characterized by a high wear resistance, and it can be used in the medium-hardened state (52–56 HRC) for deep drawing, rolling, punching, and extrusion dies. Since the late 1970s hard turning of hardened steels such as D2 has been technically and economically competitive to cylindrical grinding [1]. The major benefits of hard turning compared with cylindrical grinding come from process flexibility and economy [2]. Dry, hard turning eliminates disposal and recycling cost of coolants. It has been found out that turned surfaces may have a fatigue life as large as twice that of ground surfaces with equivalent surface finish [3].

Historically, the first ceramic material used as a cutting tool for hard turning was alumina (Al_2O_3). However, this material has limited applications due to its poor fracture toughness and low thermal conductivity. These disadvantages of alumina have been improved by means of additives such as ZrO_2, SiC, TiC and TiCN. Nowadays, (Al_2O_3+TiC) mixed ceramic is widely used as a cutting tool material due to a beneficial combination of physical properties such as high thermal shock resistance, fracture toughness, and high wear resistance [4]. Moreover, they are excellent materials for high speed cutting due to their high hardness, especially at high temperatures, and their relatively low chemical reactivity with steels and many other materials [5]. The presence of Al_2O_3 in a cutting tool assists in reducing the adhesion of the workpiece material to the cutting tool surface, consequently increasing the cutting tool life [6,7].

Polycrystalline cubic boron nitride (PCBN) has also been considered as a suitable choice for hard turning applications, particularly those that require high accuracy and good surface finish. TiN coatings have been used to improve performance of the PCBN [8].

In spite of the extensive work in that field, turning of hardened alloy steels still constitutes a challenge to the machining process, and in particular the performance of the cutting tools. The presence of multiple alloying elements leads to the formation of very hard carbide particles in the structure of such steels when heat treated, leading to excessive tool wear. The resultant cutting tool wear plays a major role during finish hard turning due to its effects on surface integrity and dimensional accuracy [9]. The capability to predict tool wear during hard turning is necessary to avoid catastrophic tool failure, which leads to damage of the workpiece surface, destruction of the cutting tool, and may affect machine tool performance. Moreover, it can be used to determine the optimum cutting speed for the minimum machining cost.

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Abrasive wear has been frequently reported as the main wear mechanism in hard turning [10,11]. Due to high temperature and high stresses in hard turning, diffusion wear also may occur and is often accompanied by the decomposition of a component of one of the sliding surfaces. Chemical reactions, including oxidation at high speeds due to a high cutting temperature have also been reported [11].

The measurement of cutting force components during hard turning is essential to determine the torque and the power in order to select the proper machine tool to carry out the machining process. Moreover, the determination of the radial force component is necessary to calculate the Machine-Fixture-Tool-Workpiece (MFTW) system deflection, which affects workpiece accuracy [12]. Cutting forces are therefore used in the present study as a machinability criterion to compare between the different cutting tool materials.

The present work provides a scientific approach to select the most proper tool material for machining of the medium hardened D2 tool steel. Three different tool materials most widely recommended by literature [13–15] for hard turning of hardened steels have been used: low content Polycrystalline Cubic Boron Nitride, PCBN (BNX20); TiN coated PCBN (7020) having the same chemical composition as the first type; and (Al_2O_3+TiC) mixed alumina ceramic, a chemically stable tool material with high red hardness and reasonable toughness.

2. Experimental work

AISI D2 high carbon high chromium tool steel hardened to 52 HRC has been used in the present work. The chemical composition of the used workpiece material is presented in Table 1. The chemical composition and the hardness of the used tool materials are given in Table 2. The cutting tool inserts were mounted on a tool holder having the specifications mentioned in the same table.

The tool nose radius (r_ε) was kept constant at 1.2 mm for all the tool materials used. Machining tests were carried out on a 3 kW digitally controlled general purpose center lathe. A tool maker's microscope was used to measure the tool flank wear land width (*VB*). Progressive flank wear has been plotted against the machining time (t), in minutes. Tool life was determined at 0.2 mm flank wear. The scatter of tool wear measurements was around 10%. Scanning electron microscope (SEM) was used to study the wear mechanisms of the different cutting tools. A 3-components tool force turning dynamometer was used for measuring the cutting force components. The calibration of the cutting forces dynamometer was carried out using a loading device with a capacity of 2000 N. The calibration procedures were repeated 3 times, and the average least squares line has finally been used. Two cutting speeds (v_c) of 100 and 175 m/min were used. The chip was collected at different cutting speeds and its thickness was measured using a digital micrometer to obtain the chip compression ratio (λ_c). After each cutting test, the workpieces were machined using a mixed-alumina tool at a relatively low cutting speed of 30 m/min to minimize the probable effect of tool wear on the machined surface during the previous pass. Considering the workpiece material's ability to harden, the machined depth of cut after all the machining passes did not exceed 4 mm, maintaining uniform workpiece properties throughout the machining tests.

The characteristics of the surface tribo-films that were formed on the worn surface were studied using the X-ray photoelectron spectroscopy (XPS) on a Kratos-HS XPS system. A MgKα X-ray source was used, running at 15 kV and 10 mA. For the detailed scans on individual elements (as shown in this work for Cr) the scan was run at a pass energy of 160 eV, a step size of 50 meV, a dwell time of 100 ms with 10 passes. To reduce the impact of surface impurities on the final result, the sample was etched in the XPS system before collection of the scan using 4 keV Ar+ ions for 5 min. The deconvolution analysis was carried out using the system-supplied software and database.

Table 1
Chemical composition of the workpiece material.

%C	%Si	%Mn	%Cr	%Mo	%V	%Fe
1.55	0.3	0.4	11.8	0.8	0.8	Balance

3. Results

3.1. Tool wear and tool life

Fig. 1 illustrates the behavior of the tool flank wear land width (*VBB*) – as wear scars occurred in the tool corner area – with the machining time (t) for the three tool materials. Firstly, a machining test was carried out at 100 m/min. It was noticed that at the beginning of the machining process, the lowest wear was obtained with the PCBN tool. However, after a machining time of 5.5 min, (after exceeding a flank wear of 0.12 mm) the lowest wear was obtained by the ceramic tool. The TiN coated PCBN gave the highest wear value amongst the used tool materials.

When the cutting speed was increased to 175 m/min, similar results were observed. The PCBN tool at first displayed the lowest wear value. However, after 4.3 min, (after reaching a flank wear land of 0.16 mm) the ceramic tool displayed the lowest wear values. The highest wear was obtained by the coated PCBN tool.

Fig. 1 shows that the running-in and the stable wear stages can be easily observed when using the ceramic tool, whereas for the two types of PCBN tool; higher flank wear values in relation to time were obtained.

The corresponding tool life values for a flank wear land width of 0.2 mm are given in Table 3. The mixed ceramic tool shows 20–34% higher tool life than uncoated PCBN, and a 100–300% higher tool life than TiN coated PCBN at the cutting speeds examined here. This can be attributed to the relatively lower red hardness of TiN as a compound compared to TiC and alumina, as clearly shown at the higher speed of 175 m/min.

Fig. 2 presents the SEM micrographs of the three worn out inserts. The abrasion marks are clear on the three cutting tool flanks. Crater wear is not found on the ceramic tool face, whilst it can be observed on the faces of the two types of PCBN inserts.

3.2. Chip formation

The chip study is important for the fundamental understanding of the entire performance of the cutting process. Chip morphology

Table 2
Chemical composition of the cutting tool materials and tool holder specifications [29–31].

Tool material	Chemical compositions	Hardness	Tool holder specifications	Inserts micro-geometry
PCBN (BNX20)	60%CBN+TiN binder	3100–3300 HV	−5° rake angle, 5° clearance angle, 75° setting angle	Chamfer angle – 25°, Effective chamfer angle – 30°, Cutting edge angle 90°
TiN coated PCBN (CB7020)	57% CBN+TiN binder TiN physical vapor deposition (PVD) coated, 2 μm thickness	2700–2900 HV		
Mixed Alumina	70% Al_2O_3+30% TiC	2000 HV		