Mechanical Properties and Microstructures of Al₂O₃/TiC/TiB₂ Ceramic Tool Material

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Abstract: In order to develop a new ceramic tool material with self-repairing capability, Al₂O₃/TiC/TiB₂ ceramic tool material was prepared by vacuum hot-pressure sintering method. The toughening and strengthening mechanism of TiB₂ on Al₂O₃/TiC substrate was analyzed. The results show that the ceramic tool material has good comprehensive mechanical properties when the TiB₂ content is 10 vol.%. Its flexural strength was 701.32 MPa, hardness was 18.3 GPa, and fracture toughness was 6.2 MPa·m¹/₂, which were improved by 11.6%, 2.2% and 16.1% respectively, compared with the Al₂O₃/TiC tool material. Fracture surfaces of the Al₂O₃/TiC/TiB₂ ceramic tool material were characterized by SEM, EDS and XRD. The results showed that the fracture mode was a mixture of transgranular fracture and intergranular fracture. The growth of Al₂O₃ and TiC grains can be effectively inhibited by adding appropriate amount of TiB₂ and the internal grains of the material can be refined. The TiB₂ has a uniform distribution in the matrix and acts as a diffusion toughening agent. The cutting performance of Al₂O₃/TiC/TiB₂ ceramic tools was further investigated. Experiments conducted on tools made of Al₂O₃/TiC and Al₂O₃/TiC/TiB₂ materials showed that the main forms of wear for both tools were abrasive wear and bonded wear. The friction coefficient of Al₂O₃/TiC/TiB₂ tools was reduced by 10.77% compared to Al₂O₃/TiC tools.

Keywords: ceramic tool; mechanical properties; microstructures; toughing mechanism

1. Introduction

Advanced ceramic tool materials have attracted a lot of attention in the past decades due to their high density, high hardness, corrosion resistance, and good thermal stability [1,2]. Al₂O₃ ceramics are widely used in the manufacture of tools due to their superior properties. However, pure Al₂O₃ ceramics have problems such as low strength and poor fracture toughness. In order to improve the mechanical properties of Al₂O₃ ceramic tool materials, many scholars have done a lot of research. The alumina-based ceramic materials were toughened and reinforced by adding carbides, oxides, and borides to the Al₂O₃ ceramic materials. The toughening mechanisms include particle toughening, phase change toughening, and whisker toughening [3–6].

TiC is often added to alumina-based materials as a reinforcing phase [7–11]. The main reason for adding TiC particles to Al₂O₃ ceramic matrix is that TiC can inhibit the ab-normal growth of Al₂O₃ grains during the sintering process, resulting in high hardness and high strength of the material. In addition, the dispersed TiC particles can hinder the crack expansion, increase the fracture energy required for the material, and improve the fracture toughness of Al₂O₃-based ceramic materials.
However, during the use of ceramic tools, the tools are continuously affected by thermal loads and mechanical forces [12,13]. The micro-cracks and defects inside the tool form macroscopic cracks through nucleation, merging, and critical expansion and seriously reduce the mechanical properties of the tool material, which intensifies the tool wear and affects the service life of the ceramic tool. This makes it difficult for ceramic tool materials to avoid cracks.

In recent years, crack self-healing materials have been developed and applied in the field of ceramic materials [14]. Some scholars have treated ceramic materials at temperatures above 1000 °C to heal cracks [15,16]. The healing mechanism is to recrystallize the grains that have lost interatomic forces at the sintering temperature to achieve crack closure. Some scholars use the additive phase in ceramic materials to be oxidized under certain atmosphere and high temperature, and the oxide migrates to the crack for crack healing [17,18]. Deng et al. [19] found that TiB₂ can be oxidized to form titanium oxide under the action of cutting heat, which plays the role of lubrication and crack healing.

Li et al. [20,21] designed Al₂O₃/TiB₂/TiSi₂ ceramic tool material and obtained the best healing effect at 800 °C for 90 min, which effectively restored the performance of Al₂O₃-TiB₂-TiSi₂ ceramic tool material. The healing mechanism is that the additive TiSi₂ undergoes oxidation reaction at high temperature, and the oxidation products TiO₂ and SiO₂ are liquid phases that migrate into the cracks under capillary action. At the same time, the oxidation reaction causes volume expansion, squeezing the crack wall and promoting crack healing. However, the mechanical properties of the tool decreased by 21.00%, 21.40% and 4.37% compared with the existing Al₂O₃-based ceramic tool LT55.18 [22].

Because of its good mechanical and thermal properties, TiB₂ is often used as a matrix material for composite materials or added as a second phase to other matrix materials [23–27]. Furthermore, the addition of TiB₂ particles has certain repair and lubrication functions for the ceramic tools [19]. Chen et al. [28] added TiB₂ as a repairing agent to Al₂O₃/TiC ceramic tool materials, and the strength of the crack-healing samples can be restored to 91.35% of the smooth samples. The healing mechanism is that liquid B₂O₃ and TiO₂ produced by oxidation of TiB₂ at high temperature fill the cracks.

The addition of TiB₂ has a toughening function for the composites, and the addition of TiB₂ to Al₂O₃/TiC composites is expected to give the material both a toughening effect and a self-healing function due to the high-temperature oxidation property of TiB₂ [29]. Furthermore, in the cutting process of Al₂O₃/TiC/TiB₂ tools, the addition of TiB₂ is expected to increase the wear resistance of ATB tools and thus improve the cutting performance.

This experiment was conducted to investigate how the content of the restorative agent TiB₂ affects the overall mechanical properties of Al₂O₃/TiC/TiB₂ composites while making them self-healing and how the addition of the restorative agent affects the actual machining process of ceramic tools. The Al₂O₃/TiC/TiB₂ ceramic cutting tool materials with TiB₂ contents of 0, 5, 10 and 15 were prepared by vacuum hot pressing method. The mechanical properties and microstructure of composite ceramics were tested and analyzed. Cutting experiments were carried out on Al₂O₃/TiC and Al₂O₃/TiC/TiB₂ tools. The test results showed that the addition of a proper amount of TiB₂ can improve the mechanical properties of the material. Additionally, Al₂O₃/TiC/TiB₂ tool had better wear resistance than Al₂O₃/TiC tool.

2. Experimental and Methods

2.1. Components and Preparation of Ceramic Tool Materials

The addition of appropriate amount of TiB₂ can lead to higher mechanical properties and better crack repair of the tool. However, excessive addition will lead to degradation of mechanical properties and excessive oxidation of the tool material, so the TiB₂ content should not be too high. Al₂O₃, TiC, and TiB₂ have good physical and chemical compatibility [30]. The effects of TiB₂ content on the mechanical properties and microstructure of Al₂O₃/TiC/TiB₂ ceramic tool materials were investigated. The ceramic tool materials were
prepared by adding 0 vol%, 5 vol%, 10 vol% and 15 vol% TiB₂ powder to the Al₂O₃/TiC matrix, respectively.

In this study, Al₂O₃/TiC was used as the ceramic matrix material, MgO as the sintering aid, and TiB₂ as the repair and toughening phase to prepare Al₂O₃/TiC/TiB₂ ceramic tool materials with self-healing capability. The raw material sources of the specific tool materials are shown in Table 1, and the distribution of each group is shown in Table 2.

Table 1. The raw material.

| Material | Particle Size (µm) | Manufacturer |
|----------|-------------------|--------------|
| Al₂O₃    | 0.5–1             | Qinhuangdao Yinuo High-tech Materials Development Co. LTD, Qingdao, China |
| TiC      | 0.5–1             | Qinhuangdao Yinuo High-tech Materials Development Co. LTD, Qingdao, China |
| TiB₂     | 1                 | Qinhuangdao Yinuo High-tech Materials Development Co. LTD, Qingdao, China |
| MgO      | 0.5               | Sinopharm Group Chemical Reagent Co. LTD, Shanghai, China |

Table 2. The content of the ceramic tool materials.

| Material         | Al₂O₃     | TiC       | TiB₂     | MgO |
|------------------|-----------|-----------|----------|-----|
| Al₂O₃/TiC        | 69.65     | 29.85     | 0        | 0.5 |
| Al₂O₃/TiC/5 vol.%TiB₂ | 66.15     | 28.35     | 5        | 0.5 |
| Al₂O₃/TiC/10 vol.%TiB₂ | 62.65     | 26.85     | 10       | 0.5 |
| Al₂O₃/TiC/15 vol.%TiB₂ | 59.15     | 25.35     | 15       | 0.5 |

Using ultrasonic stirring and dispersing, the above powders were uniformly mixed and poured into the ball mill tank. Under the protection of nitrogen gas, the ball mill was continuously ball-milled with cement trolley balls for 48 h, and then the obtained multi-phase suspension was put into a vacuum drying oven and dried at 100 °C for 24 h and the completely dried powder material sieved with a 200-mesh sieve. Appropriate amount of the sieved powder was weighed, and the sieved powder was loaded into a graphite mold for cold pressing. The Al₂O₃/TiC/TiB₂ ceramic tool materials were prepared by sintering in a vacuum hot-pressure sintering furnace under the process parameters of sintering temperature of 1650 °C, holding time of 20 min and hot-pressure pressure of 32 MPa. (For each component, this sintering parameter was optimal.)

2.2. Performance Testing of Tool Materials

The comprehensive mechanical properties of the Al₂O₃/TiC/TiB₂ ceramic tool materials prepared by vacuum hot-pressure sintering were tested. First, the materials were pretreated by slicing, coarse grinding, fine grinding, lapping and polishing. The materials were processed into standard strip samples with surface roughness Ra less than 0.1 µm and dimensions of 3 mm × 4 mm × 35 mm. In the hardness test, bending strength test, and fracture toughness test, 10 samples of the same material were tested and the arithmetic mean of the test results was calculated.

The three-point bending method was used to test the flexural strength of the specimen with a microcomputer-controlled electronic universal testing machine (WDW-50E). The span of the support point was set to 20 mm, and the loading speed was set to 0.5 mm/min. The bending test followed the standard GB/T 6569-86. The hardness of the sample was measured by indentation method using a Vickers hardness tester (Hv-120). The selected indenter was a diamond quadrilateral indenter with an inclusion angle of 136° between
the opposite faces. The load was set to 196 N, and the loading time was 15 s. The hardness calculation equation was:

\[ H_V = \frac{1.8544P}{(2a)^2} \]

where \( H_V \) was the Vickers hardness of the material (MPa), and \( P \) was the set load, which was set to 196 N in this experiment; the length of the diagonal of the indentation was measured and the arithmetic mean was taken as \( 2a \).

The fracture toughness of the specimen was measured by the indentation method. The calculation equation [31] was as follows:

\[ K_{IC} = 0.203H_V a^1 \left( \frac{C}{a} \right)^{-2} \]

where \( K_{IC} \) was the fracture toughness of the specimen material (MPa·m^{1/2}); \( H_V \) was the Vickers hardness measured by the indentation method (MPa); \( c \) was half of the length of the crack indented by the hardness tester (mm); and \( a \) was half of the length of the diagonal of the indentation (mm).

For phase composition, the sintered materials were analyzed using X-ray diffraction (XRD, D8-ADVANCE, Bruker AXS, Karlsruhe, Germany) in the 2\( \theta \) angle range of 10–90\( ^\circ \). Scanning electron microscopy (SUPRA\textsuperscript{TM} 55, Jena, Germany) was used to characterize the micro-morphology of the fracture surface, and energy dispersive spectrometer (EDS) was used to analyze the element distribution of the material.

2.3. Cutting Test of Ceramic Tool Materials

Cutting experiments were performed on a CDE6140A lathe. The tool holder was Kennametal GSSN R/L 2525M12-MN7 (Kennametal Inc., Latrobe, PA, USA). The roughness of the machined workpiece surface was measured by a TR200 handheld roughness tester (Time Group Inc., Jinan, China), and the change in cutting force during cutting was measured by a Kistler-9129A force tester. The material for cutting the workpiece was 40Cr hardened steel with a hardness of 48–50 HRC.

3. Results and Discussion

3.1. XRD Pattern of Al\(_2\)O\(_3\)-TiC-TiB\(_2\) Ceramic Tool Material

As can be seen from Figure 1, there are obvious characteristic peaks of Al\(_2\)O\(_3\), TiC, and TiB\(_2\) with sharp peaks and good crystallinity in the X-ray diffraction patterns (XRD) of the Al\(_2\)O\(_3\)/TiC/10 vol.%TiB\(_2\) ceramic tool material. In addition, no other impurity peaks appear, which indicates that there is no high-temperature reaction between the components of the material and good chemical compatibility. This is consistent with the results of energy dispersive spectroscopy (EDS) spectra. The peak shape of the sintering aid MgO was not found, due to the low content of MgO, which was difficult to detect.

Moreover, there are no other impurity peaks, which indicates that there is no high-temperature reaction between the components of the material and it has good chemical compatibility. This is consistent with the results of energy dispersive spectrometer (EDS) spectra. The peak shape of the sintering additive MgO is not found, which is difficult to detect due to the low content of MgO.

3.2. Mechanical Properties of Al\(_2\)O\(_3\)/TiC/TiB\(_2\) Ceramic Tool Materials with Different TiB\(_2\) Content

Four ceramic tool materials—Al\(_2\)O\(_3\)/TiC, Al\(_2\)O\(_3\)/TiC/5 vol.%TiB\(_2\), Al\(_2\)O\(_3\)/TiC/10 vol.%TiB\(_2\), and Al\(_2\)O\(_3\)/TiC/15 vol.%TiB\(_2\)—were prepared under the same experimental preparation process and sintering process (sintering temperature 1650 °C, holding time 20 min, hot pressing pressure 32 MPa). The mechanical properties of the four materials were tested.
Figure 1. XRD pattern of Al₂O₃/TiC/10 vol.% TiB₂ ceramic tool material surface.

The results of the mechanical properties tests of the four materials are shown in Figure 2. The error bars in Figure 2 represent the standard deviation of the sample test data. From Figure 2a, the flexural strength of the tool materials gradually increased and then decreased with the increase of TiB₂ content. When the TiB₂ content is 10 vol.%, the strength of Al₂O₃/TiC/TiB₂ material reaches 701.32 MPa, which is 11.6% higher compared with the strength of 628.29 MPa of Al₂O₃/TiC ceramic tool material. When the TiB₂ content is 15%, the flexural strength of the tool material decreases slightly. The reason is that the excessive TiB₂ content leads to abnormal grain growth and reduces the relative density of the tool material. In addition, the thermal expansion mismatch between TiB₂ particles and the base material generated residual tensile stresses in the base material. With the increase of TiB₂ particles, the excessive residual stress will lead to the cracking of the matrix material and thus reduce the strength of the material, so the TiB₂ content should not be too high. Figure 2b shows the variation of Vickers hardness for different tool materials. With the increase of TiB₂ content, the hardness of the material gradually increases and then tends to level off. The hardness of the material increased significantly from 17.9 GPa to 18.3 GPa with the addition of 10 vol.% TiB₂. However, when the content of TiB₂ is too high, it is not uniformly distributed in the matrix, which tends to cause phenomena such as particle aggregation and re-generation of pores and cracks in the matrix material, which is not conducive to the improvement of the tool material performance. Figure 2c shows that the fracture toughness of the material increased significantly with the increase of TiB₂ content in the matrix material, and then leveled off, increasing from the initial 5.2 MPa·m¹/² to 6.2 MPa·m¹/², an increase of 16.1%. Among them, the TiB₂ content increased the most from 0% to 5%. This is because the addition of TiB₂ refines the internal grains of the material, and from Table 3 it is also clear that the addition of TiB₂ significantly reduces the average grain size of the composite. The densification of the material increases, which in turn increases the grain boundaries and grain boundary area. As a result, the energy required to fracture the material increases and the fracture toughness of the material increases.

Table 3. Average particle size of different components of the material.

| Material                  | The Average Particle Size (µm) |
|---------------------------|-------------------------------|
| Al₂O₃/TiC                | 1.39                          |
| Al₂O₃/TiC/5 vol.% TiB₂   | 1.31                          |
| Al₂O₃/TiC/10 vol.% TiB₂  | 1.28                          |
| Al₂O₃/TiC/15 vol.% TiB₂  | 1.40                          |
Figure 2. Effect of TiB$_2$ content on (a) flexural strength, (b) Vickers hardness, and (c) fracture toughness.

The above mechanical property test results of ceramic tool materials with different TiB$_2$ contents show that the addition of appropriate amount of TiB$_2$ can significantly improve the comprehensive mechanical properties of Al$_2$O$_3$/TiC-based ceramic materials.

Figure 3 shows the crack healing properties of Al$_2$O$_3$/TiC/10 vol.% TiB$_2$ tool materials. The cracks were made by Vickers hardness tester, as shown in Figure 3a. The trace at the ellipse mark in Figure 3b indicates that the cracks were filled with oxidation products and healing was achieved after heat treatment. The results indicate that the Al$_2$O$_3$/TiC/10 vol.% TiB$_2$ ceramic tool material has some healing properties.

Figure 3. Repair properties of Al$_2$O$_3$/TiC/TiB$_2$ ceramic. (a) prefabricated crack (b) healed crack.
3.3. Microstructures of Al$_2$O$_3$/TiC/TiB$_2$ Ceramic Tool Materials with Different TiB$_2$ Content

Scanning electron microscopy (SEM) micrographs of the fracture surfaces of Al$_2$O$_3$/TiC-based ceramic tool materials with different TiB$_2$ contents are shown in Figure 4. From Figure 4, the Al$_2$O$_3$/TiC ceramic tool material has some uneven particle size and has pores (as marked by arrows in Figure 4a). Compared with the Al$_2$O$_3$/TiC ceramic tool material, the grain size of the material decreases when the TiB$_2$ content in the material is 5%. When the TiB$_2$ content is 10%, the grain size of the composite cross-section is uniform and the grain boundary between each grain is obvious. Additionally, some tough nests left after grain pull-out were found (as shown by the arrows in Figure 4c). In the process of grain pull-out, the grains rubbed against the matrix material, which increased the energy consumption at fracture and played a toughening effect. However, when the TiB$_2$ content is 15%, abnormally grown grains appear in the material, which affects the denseness of the material and thus reduces the flexural strength of the material, which is consistent with the results in Figure 2a. In addition, distinct stepped traces and river-like patterns can be observed at the fracture, which is an important morphological feature to explain the through-grain fracture. Therefore, the fracture mode of the tool material is mixed transgranular/intergranular fracture, which will consume more fracture energy and help to improve the mechanical properties of the material.

![Figure 4](image_url)

Figure 4. The microstructures of fracture surface of Al$_2$O$_3$/TiC/TiB$_2$ ceramic tool materials with different TiB$_2$ content (a) Al$_2$O$_3$/TiC, (b) Al$_2$O$_3$/TiC/5 vol.% TiB$_2$, (c) Al$_2$O$_3$/TiC/10 vol.% TiB$_2$, and (d) Al$_2$O$_3$/TiC/15 vol.% TiB$_2$.

The average grain size of Al$_2$O$_3$/TiC ceramic tool materials with different TiB$_2$ contents was measured using the cross-sectional method. For each material, 200 grains were taken and the grain size was counted, and the arithmetic mean was taken as the measurement result, which is shown in Table 3. The results showed that the average grain size of the composites decreased with the addition of TiB$_2$ but increased with the excess of TiB$_2$. When the TiB$_2$ content was 10%, the average particle size of the composites was the smallest. When the TiB$_2$ content was 15%, the average particle size of the composites was the largest and slightly larger than that of the Al$_2$O$_3$/TiC material. The reason for this is that excessive
TiB$_2$ led to its agglomeration in the matrix material and the inhibitory effect of TiB$_2$ on Al$_2$O$_3$ and TiC grains in the composite is weakened, resulting in abnormal grain growth. The test results of the average grain size showed that the appropriate TiB$_2$ can refine the grains of the composites.

From the test results in Figure 4 and Table 3, it is clear that the addition of TiB$_2$ has a great influence on the microstructure of the Al$_2$O$_3$/TiC matrix material. The addition of appropriate amount of TiB$_2$ can refine the internal grains of the material, effectively inhibit the growth of Al$_2$O$_3$ and TiC grains, and make the internal grains of the material more uniform. This is the reason why the mechanical properties of Al$_2$O$_3$/TiC/10 vol.% TiB$_2$ ceramic tool materials are improved.

The relative densities of Al$_2$O$_3$/TiC-based composites with different TiB$_2$ contents were measured by Archimedes drainage method, and the experimental results are shown in Figure 5. The relative densities of the composites first increased and then decreased as the TiB$_2$ content increased. When the content of TiB$_2$ was 10%, the relative density of the composites was the best, reaching 99.5%. When the TiB$_2$ content was 15%, the density of the material started to decrease, but it was still higher than that of the Al$_2$O$_3$/TiC material. The reason is that too high TiB$_2$ content in the composites leads to agglomeration of TiB$_2$ particles, which reduces the denseness of the material.

![Figure 5](image.png)

Figure 5. The relative density of Al$_2$O$_3$/TiC/TiB$_2$ ceramic tool materials with different TiB$_2$ contents.

Further, elemental analysis of the Al$_2$O$_3$/TiC/10 vol.% TiB$_2$ ceramic tool material was carried out, and the test results are shown in Figure 6. It can be seen in Figure 6a that the internal grains of the material are uniform and fine in size, and the grains are tightly bonded, with obvious traces of steps in many places. From the elemental analysis in Figure 6b–f, the main elements in this region are C, O, Al, Ti and B, and no other impurity elements exist. This indicates that the materials in this part are Al$_2$O$_3$, TiC and TiB$_2$, and there are no other impurities. In addition, it can be seen that the elements in each phase have good dispersion and no obvious aggregation, showing a cross-distributed spatial structure. Figure 6c,d indicates the distribution of Al$_2$O$_3$, Figure 6b–e indicates the distribution of TiC, and Figure 6e,f indicates the distribution of TiB$_2$. According to Figure 6a–f, the Al$_2$O$_3$ grains were uniform in size without abnormal growth, and there were no obvious pores between Al$_2$O$_3$, TiC and TiB$_2$ grains, and the grains were tightly bonded to each other. The results show that the addition of TiB$_2$ effectively inhibits the growth of Al$_2$O$_3$ and TiC grains, refines the grains, and improves the denseness of the composites. The morphology of grain-piercing fracture mainly occurred on the TiB$_2$ grains. Moreover, TiB$_2$ grains are uniformly distributed in the material matrix, which can play the role of diffusion toughening.
Figure 6. SEM micrographs (a) and EDS elemental distribution maps (b-f) of fracture surfaces of Al₂O₃/TiC/10 vol.% TiB₂ ceramic tool material.

The mass percentages of each element in the energy spectrum analysis in Figure 6 are shown in Table 4. According to the EDS energy spectrum in Figure 6 and the contents of various elements in Table 4, the contents of Al₂O₃, TiC and TiB₂ in the tested materials are basically consistent with those of Al₂O₃/TiC/10 vol.% TiB₂ materials. Furthermore, the distribution of the composites is uniform.

Table 4. Mass percentage of each element in the energy spectrum analysis in Figure 6.

| Element | Mass Percentage (Wt%) |
|---------|-----------------------|
| O       | 32.6                  |
| Ti      | 22.9                  |
| Al      | 18.3                  |
| C       | 14.1                  |
| B       | 12.0                  |
Figure 7 shows the comparison of sintering of ceramic tool materials with Al$_2$O$_3$ /TiC and Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$. From Figure 7, it can be seen that the tool material without TiB$_2$ has uneven grain size and pores in the material; the tool material with 10 vol.% TiB$_2$ added has uniform grain size and better denseness.

![Sintering comparison chart of Al$_2$O$_3$ /TiC and Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$ ceramic tool materials.](image)

**3.4. Cutting Performance of Al$_2$O$_3$ /TiC Ceramic Tool and Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$ Ceramic Tool**

To investigate the effect of improved mechanical properties of Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$ ceramic tool material on cutting performance, cutting experiments were carried out on Al$_2$O$_3$ /TiC ceramic tools and Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$ tools under the same experimental conditions. The cutting speed of the cutter was 300 m/min, the back cutting amount was 0.2 mm, the feed rate was 0.102 mm/r, and the cutting distance was 3500 m. For the convenience of description, the Al$_2$O$_3$ /TiC tool was noted as AT and the Al$_2$O$_3$ /TiC/10 vol.% TiB$_2$ tool was noted as ATB.

**3.4.1. Effect of TiB$_2$ Addition on Tool Wear Performance**

Figure 8 shows the wear patterns of the AT tool and ATB tool. From Figure 8a,b, it can be seen that the front face wear of both tools is mainly adhesive wear. During the cutting process, the front tool face of the tool is subjected to a combination of high mechanical and thermal stresses, resulting in partial grain loss on the tool surface. From Figure 8c,d, it can be learned that the rear tool face wear of both tools is mainly in the form of abrasive and partially adhesive wear. Compared with the ATB tool, the mechanical furrow shape on the rear tool face of the AT tool is more serious. A lubricating film appears on the rear tool face of the ATB tool, and the degree of wear is significantly less than that of the AT tool. Both tools have micro chipping phenomenon, but the degree of micro chipping of ATB tool is significantly smaller than that of AT tool, and the crescent concave shape of the front face of AT tool is deeper. The reason for this is that the addition of TiB$_2$ improves the mechanical properties of the material and increases the anti-wear ability of the ATB tool. Figure 8e is an enlarged view of the area No. 1 marked by the dashed box in Figure 8d, and Figure 8f is an enlarged view of the area No. 2 marked by the dashed box in Figure 8d. In Figure 8e,f, some damaged areas of the cutting edge and rear face of the ATB tool are gradually filled and repaired. Under the action of cutting heat, TiB$_2$ in the ATB tool is...
oxidized to produce $\text{B}_2\text{O}_3$ and $\text{TiO}_2$ [21]. These oxidation products cover the tool surface by the action of the tool and the workpiece and gradually fill in the damage and cracks of the tool during the machining process. At the same time, the $\text{TiO}_2$ and $\text{B}_2\text{O}_3$ present on the tool surface also play a certain role in lubrication [19].

The surface energy spectrum analysis of the ATB tool after cutting is shown in Figure 9. Figure 9b shows the elemental analysis at point 1 in Figure 9a, and Figure 9c shows the elemental analysis at point 2 in Figure 9a. From Figure 9b, it can be seen that the main elements at point 1 on the tool surface in Figure 9a are Al, O, Ti, Fe and B. This indicates that the materials here on the tool surface are oxides of Al, Fe, Ti and B, which is consistent with the previous analysis. In Figure 9c, it can be seen that the main elements at point 2 on the tool surface in Figure 9a are Al, O, Ti and Fe. Among them, Fe and O are more, Ti and Al are less, and Mn and Si originating from 40Cr workpiece appear. This indicates that the chips oxidize and adhere to the tool surface under high temperature cutting heat.

### 3.4.2. Effect of TiB$_2$ Addition on Cutting Force of Ceramic Tool

The comparison of cutting forces between AT tool and ATB tool is shown in Figure 10. The main cutting force $F_z$, radial force $F_y$, and axial force $F_x$ of ATB tool are smaller than that of AT tool, and the main cutting force is 6% lower than that of AT tool. The better comprehensive mechanical properties of ATB tool and the certain repair and lubrication

![Figure 8. Wear morphology and partial enlargement of the flank of two kinds of ceramic tools (a,c) AT (b,d–f) ATB.](image-url)
ability of TiB$_2$ in tool material reduce the damage of ATB tool during cutting. Therefore, the cutting process of ATB tool is more stable and the impact force to which the tool is subjected is smaller.

Figure 9. Scanning electron microscope photograph (a) and energy spectrum element diagram (b,c) of ATB tool surface.

Figure 10. Comparison of cutting forces of different cutting tools.

Based on the measured main cutting force $F_z$ and radial force $F_y$, the friction coefficient of the front tool face is calculated for both tools. The calculation formula is as follows:

$$\mu = \tan(\gamma_0 + \arctan\left(\frac{F_y}{F_z}\right))$$

In the equation, $\mu$ is the friction coefficient of the front tool face and $\gamma_0$ is the front angle of the tool. After calculation, the friction coefficient of AT tool is 0.65, while the friction coefficient of ATB tool is 0.58. Compared with AT tool, the friction coefficient of
leading-edge surface of ATB tool is decreased by 10.77%. The experiments show that the wear resistance of ATB tool material is better than that of AT tool material.

The surface roughness of the workpiece after cutting with both tools is compared in Figure 11. The surface roughness of the workpiece increases with increasing cutting distance for both tools. The surface roughness of the workpiece machined with the ATB tool increases gently, while the surface roughness of the workpiece machined with the AT tool increases rapidly. This is because the machining process of the ATB tool is more stable due to its good mechanical properties. This is consistent with the analysis of cutting forces.

![Figure 11. Surface roughness of different cutting tools.](image1)

Figure 12 shows a schematic diagram of the restoration function of ATB tools during cutting. The main factor for tool restoration during cutting is TiB\textsubscript{2} oxidation due to cutting heat.

![Figure 12. Repair mechanism of ATB tool in cutting process.](image2)

4. Conclusions

The Al\textsubscript{2}O\textsubscript{3}/TiC/TiB\textsubscript{2} ceramic tool materials with different TiB\textsubscript{2} contents were prepared, and the effects of TiB\textsubscript{2} contents on the mechanical properties and microstructure of the composites were investigated. The cutting experiments of Al\textsubscript{2}O\textsubscript{3}/TiC and Al\textsubscript{2}O\textsubscript{3}/TiC/TiB\textsubscript{2} tools were carried out.
(1) With the increase of TiB₂ content, the comprehensive mechanical properties of Al₂O₃/TiC/TiB₂ ceramic tool materials showed a trend of first increase and then decrease. When the TiB₂ content is 10 vol.%, the best comprehensive mechanical properties of ceramic tool materials are obtained. The flexural strength, hardness, and fracture toughness were 701.32 MPa, 18.3 GPa, and 6.2 MPa·m⁹/₂, which were 11.6%, 2.2%, and 16.1% higher than those of Al₂O₃/TiC ceramic tool material, respectively.

(2) TiB₂ content has a significant influence on the microstructures of Al₂O₃/TiC/TiB₂ ceramic tool materials. The fracture modes of ceramic tool materials are mainly transgranular fracture and intergranular fracture. The addition of TiB₂ can effectively refine the grains, inhibit the abnormal growth of Al₂O₃ grains, and reduce the porosity of the material. However, excessive TiB₂ can lead to the abnormal growth of some grains. TiB₂ particles can induce transgranular fracture and significantly improve the mechanical properties of the tool material. Phase analysis shows that TiB₂ has good chemical stability and does not react chemically with other components under vacuum sintering conditions.

(3) The addition of TiB₂ enhances the wear resistance of the tool to a certain extent. Compared with Al₂O₃/TiC tool material, Al₂O₃/TiC/10 vol.% TiB₂ tool material has better wear resistance. When cutting with Al₂O₃/TiC/10 vol.% TiB₂ tool, the TiB₂ of the tool undergoes oxidation reaction at high cutting temperature, and the oxidation products can repair the cracks of the tool to some extent. At the same time, B₂O₃ and TiO₂ produced during the cutting process are dragged to the surface of the tool, which plays a certain role of lubrication. The friction coefficient of the Al₂O₃/TiC/10 vol.% TiB₂ tool is 10.77% lower than that of the Al₂O₃/TiC tool.

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