Self-lubricating behaviors of Al$_2$O$_3$/TiB$_2$ ceramic tools in dry high-speed machining of hardened steel

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Abstract

In this paper, Al$_2$O$_3$/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$_2$O$_3$/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$_2$O$_3$/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.

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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
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 (ZrO2), titanium carbide (TiC), silicon carbide whiskers (SiCw), titanium boride (TiB2), 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, Al2O3/TiB2 ceramic cutting tools with different TiB2 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. 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 Al2O3/TiB2 ceramic cutting tools during dry high-speed machining.

2. Materials and experimental procedures

2.1. Preparation of Al2O3/TiB2 ceramic cutting tools

The average particle size of the Al2O3 and TiB2 source powders is less than 2 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 then filled in a graphite die, and the final densification was accomplished by hot pressing with a pressure of 36 MPa in nitro- gen 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’ method. Test pieces of 3 mm × 4 mm × 36 mm were prepared from the hot-pressed disks by cut- ting and grinding using a diamond wheel22 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 measure- ment was performed using indentation method in a hard- ness 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 γr = −5°, clearance angle αo = 5°, inclination angle λs = −5°, side cutting edge angle κs = 75°. The geometry of the Al2O3/TiB2 tool inserts was of ISO SNGN150608 with a 0.2 mm at 20° edge chamfer. The work- piece material used was 45 steel hardened to a hardness of HRC45–50 in the form of round bar with an external di-
ameter of 150 mm. No cutting fluid was used in the machin-
ing processes. Nitrogen and air atmosphere were used to in-
vestigate the effect of various atmosphere on the tool wear behaviors under similar conditions. All tests were carried out
with the following parameters: depth of cut \( a_p = 0.4 \) mm,
feed rates \( f = 0.15 \) mm/min, cutting time \( t = 12 \) min.
Tool flank wear was measured using a 20× optional mi-
croscope system linked via transducers to a digital read out.
Cutting forces were obtained with a KISTLER piezoelec-
tric quartz dynamometer linked via change amplifiers to a chart recorder. The average cutting temperature of the tool
face was measured by means of nature thermocouple tech-
nique.25 The worn rake and flank regions on the ceramic
tools were examined using scanning electron microscopy
(SEM). The elemental chemical composition of the worn
areas was determined by X-ray diffraction analysis.

3. Results and discussions

3.1. Mechanical properties and microstructural
characterization of \( \text{Al}_2\text{O}_3/\text{TiB}_2 \) ceramic tools

Results of the fracture toughness, flexural strength, hard-
ness and relative density of \( \text{Al}_2\text{O}_3/\text{TiB}_2 \) ceramic tool materi-
als with different content of \( \text{TiB}_2 \) are presented in Table 1. It
was shown that the fracture toughness increase with increas-
ing \( \text{TiB}_2 \) content up to 30 vol.% and slightly decreased at
40 vol.%, the trend of the flexural strength being the same as
that of the fracture toughness. However, the specimen with
higher \( \text{TiB}_2 \) content showed higher hardness, and the hard-
ness increased with increasing \( \text{TiB}_2 \) content up to 40 vol.%
The SEM micrograph of the fracture surface of
\( \text{Al}_2\text{O}_3/\text{TiB}_2 \) (AB30) ceramic tool material was shown in
Fig. 1. As can be seen that \( \text{Al}_2\text{O}_3/\text{TiB}_2 \) composite exhibited
a rough fracture surface and showed signs of longer crack
deflection path. The fracture mode was mixed transgranular
and intergranular. Fig. 2 shows typical backscattered elec-
tron image of \( \text{Al}_2\text{O}_3/\text{TiB}_2 \) (AB30) ceramic tool material.
Polished surface of the ceramic specimens were etched us-
ing a hot-solution of phosphoric acid for five hours. In this
structure, the white phases with clear contrast are \( \text{TiB}_2 \) and
the grey phases are \( \text{Al}_2\text{O}_3 \). It is indicated that porosity is
virtually absent, and the second phases were uniformly dis-
tributed with the matrix, and there were few second phases
agglomerates or matrix-rich regions.

3.2. Cutting performance and self-lubricating behaviors of
\( \text{TiB}_2 \) strengthening \( \text{Al}_2\text{O}_3 \) ceramic tools with different \( \text{TiB}_2 \)
content

Fig. 3 shows the flank wear of \( \text{Al}_2\text{O}_3/\text{TiB}_2 \) ceramic tools
with different \( \text{TiB}_2 \) content when dry machining hard-
Fig. 4. SEM micrograph of the wear profile of Al₂O₃/TiB₂ (AB30) ceramic cutting tool (test conditions: cutting speed \( v = 60 \text{ m/min} \), depth of cut \( a_p = 0.4 \text{ mm} \), feed rates \( f = 0.15 \text{ mm/r} \), cutting time \( t = 12 \text{ min} \)).

Enamelled steel at different cutting speeds. It can be seen that the flank wear of these ceramic tools increased very fast up to cutting speeds of 120 m/min, followed by a downward trend (with the exception of AB10). This action was even more effective with higher TiB₂ content. The ceramic tools with higher TiB₂ content showed more wear resistance.

Fig. 4 shows the SEM micrograph of the wear profile of Al₂O₃/TiB₂ (AB30) ceramic tool when the cutting speed was 60 m/min. It appears that both the rake face and flank face were severely worn under these test conditions. Fig. 5 shows SEM micrographs of the crater wear and flank wear area of Al₂O₃/TiB₂ (AB30) ceramic tool, respectively. It can be seen that there were many mechanical plowing grooves on the worn flank face, and it was indicative of typical abrasive wear. While on the worn rake face, serious adhesive wear can be clearly seen.

The crater depth profiles of Al₂O₃/TiB₂ (AB30) ceramic tool obtained at different cutting speeds and atmosphere are illustrated in Fig. 6. It was shown that the crater wear profiles of Al₂O₃/TiB₂ ceramic tool are different when machining in air and nitrogen atmosphere. The crater depth increased gradually when cutting in nitrogen atmosphere. While in air atmosphere, Al₂O₃/TiB₂ ceramic tool showed wider and deeper crater wear at cutting speed lower than 100 m/min, and exhibited very small crater wear at cutting speed higher than 150 m/min. No obvious crater wear was developed on the rake face at a cutting speed of 210 m/min.

Fig. 7 shows the cutting temperatures of Al₂O₃/TiB₂ ceramic tool as a function of cutting speeds in dry machining of hardened steel. It was found that the cutting temperature increased exponentially with increasing cutting speeds. The cutting temperature is higher than 800° C when the cutting speed is above 120 m/min, and 1190° C up to cutting speed of 210 m/min. Under such high cutting temperature, the TiB₂ of the ceramic tool material may be oxidized. The oxidation reaction can be described as the following formula:

\[
2\text{TiB}_2 + 5\text{O}_2 \rightarrow 2\text{TiO}_2 + 2\text{B}_2\text{O}_3
\]  

According to Eq. (1), the oxidation products of TiB₂ grain are composed of phases of TiO₂ and B₂O₃. The X-ray diffraction analysis of Al₂O₃/TiB₂ ceramic tool before and after cutting at 210 m/min, showed the presence of TiO₂ on the wear track, as shown in Fig. 8. No B₂O₃ is observed on the wear track because of the vaporizing due to its low melting point (about 570° C). The SEM micrograph of the worn rake face of Al₂O₃/TiB₂ ceramic tool in dry machining of hardened steel at a cutting speed of 210 m/min in air atmosphere is shown in Fig. 9. In comparison with Fig. 5, it exhibited a relative smooth surface, both mechanical plowing grooves and adhesion could not be observed, and there

Fig. 6. SEM micrographs of the crater wear profile of Al₂O₃/TiB₂ (AB30) ceramic cutting tool (test conditions: cutting speed \( v = 60 \text{ m/min} \), depth of cut \( a_p = 0.4 \text{ mm} \), feed rates \( f = 0.15 \text{ mm/r} \), cutting time \( t = 12 \text{ min} \)).

Fig. 5. SEM micrographs of the crater wear and flank wear area of Al₂O₃/TiB₂ (AB30) ceramic cutting tool (test conditions: cutting speed \( v = 60 \text{ m/min} \), depth of cut \( a_p = 0.4 \text{ mm} \), feed rates \( f = 0.15 \text{ mm/r} \), cutting time \( t = 12 \text{ min} \)).
Fig. 6. Schematic diagram of the crater wear profiles of Al₂O₃/TiB₂ (AB30) ceramic cutting tool at different atmosphere and cutting conditions.

Fig. 7. Effect of cutting speed on the cutting temperature of Al₂O₃/TiB₂ ceramic tool in dry machining of hardened steel (test conditions: depth of cut \( a_p = 0.4 \) mm, feed rates \( f = 0.15 \) mm/r, cutting time \( t = 12 \) min).

is no distinct crack on the wear track. Fig. 10 gives SEM micrograph of the cross-sectional views of Al₂O₃/TiB₂ ceramic tool in dry machining of hardened steel at a cutting speed of 210 m/min in air atmosphere. It is clearly that there is a thin film on the wear track. The thickness of this film is about 2–4 \( \mu m \). It was found that this thin film was created by the oxidation of TiB₂.

The friction coefficient between two smooth bodies sliding under elasticity loaded conditions in an elliptical contact can be decreased as:

\[
\mu = A \left( \frac{\tau}{P E'} \right)^{2/3}
\]

where \( A \) is a constant determined by contact geometry; \( \tau \), critical shear stress at the interface, which may be an oxide film; \( P \), normal load, and \( E' \), effective elastic modulus of the contact materials.

For a given contact geometry Eq. (2) shows that the friction coefficient varies linearly with critical shear stress. When there is an oxide film on the wear surface, the matrix endures the load, and friction occurs on the oxide film. As the oxide film on the wear surface had a much smaller critical shear stress than the substrate and thus resulted in a reduced friction coefficient according to Eq. (2) when dry.

Fig. 8. The X-ray diffraction patterns of Al₂O₃/TiB₂ ceramic tool before and after cutting at 210 m/min.

Fig. 9. SEM micrograph of the worn rake face of Al₂O₃/TiB₂ ceramic tool in dry machining of hardened steel in air atmosphere (test conditions: cutting speed \( v = 210 \) m/min, depth of cut \( a_p = 0.4 \) mm, feed rates \( f = 0.15 \) mm/r, cutting time \( t = 12 \) min).
high-speed machining of hardened steel. This means that the oxide film on the tool rake face acted as lubricant. Thus, self-lubrication can be accomplished under these conditions.

The friction coefficient between the tool and the chip interface could be calculated based on the following formula:\[25\]

\[
\mu = \tan(\beta) = \tan(\gamma_o + \arctan\left(\frac{F_r}{F_z}\right))
\]

(3)

where \(\beta\) is the friction angle; \(\gamma_o\), rake angle; \(F_r\), radial force; \(F_z\), main cutting force.

Fig. 11 illustrates the friction coefficient between the tool–chip interface of Al\(_2\)O\(_3\)/TiB\(_2\) ceramic tool with different TiB\(_2\) content as a function of cutting speeds in dry machining of hardened steel. It was found that the friction coefficient showed a downward trend with the increasing of the cutting speeds. The ceramic tools with higher TiB\(_2\) content showed lower friction coefficient under the same test conditions. The friction coefficient kept almost constant at low cutting speeds (smaller than 150 m/min), and within further increasing of the cutting speed the friction coefficient decreased gradually. This action was even more effective with higher TiB\(_2\) content. This may be explained by the oxide film formed on the tool rake face owing to the tribological–chemical reaction by the elevated cutting temperature. Therefore, formation of the lubricious oxide film on the wear surface resulted in a decrease in friction coefficient and wear rates. Oxidation wear of the ceramic tools was the dominant wear mechanism in dry high-speed machining hardened steel due to the very high cutting temperature.

The SEM micrograph of the worn rake face of Al\(_2\)O\(_3\)/TiB\(_2\) ceramic tool in dry machining of hardened steel at speed of 210 m/min in nitrogen atmosphere is shown in Fig. 12. It can be seen that Al\(_2\)O\(_3\)/TiB\(_2\) ceramic tool exhibited serious adhesion wear on the rake face. Nitrogen was found to have obvious effect on the tool wear because it is easy for nitrogen to enter into the tool–chip interface. The nitrogen in the tool–chip interface prohibited the oxidation of the TiB\(_2\), no lubricious oxide film was formed, and this was found to be responsible for the decreasing of wear resistance of Al\(_2\)O\(_3\)/TiB\(_2\) ceramic tool under this test conditions.

4. Conclusions

Al\(_2\)O\(_3\)/TiB\(_2\) ceramic cutting tools with different TiB\(_2\) content were produced by hot pressing. Dry high-speed machining tests were carried out on hardened steel. Results showed that:

1. Both the wear rates and the friction coefficient between the tool and chip interface of TiB\(_2\) strengthening Al\(_2\)O\(_3\)
ceramic tools were reduced in dry high-speed machining of hardened steel. 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.

2. The composition of the self-lubricating film was found to be the oxidation product of TiB₂ grains, which serves as lubricating additive. The appearance of this self-lubricating oxide film on the wear track contributed to the improvement in wear resistance and decrease of the friction coefficient. This action was even more effective with higher TiB₂ content.

3. Cutting speed was found to have a profound effect on the self-lubricating behavior of these ceramic tools during dry high-speed machining processes. In dry low-speed machining of hardened steel, the Al₂O₃/TiB₂ 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.

4. No oxide film was formed on the tool–chip interface while machining in nitrogen atmosphere, and the tool wear resistance was correspondingly decreased.

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