Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of the European Ceramic Society 25 (2005) 1073–1079

www.elsevier.com/locate/jeurceramsoc

Self-lubricating behaviors of Al_2O_3/TiB_2 ceramic tools in dry high-speed machining of hardened steel

Deng Jianxin*, Cao Tongkun, Liu Lili

Department of Mechanical Engineering, Shandong University, Jinan 250061, Shandong Province, PR China

Received 9 December 2003; received in revised form 15 March 2004; accepted 26 March 2004
Available online 10 July 2004

Abstract

In this paper, Al_2O_3/TiB_2 ceramic cutting tools with different TiB_2 content were produced by hot pressing. The fundamental properties of these ceramic cutting tools were examined. Dry high-speed machining tests were carried out on hardened steel. The tool wear, the cutting temperature, the cutting forces, and the friction coefficient between the tool and the chip were measured. It was shown that both the wear rates and the friction coefficient at the tool–chip interface of Al_2O_3/TiB_2 ceramic cutting tools in dry high-speed machining of hardened steel were reduced compared with that of in low-speed machining. The mechanisms responsible were determined to be the formation of a self-lubricating oxide film on the tool–chip interface owing to the tribological–chemical reaction by the elevated cutting temperature. The composition of the self-lubricating film was found to be the oxidation product of TiB_2 grains, which serves as lubricating additive on the wear track of the tool rake face. The appearance of this self-lubricating oxide film contributed to the improvement in wear resistance and the decrease of the friction coefficient. This action was even more effective with higher TiB_2 content. Cutting speed was found to have a profound effect on the self-lubricating behavior. In dry low-speed machining of hardened steel, the Al_2O_3/TiB_2 tools showed mainly adhesive and abrasive wear. While in dry high-speed machining, oxidation wear of the ceramic tools was the dominant mechanism due to the very high cutting temperature. No oxide film was formed on the tool–chip interface while machining in nitrogen atmosphere, and the tool wear resistance was correspondingly decreased.

Keywords: Cutting tools; Machining; Cutting; Lubrication; Friction; Al_2O_3; TiB_2

1. Introduction

Machining without the use of any cutting fluid (dry or green machining) is an important objective in industry to reduce environmental and production costs. The advantages of dry machining include:[1–4] non-pollution of the atmosphere or water; no residue on the swarf which will be reflected in reduced disposal and cleaning costs, no danger to health, being non-injurious to skin and allergy free. Moreover, it offers cost reduction in machining. The use of cutting fluids will be increasingly more expensive as stricter enforcement of new standards is imposed, leaving no alternative but to consider dry machining. Dry machining is becoming increasingly popular due to concern regarding the safety of the environment. Recently, consumption of cutting fluids has been reduced considerably by using mist lubrication.[5–7] However, mist in the industrial environment can have serious respiratory effects on the operator.

High-speed machining (HSM) is recognized as one of the key manufacturing technologies for higher productivity and lower production costs.[8–12] The process has been adapted to a wide range of applications. In the aerospace sector, HSM is used to remove large volumes of aluminum quickly and to produce thin walled sections in wings.[12] One of the more recent applications of HSM is in the manufacture of molds and dies from hardened tool steels.[11] Cavities can be produced from solid in the hardened state using HSM, rather than via the more traditional route: machining in the soft condition followed by electrical discharge machining, grinding and hand finishing.

In dry machining, there will be more friction and adhesion between the tool and the workpiece, since they will be subjected to higher temperatures. This will result in increased tool wear and hence reduction in tool life. In high-speed machining, the maximum cutting temperature of the insert involved can reach more than 1000 °C. Conversely, the limit

* Corresponding author.
E-mail address: jxdeng@sdu.edu.cn (D. Jianxin).

0955-2219/$ – see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jeurceramsoc.2004.03.033

on cutting speed is a function of the cutting tools used. It was thought that a reduction in all these problems could be achieved by using advanced cutting tool materials to reduce the heat generation by lowering the friction coefficient. The possible strategies involve:[13,14] (1) the isolation of the tool from the workpiece such as introducing a protective layer on the tool face; (2) promoting the transition to the diffusion limited wear regime; (3) picking a tool material chemically stable with respect to the workpiece.

Advances in ceramic processing technology have resulted in a new generation of high performance ceramic cutting tools exhibiting improved properties. Improvements have been made in tool properties such as flexural strength, fracture toughness, thermal shock resistance, hardness, and wear resistance.[15–17]

Alumina is widely used as cutting tool material and it is strengthened by the addition of particles like zirconium oxide (ZrO_2), titanium carbide (TiC), silicon carbide whiskers (SiC_w), titanium boride (TiB_2), and titanium nitride (TiN) to improve the properties. The strengthening or the toughening mechanisms of these ceramic composites are phase transformation toughening, whisker toughening and precipitate or dispersion strengthening.[18,19] These developments have now enabled ceramic tools to be used in the machining of various types of steel, cast iron, non-ferrous metals, and refractory nickel based alloys at very high-speed.[17,20,21] Thus, the productivity is improved by shorter cycle times, and the cost of manufacturing is reduced.

Now ceramic cutting tools are applied widely for machining hard materials in industry due to their unique mechanical properties. In most cases, the machining is conducted under dry or high-speed conditions, which causes high cutting temperature, high friction coefficient and wear rate, especially when cutting some difficult-to-cut materials like hardened steel. In this study, Al_2O_3/TiB_2 ceramic cutting tools with different TiB_2 content were produced by hot pressing. The fundamental properties of these ceramic cutting tools were examined. Dry high-speed machining tests were carried out on the hardened steel with these ceramic tools. The tool wear, the cutting temperature, the cutting forces, and the friction coefficient between the tool and the chip were measured. The wear mechanisms of these tools were investigated and correlated to the oxide film formed on the tool–chip interface owing to the tribological–chemical reaction. The purpose was to characterize the self-lubrication behaviors of Al_2O_3/TiB_2 ceramic cutting tools during dry high-speed machining.

2. Materials and experimental procedures

2.1. Preparation of Al_2O_3/TiB_2 ceramic cutting tools

The average particle size of the $A1_2O_3$ and TiB_2 source powders is less than 2.0 μm, and the combinations are listed in Table 1. The combined powders were prepared by wet ball milling in alcohol with cemented carbide balls for 100 h. Following drying, the powdered material was formed and compacted in a metal die with a pressure of 60 MPa. Following the forming stage, the compacted powders was then filled in a graphite die, and the final densification was accomplished by hot pressing with a pressure of 36 MPa in nitrogen atmosphere for 20–60 min to produce a disk. The required sintering temperature was in the range of 1650–1800 °C. Details of these procedures and specific processing parameters employed are described elsewhere.[22,23]

Densities of the hot-pressed materials were measured by the Archimedes's method. Test pieces of 3 mm × 4 mm × 36 mm were prepared from the hot-pressed disks by cutting and grinding using a diamond wheel[22] and were used for the measurement of flexural strength, Vickers hardness and fracture toughness. A three-point bending mode was used to measure the flexural strength over a 30 mm span at a crosshead speed of 0.5 mm/min. Fracture toughness measurement was performed using indentation method in a hardness tester (ZWICK3212) using the formula proposed by Cook and Lawn.[24] On the same apparatus the Vickers hardness was measured on the polished surface with a load of 98 N. Data for flexural strength, hardness and fracture toughness were gathered on five specimens.

2.2. Cutting tests

Cutting tests were carried out on a CA6140 lathe equipped with a commercial tool holder having the following geometry: rake angle $\gamma_o = -5^\circ$, clearance angle $\alpha_o = 5^\circ$, inclination angle $\lambda_s = -5^\circ$, side cutting edge angle $K_r = 75^\circ$. The geometry of the Al_2O_3/TiB_2 tool inserts was of ISO SNGN150608 with a 0.2 mm at 20° edge chamfer. The workpiece material used was 45# hardened steel with a hardness of HRC45–50 in the form of round bar with an external di-

Table 1
Mechanical properties of Al_2O_3/TiB_2 ceramic tools with different TiB_2 content

Sample	Composition (vol.%)		Relative density (%)	Fracture toughnes (MPa m$^{1/2}$)	Flexural strength (MPa)	Hardness (GPa)
	$A1_2O_3$	TiB_2				
AB10	90	10	99.9	3.7	650	19.6
AB20	80	20	99.7	4.7	775	20.1
AB30	70	30	99.2	5.2	785	20.8
AB40	60	40	98.5	4.9	670	21.3