Preparation and Performance of Al$_2$O$_3$/Ti(C,N)-Added ZrO$_2$ Whisker and NanoCoated CaF$_2$@Al(OH)$_3$ Powder

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Abstract: The Al$_2$O$_3$/Ti(C,N) ceramic material added micron ZrO$_2$ whisker and nano coated CaF$_2$@Al(OH)$_3$ powder was fabricated. The micron ZrO$_2$ whisker was for the toughening and reinforcing phase and the nano coated CaF$_2$@Al(OH)$_3$ powder was the lubricant. For obtaining a ceramic material with optimal comprehensive mechanical properties and friction properties, the influences of different compositions of the ZrO$_2$ whisker and nano coated CaF$_2$@Al(OH)$_3$ powder on the microstructure and mechanical properties were analyzed, respectively. The result demonstrated that as the addition of the ZrO$_2$ whisker was 6 vol% and the addition of the nano coated CaF$_2$@Al(OH)$_3$ powder was 10 vol%, the optimal self-lubricating ceramic material had optimal mechanical properties. The hardness of the ceramic material was 16.72 GPa, the flexural strength was 520 MPa and the fracture toughness reached 7.16 MPa·m$^{1/2}$. The formation of the intragranular structure, whisker toughening and the phase transition of ZrO$_2$ were the main mechanisms.

Keywords: ZrO$_2$ whisker; nano coated powder; toughening and reinforcing; intragranular structure; mechanism analysis

1. Introduction

The ceramic materials can be generally used in various fields because of excellent chemical and physical properties [1–3]. Aluminum oxide is an ideal material due to its inherent high hardness and excellent thermal stability [4–6]. Currently, aluminum oxide-based ceramic materials are broadly used in cutting tool molds, sealing rings and various high temperature engine parts [7–9]. However, the low-fracture toughness and the brittleness contribute to the aluminum oxide-based ceramic risk of being easily chipped in the course of processing, which seriously influences the cutting performance of the ceramic tool material [10–12]. The self-lubricating ceramic tool materials with excellent mechanical properties and friction properties have always been people’s pursuit goal.

To acquire the ceramic material with excellent mechanical properties, many scholars have studied gradient design and layered design [13–15]. Yang [16] prepared the gradient composite Al-7Si-5Cu/Al$_2$O$_3$. The flexural strength of the material increased significantly. Katsui [17] studied the deposition of SiC layers on SiO$_2$ and diamond powders. The result showed that the formation of the microstructure enhanced the mechanical properties. Dang [18] prepared mullite using Al$_2$O$_3$ powders and coated SiO$_2$@SiC powders. The mechanical properties were better than without whisker. The surface modification technology can effectively enhance the mechanical properties of the ceramic materials, and the preparation is becoming more and more mature, which has become the first choice of many scientists.
At present, strengthening the toughness of the ceramic tool material with fiber (including whisker) is an effective means [19–22]. Zhu [23] prepared an Al2O3 membrane by introducing ZrO2 fiber. Compared with the sample of unadded ZrO2 fiber, the addition of ZrO2 fiber increased the flexural strength of the material. Zu [24] investigated multi-walked carbon nanotubes to optimize the carbon fiber-reinforced ZrB2-based ceramic material. The fracture toughness was 7.0 ± 0.4 MPa·m1/2, 1.6 times the value of the ceramic without the multi-walked carbon nanotubes. Zhai [25] prepared the Al2O3/MgAl2O4/ZrO2 ternary eutectic ceramic. The ZrO2 phase acted as a whisker in the ceramic. The fracture toughness reached 6.1 MPa·m1/2, 1.7 times the value of the pre-sintered ceramic. The ZrO2 has an extremely special phase transition toughening [26–28]. The Al2O3/ZrO2/CeO2 composites were processed in his research [29]. The transformation of m-ZrO2 into t-ZrO2 resulted in the toughening of the Al2O3 composite. Yu [30] prepared the Al2O3–ZrO2 (Y2O3) powders with different Y2O3 addition. The additional Y2O3 phase contributed to the abundance of ZrO2 polymorphs in the powders. The phase transition of ZrO2 significantly enhances the mechanical properties of the ceramics.

The ceramic tool materials with lubricant have also been extensively studied. Wu [31] prepared Al2O3/TiC/CaF2 self-lubricating ceramic material. The fracture toughness increased by 5.9%. Wu [32] prepared Al2O3/(W,Ti)C ceramic material added with h-BN@Ni powders. The friction coefficient and wear rate were both less than the Al2O3/(W,Ti)C/h-BN ceramic materials. Chen [33] prepared the self-lubricating tool with SiO2-coated h-BN. The flexural strength and fracture toughness were obviously improved. The reasonable addition of lubricant can improve the mechanical properties and friction properties.

Herein, to acquire the ceramic tool material with excellent mechanical properties and friction properties, a kind of self-lubricating ceramic material added micron ZrO2 whisker and nano coated CaF2@Al(OH)3 powder was introduced. The Al2O3 was the matrix material. Due to the high hardness, the flexural strength and the fracture toughness of Ti(C,N), the Ti(C,N) was the matrix material. The micron ZrO2 whisker was the toughening and reinforcing phase. The nano coated CaF2@Al(OH)3 powder was the solid lubricant. The influences of the different compositions of the ZrO2 whisker and nano coated CaF2@Al(OH)3 powder on the microstructure and mechanical properties were analyzed, respectively. The main mechanisms of the self-lubricating ceramic tool material were revealed.

2. Materials and Methods

2.1. Fabrication of Nano Coated CaF2@Al(OH)3 Powder

The preparation process of nano coated CaF2@Al(OH)3 powder was as follows: The ethanol, benzene and water were mixed according to the volume ratio of 6:2:1 as a solvent. The polyvinylpyrrolidone (PVP) was added to prepare the solution containing 0.5 mol/L. The nano CaF2 (5–10 nm, self-made) was added to prepare the solution containing CaF2 0.1 mol/L, and afterward ultrasonic treatment was carried out for 40 min. The dilute ammonia water was mixed alcohol and ammonia water with a volume ratio of 5:1. The CaF2 suspension was stirred with a magnetic stirrer (DF-101S) at 25 °C. The aluminum nitrate solution of 0.5 mol/L was slowly poured into the CaF2 suspension, and the solution was continuously stirred for 20 min until the solution was uniform. Dropwise, diluted ammonia water was added at 2 mL/min to adjust the pH of the solution to 7. The Al(OH)3 finally formed the heterogeneous nucleation coating on the surface of nano CaF2. The nano coated CaF2@Al2O3 powder can be obtained by centrifuging, washing and sintering the CaF2@Al(OH)3.

2.2. Fabrication of Al2O3/TiC/N/ZrO2/CaF2@Al(OH)3 Ceramic Material

Commercially available Al2O3 (200 nm, purity ≥ 99.9%, Shanghai Chaowei New Material Co., Ltd., Shanghai, China) and Ti(C,N) (80 nm, purity ≥ 99.9%, Hefei Yulong New Material Co., Ltd., Hefei, China) used here were raw materials. The ZrO2 whisker (mean diameter and length were 1–3 μm and 10–20 μm, respectively) was raw material. MgO (1 μm, purity ≥ 99.9%, Sinopharm Chemical Reagent
The Al₂O₃ and MgO powders, Ti(C,N) powders were added to the absolute ethyl alcohol with polyethylene glycol, respectively. Then, the dispersions were ultrasonically dispersed and mechanically stirred for 20–30 min. Mixing the Al₂O₃ dispersion, the Ti(C,N) dispersion and the dispersion containing the nano coated CaF₂@Al(OH)₃ powder, the mixed solution was ultrasonically dispersed and mechanically stirred for 10–30 min, thereafter the dispersion was poured into ball mill tank for ball milling. After 44 h of ball milling, the ZrO₂ whisker was added to the ball mill tank. The prepared multiphase suspension was dried in the vacuum drying oven (DZF-6050, Shanghai, China), and then the multiphase suspension was sieved to obtain composite powder. The composite powder was put into a graphite sleeve for cold-pressing. After the hot pressing in the vacuum hot-pressing sinter (ZR1050, Jinan, China), the Al₂O₃/Ti(C,N)/ZrO₂/CaF₂@Al(OH)₃ ceramic material was fabricated. The preparation process influenced the microstructure and further influenced properties of the material [34,35]. The parameters selected in this experiment were as follows: the sintering temperature was set to 1650 °C under 30 MPa, the soaking time was selected as 20 min and the heating rate of the preparation progress was set to 20 °C/min. Figure 1 shows the process flow chart of the composite ceramic material preparation.

![Figure 1. The flow chart of the composite ceramic material preparation.](image_url)

### 2.3. Performance Testing of the Ceramic Material

The ceramic material after hot pressing was cuboid with the size of 3 mm × 4 mm × 35 mm. The surface roughness Ra of the ceramic material was less than 0.1 μm. The instrument used for the hardness test of the ceramic tool material was the Hv-120 Vickers hardness tester (Hv-120, Jinan, China), which measured with the Vickers indentation method. The indentation load was set to 196 N for 15 s. The indentation of the ceramic material was observed and measured by optical microscope. Then, the length of the diagonal of the two indentations was recorded. The hardness of the ceramic material could be calculated by the function:

\[
H_v = \frac{1.8544P}{(2a)^2}
\]
where $H_V$ is the hardness value (GPa); $P$ is the indentation load (N); and $2a$ is the arithmetic average value of the diagonal lengths of the two indentations produced.

The flexural strength of the ceramic material was measured by the three-point bending method. The span value was 20 mm and the displacement loading speed was 0.5 mm/min. The flexural strength of the ceramic material could be calculated by the function:

$$\sigma_f = \frac{3PL}{2bh^2}$$  

where $\sigma_f$ is the flexural strength (MPa); $P$ is the maximum load (N) value loaded when the sample is broken; $L$ is the distance (mm) between the two supports supporting the sample; and $b$ and $h$ are the width (mm) and height (mm) of the sample, respectively.

The fracture toughness was also measured by the indentation method. The instrument used for fracture toughness test of the ceramic material was the Hv-120 Vickers hardness tester (Hv-120, Jinan, China). The fracture toughness of the ceramic material could be calculated by the function:

$$K_{IC} = 0.203H_Va^{1/2}\left(\frac{c}{a}\right)^{3/2}$$  

where $K_{IC}$ is the fracture toughness (MPa$\cdot$m$^{1/2}$); $H_V$ is the hardness value (GPa) measured by the Vickers indentation method; $a$ is the half length (mm) of the diagonal lengths; and $c$ is the half length (mm) of the crack diagonal.

Density test of the ceramic material was performed by the drainage method. The dry weight $M_1$, submerged weight $M_2$ and wet weight $M_3$ of the sample were weighed by a precision electronic balance (ME105DU, Jinan, China). The density of the ceramic material could be calculated by the function:

$$\rho_s = \frac{M_1\rho_0}{M_3 - M_2}$$  

where $\rho_s$ is the density (g/cm$^3$) of the sample; $\rho_0$ is the density (g/cm$^3$) of the distilled water; $M_1$ is the weight (g) when the sample is dried; $M_2$ is the submerged weight (g) in the liquid; and $M_3$ is the wet weight (g) measured in the air after the sample is sufficiently absorbed. The relative density of the ceramic material could be calculated by the function:

$$\rho = \frac{\rho_s}{\rho_t} \times 100\%$$  

where $\rho$ is the relative density of the ceramic material; $\rho_s$ is the density (g/cm$^3$) of the sample; and $\rho_t$ is the theoretical density (g/cm$^3$).

To decrease the measurement error and ensure the accuracy of the measurement, every ceramic material was tested 5 times. The arithmetic average value was the measured value of the ceramic material.

3. Results and Discussion

3.1. XRD Phase Composition Diagram of the Ceramic Material

The XRD (X-Ray Diffraction) diffraction analysis of the ceramic material with 6 vol% $\text{ZrO}_2$ whisker and 10 vol% nano coated $\text{CaF}_2@\text{Al(OH)}_3$ powder is shown in Figure 2. In the ceramic material, the phase analysis indicates that the predominant phases for the composites are $\text{Ti(C,N)}$ and $\text{Al}_2\text{O}_3$. Before the experiment, the $\text{ZrO}_2$ whisker exists in monoclinic phase. From Figure 2, it can be seen that $\text{ZrO}_2$ exists mainly in the form of t-$\text{ZrO}_2$ in the ceramic material. This indicates that the phase transition took place during the sintering. The $\text{ZrO}_2$ whisker underwent a phase change. The introduction of nano coated powder does not have a significant influence on it, which provides the
With the increase in ZrO\(_2\) whisker increasing, the relative density decreases first and afterward increases. As can be seen from the ceramic material without ZrO\(_2\) whisker, it obtains maximum flexural strength when the ZrO\(_2\) whisker addition is 6 vol%. The occurrence of pores leads to a decrease in the relative density. Due to the contrast, less pores can be seen in the cross section when the additive amount ZrO\(_2\) whisker is low. The existence of pores influences the densification of the ceramic material and thus reduces the mechanical properties of the ceramic material. Whisker reunion can be found in Figure 3c mark 1, and the whisker section can also be observed by magnification, as showed in Figure 3d.

3.2. Influence of ZrO\(_2\) Whisker Addition on Al\(_2\)O\(_3\)/Ti(C,N) Ceramic Material

Figure 3a–c represents the scanning electron microscope photographs of the fracture surfaces of the Al\(_2\)O\(_3\)/Ti(C,N) ceramic material with 3 vol%, 6 vol% and 9 vol% ZrO\(_2\) whisker, respectively. It can be observed that the grains are coarser in Figure 3a or Figure 3c. However, the grains in Figure 3b are finer than those in Figure 3a and the uniformity of Figure 3b is improved. The addition of the ZrO\(_2\) whisker has an influence on the grain refinement of the ceramic material, and the ZrO\(_2\) whisker can suppress the abnormal growth of the crystal grain. When the addition of the ZrO\(_2\) whisker is 9 vol%, more pores can be seen in the cross section. A possible reason for this is that under the process conditions selected by the experiment, the dispersion of the ceramic material with 9 vol% ZrO\(_2\) whisker may not achieve the desired effect, contributing to the bridging or agglomeration of the whisker. The occurrence of pores leads to a decrease in the relative density. Due to the contrast, less pores can be seen in the cross section when the additive amount ZrO\(_2\) whisker is low. The existence of pores influences the densification of the ceramic material and thus reduces the mechanical properties of the ceramic material. Whisker reunion can be found in Figure 3c mark 1, and the whisker section can also be observed by magnification, as showed in Figure 3d.

The consequences of adding 0, 3 vol%, 6 vol% and 9 vol% ZrO\(_2\) whisker on the mechanical properties of the Al\(_2\)O\(_3\)/Ti(C,N) ceramic material are shown in Figure 4. The ceramic material without ZrO\(_2\) whisker has a high hardness of 20.47 GPa. With the increasing addition of ZrO\(_2\) whisker, the hardness is prone to decrease. When the addition of ZrO\(_2\) whisker increases, the flexural strength of the ceramic material increases significantly from 555 to 584 MPa. Whereas when the additive amount of ZrO\(_2\) is more than 6 vol%, the flexural strength of the ceramic material shows a decreasing trend. The ceramic material obtains maximum flexural strength when the ZrO\(_2\) whisker addition is 6 vol%. With the increase in ZrO\(_2\) whisker addition, the fracture toughness also shows an increasing trend. It reveals that the introduction of ZrO\(_2\) whisker can enhance the fracture toughness of the material. The ceramic material without ZrO\(_2\) whisker has the highest relative density. With the addition of ZrO\(_2\) whisker increasing, the relative density decreases first and afterward increases. As can be seen from

![Figure 2. XRD (XRD is the abbreviation of X-Ray Diffraction) diffraction analysis of the ceramic material.](image)
the analysis in SEM (Scanning electron microscope) morphology the presence of pores reduces the
density of the material.

![SEM morphology photograph added with 10 vol% nano CaF2 observed by scanning electron microscope (SEM). The results are displayed in Figure 5. Figure 5a is a SEM morphology photograph added with 10 vol% nano CaF2 powder. It can be found that a few grains have an abnormal growth and the grain distribution is not uniform. Figure 5b is a SEM morphology paragraph added with 10 vol% nano coated CaF2@Al(OH)3 powder. Compared to the material added with the same components, the nano CaF2 powder, the grain distribution is uniform.](image)

**Figure 3.** SEM (Scanning electron microscope) morphology: (a) 3 vol% ZrO2; (b) 6 vol% ZrO2; (c) 9 vol% ZrO2; (d) mark 1 partial enlargement of (e).

![Fracture toughness and Relative density.](image)

**Figure 4.** Mechanical properties of Al2O3/Ti(C,N) with ZrO2 whisker. (a) Hardness and Flexural strength, (b) Fracture toughness and Relative density.

### 3.3. Influence of Nano Coated CaF2@Al(OH)3 Powder on Al2O3/Ti(C,N) Ceramic Material

The nano powder and nano coated powder have a crucial influence on the microstructure and mechanical properties of the ceramic material. The cross sections of the two ceramic materials were observed by scanning electron microscope (SEM). The results are displayed in Figure 5. Figure 5a is a SEM morphology photograph added with 10 vol% nano CaF2 powder. It can be found that a few grains have an abnormal growth and the grain distribution is not uniform. Figure 5b is a SEM morphology...
paragraph added with 10 vol% nano coated CaF$_2$@Al(OH)$_3$ powder. Compared to the material added with the same components, the nano CaF$_2$ powder, the grain distribution is uniform and the density of the material is superior to the former. In Figure 5b, the material of the surface coating is nano coated CaF$_2$@Al(OH)$_3$ powder. Moreover, the nano coated CaF$_2$@Al(OH)$_3$ powder is well combined with the ceramic matrix. Compared with the added nano CaF$_2$ powder, there are many intragranular structures in the ceramic material. The intragranular structures have a good effect on enhancing the mechanical properties of ceramic material [36]. In the sintering process of the material, with the growth of crystal grains, the nano powders enter the crystal with the motion of boundaries of particles. The matrix grains merge and grow, forming the intragranular structures. The nano CaF$_2$ can be considered as completely entering the crystal. From Figure 5b, the fracture mode is mainly intergranular fracture, and partly transgranular fracture, which can also be found. The transgranular fracture consumes quantities of fracture energy, which is conducive to enhance mechanical properties. This is also one of the main reasons for the improvement of the mechanical properties of the prepared ceramic material. Nano coated powder contributes to the dispersion of CaF$_2$ in ceramic matrix material. As it can be found from Figure 5b, CaF$_2$ is more evenly distributed in the matrix material.

The results of adding 5 vol%, 10 vol% and 15 vol% nano coated CaF$_2$@Al(OH)$_3$ powder on the mechanical properties of the Al$_2$O$_3$/Ti(C,N) ceramic material are displayed in Figure 6. From Figure 6a, with the increasing addition of CaF$_2$@Al(OH)$_3$, the hardness is prone to decrease. The main reason is the low mechanical properties of the CaF$_2$. The increase in lubricant addition inevitably leads to a decrease in the hardness and other properties. The flexural strength of the ceramic material first increases and afterward decreases. When the addition of nano coated CaF$_2$@Al(OH)$_3$ powder is 10 vol%, the flexural strength is up to 471 MPa. From Figure 6b, with the increasing addition of nano coated CaF$_2$@Al(OH)$_3$ powder, the fracture toughness is increased from the initial 6.50 MPa-m$^{1/2}$ to 6.60 MPa-m$^{1/2}$. The main reason may be that the presence of massive nano coated CaF$_2$@Al(OH)$_3$ powder enhances the material’s fracture toughness. The relative density of the ceramic material shows a trend of increasing first and afterward decreasing. When the addition of the CaF$_2$@Al(OH)$_3$ powder is 10 vol%, excellent comprehensive mechanical properties are obtained.

**Figure 5.** SEM morphology: (a) 10 vol% nano CaF$_2$ powder; and (b) 10 vol% nano coated CaF$_2$@Al(OH)$_3$ powder.
powder have a significant influence on the ceramic material. The Al

Appl. Sci. 2020, 10, x FOR PEER REVIEW 7 of 12

Figure 6. Mechanical properties of Al2O3/Ti(C,N) with the nano coated CaF2@Al(OH)3 powder. (a) Hardness and Flexural strength, (b) Fracture toughness and Relative density.

3.4. Mechanism Analysis of Co-Modification of Micron ZrO2 Whisker and Nano Coated CaF2@Al(OH)3 Powder

From the analysis above, the addition of micron ZrO2 whisker and nano coated CaF2@Al(OH)3 powder have a significant influence on the ceramic material. The Al2O3/Ti(C,N) ceramic material added 6 vol% ZrO2 whisker and 10 vol% nano coated CaF2@Al(OH)3 powder was fabricated. The performance of the ceramic material was measured. The hardness of the Al2O3/Ti(C,N)/ZrO2/CaF2@Al(OH)3 ceramic material is 16.72 GPa, the flexural strength is 520 MPa and the fracture toughness is up to 7.16 MPa·m1/2. For the convenience of analysis, the sintering diagram of the material is drawn in Figure 7, and the micro-morphology of the ceramic material after sintering is observed.

Figure 7. Schematic diagram of sintering the Al2O3/Ti(C,N)/ZrO2/CaF2@Al(OH)3 ceramic material.

In the sintering course of the Al2O3/Ti(C,N)/ZrO2/CaF2@Al(OH)3 ceramic material, with the development of temperature and soaking time, the crystal grains grow gradually. The matrix powders accommodated by ball milling will have the situation that small powders are gradually absorbed by large powders and the number of powders is continuously reduced. The growth of crystal grain rests with the motion of boundaries of particles. The boundaries in the matrix tend to migrate to the center, as indicated by mark 1 in Figure 7. Due to the shell material (Al2O3) of the lubricant being the same as the matrix powders (Al2O3) of the ceramic material, the nano powders are dispersed into the interior of the matrix material during the sintering of the ceramic material. With the intergranular...
nanostructure of the nano CaF\(_2\) powders dispersed inside, the surface coating design avoids powder agglomeration growth.

After hot pressing, the nano powder exists inside the matrix crystal, and the matrix and nano powders form the intragranular structure. The related studies have shown that the intragranular structure can toughen the ceramic material [37,38]. The nano powder promotes the generation of more intragranular structures, which enhances the mechanical properties of the ceramic material. As shown in Figure 7, the nano powders form intragranular structures. The appearance of this intragranular structure is one of the main reasons for enhancing the mechanical properties of the ceramic material prepared in this paper. The ZrO\(_2\) whiskers have a unique phase transition effect. In the sintering process, when the temperature reaches 1170 °C, the m-ZrO\(_2\) is completely converted into the t-ZrO\(_2\). In the cooling process, when the temperature is less than 950 °C, the matrix materials have the binding effect on the t-ZrO\(_2\), which hinders the conversion of the t-ZrO\(_2\) into the m-ZrO\(_2\) and enables the t-ZrO\(_2\) to be preserved at room temperature. The toughening effect of the phase transition generated by the ZrO\(_2\) is mainly attributed to the crack growth being inhibited by the phase transition of t-ZrO\(_2\). The existence of the t-ZrO\(_2\) in the material is the necessary condition for phase transformation toughening. This makes up for the natural defects caused by the azimuth angle of the dispersion whisker reinforced the ceramic materials. This synergistic effect makes the ZrO\(_2\) whisker-toughened ceramic material obviously different from the ceramic material toughened by adding the dispersion whisker alone. As indicated by the mark 2 partially ZrO\(_2\) whiskers after hot pressing are distributed in intercrystalline, which provides the conditions for whisker toughening in the process of crack propagation [39]. The toughening mechanisms of the ZrO\(_2\) whisker in the ceramic material are the whisker bridging and the crack deflection. During the whisker bridging and the crack deflection, the energy consumption occurs [40], which is conducive to enhancing the fracture toughness of the ceramic material.

4. Conclusions

The ZrO\(_2\) whisker and nano coated CaF\(_2@\)Al(OH)\(_3\) powder were added to the Al\(_2\)O\(_3\)/Ti(C,N) self-lubricating ceramic material simultaneously. The modification of the Al\(_2\)O\(_3\)/ZrO\(_2)/\)CaF\(_2@\)Al(OH)\(_3\) ceramic tool material was completed by using two different toughening mechanisms.

(1). The ZrO\(_2\) whisker with 0, 3 vol%, 6 vol% and 9 vol% were added to the Al\(_2\)O\(_3\)/Ti(C,N) ceramic material. The result revealed that when the additive amount of the ZrO\(_2\) whisker was 6 vol%, the hardness, the flexural strength and the fracture toughness values were 19.1 GPa, 584 MPa and 6.61 MPa·m\(^{1/2}\), respectively. Whisker toughening and the phase transition toughening of the ZrO\(_2\) enhanced the mechanical properties of the ceramic material.

(2). The addition of nano coated CaF\(_2@\)Al(OH)\(_3\) powder also had a significant influence on the mechanical properties of the ceramic material. The intragranular structures played a good role in enhancing the mechanical properties of the ceramic material. When the nano coated CaF\(_2@\)Al(OH)\(_3\) powder addition was 10 vol%, the mechanical properties of the ceramic material was the best. The hardness, flexural strength and fracture toughness values of the prepared ceramic material were 18.58 GPa, 471 MPa and 6.50 MPa·m\(^{1/2}\), respectively.

(3). The ZrO\(_2\) whisker of 6 vol% and nano coated CaF\(_2@\)Al(OH)\(_3\) powder of 10 vol% were simultaneously added to the Al\(_2\)O\(_3\)/Ti(C,N) ceramic material. The hardness of the Al\(_2\)O\(_3\)/Ti(C,N)/ZrO\(_2)/CaF\(_2@\)Al(OH)\(_3\) ceramic material was 16.72 GPa, the flexural strength was 520 MPa, and the fracture toughness reached 7.16 MPa·m\(^{1/2}\). The fracture toughness of the Al\(_2\)O\(_3\)/Ti(C,N)/ZrO\(_2)/CaF\(_2@\)Al(OH)\(_3\) self-lubricating ceramic tool material was better than the added ZrO\(_2\) whisker or added nano coated CaF\(_2@\)Al(OH)\(_3\) powder of the Al\(_2\)O\(_3\)/Ti(C,N) ceramic material, separately. The formation of intragranular structure, whisker toughening and phase transition of ZrO\(_2\) were the main mechanisms.
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