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Research on the Influence of Additives on the Mechanical Properties of Zirconia-Toughened Alumina Ceramics

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Abstract: *This paper focus on the effects of the additions of MgO and TiO_2 on the various properties of Zirconia-Toughened Alumina ceramic composites made of electro-fused zirconia. The results show that at 1643 ^0C, the compactness, strength and hardness of Zirconia-Toughened Alumina ceramic materials can be improved when the respective addition amounts of MgO and TiO_2 are 0.5%. But the comprehensive performance of Zirconia-Toughened Alumina ceramic materials are greatly improved when the total content of both is 1%. After mixing the powders and washing with sand for 1 hour, the comprehensive performance of Zirconia-Toughened Alumina composite ceramic is optimal, which the density, hardness, and flexural strength are 4.36g.cm^{-3}, 73HRC, and 391MPa respectively.*

Keywords: *Zirconia-toughened alumina, Electro-fused zirconia, Magnesium oxide, Titanium oxide*

1. Introduction

Alumina ceramics are widely used in engineering ceramic materials for their excellent thermodynamic properties, high modulus of elasticity and high wear resistance. However, alumina ceramics have low strength and toughness, and the introduction of zirconium oxide can improve its mechanical properties, and this kind of material which introduces zirconium oxide into alumina is called zirconia-toughened alumina (ZTA) ceramic composites. It is a high-performance composite material with excellent mechanical properties such as high hardness, high strength, high toughness, etc. It is an ideal composite material for different engineering applications[1-6].

In the field of mining, conveying equipment for undertaking the crushing of ore raw materials, transportation, sorting, ball milling and other tasks, and the contact parts of the ore raw materials, need to have a high impact resistance and wear resistance. Therefore, the protection of mining conveyor equipment, improve the toughness and wear resistance of wear-resistant materials in the conveyor equipment is to determine the efficiency of mining, reduce production costs, take the road to sustainable development. Engineering ceramic materials, whose hardness is higher than that of metal materials, have a series of advantages such as high compressive strength, wear resistance, corrosion resistance, oxidation resistance, etc., and have become the preferred material in wear-resistant materials. In recent years, the ZTA ceramic system has been extensively studied, including the preparation technology of ZTA ceramics, the toughening and strengthening mechanism of ZrO_2 particles on Al_2O_3, and the microstructure and mechanical properties of ZTA ceramics [7]. Most of the studied ZTA ceramic systems use chemical zirconium oxide raw materials, and there is no report on the use of electro-fused zirconium oxide raw materials. In this paper, we take ZTA materials as the research object, take advantage of the low cost of electro-fused zirconia, replace chemical zirconia with electro-fused zirconia, and focus on the effect of introducing additives on the various properties of ZTA composite ceramic materials. As a basic experimental research, this study has certain guiding significance for the rational design of electro-fused zirconia toughened alumina materials. Replacing expensive chemical zirconia with inexpensive electro-fused zirconia has very considerable economic benefits.

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2. Experiment

2.1. Preparation

Various powders (alumina, yttrium oxide, electro-fused zirconia, magnesium oxide, titanium oxide) were mixed with water in a certain proportion and added to a ball milling jar, a certain amount of PVA and ethanol was added to the ball milling jar, and then ball milling was carried out for 2 h at a certain rotational speed, and the slurry obtained was baked at 85 0C for 24 h. The slurry was milled through a sieve, and then pressed into rounds and lengths in a universal testing machine, and then sintered at a certain temperature, to obtain the ZTA ceramic Sample.

2.2. Analysis and Characterization

A density tester was used to analyze the density of the material. THRP-150D Rockwell hardness tester was used to analyze the hardness of the material. Sansi UTM-6000 Electronic Universal Testing Machine was used to test the flexural strength of the materials. BRUKER-UMT3 Universal Friction Tester was used to test the abrasion resistance of the materials.

3. Results and Discussion

3.1. Effect of sintering temperature on the properties of ZTA composites with the addition of 0.5% MgO

The effect of sintering temperature on the properties of ZTA composites with the addition of 0.5% MgO is shown in Figure 1, Figure 2, and Figure 3. The sintering temperatures were 1522 ^{0}C, 1587 ^{0}C, 1632 ^{0}C, 1643 ^{0}C, and 1667 ^{0}C respectively. And the density of the ZTA composites with 0.5% MgO additive was rapidly increased to 4.16 g.cm-3 at 1643 ^{0}C. The ZTA composites have a hardness of 70 HRC and a flexural strength of 328 MPa obtained at 1643^{0}C. The hardness and flexural strength of ZTA composites cannot be measured when the temperature is at 1520 ^{0}C. This is probably because the atomic diffusion rate of MgO increases and the porosity between particles gradually decreases as the temperature rises.And the binding force gradually increases. It tends to stabilize at 1643 ^{0}C. When the sintering temperature exceeds 1643 ^{0}C, abnormal grain growth occurs, new pores are generated or existing closed pores expand. Stress concentration at grain boundaries is more pronounced. The material is prone to cracking and crack propagation when subjected to external forces, which leading to a decrease in performance of ZTA.

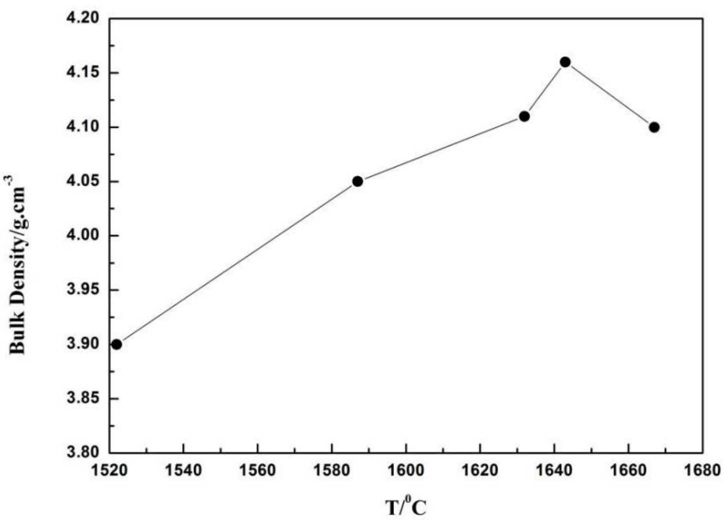

Figure 1: Density of ZTA ceramic materials with the addition of 0.5% MgO for sintering at different temperatures.

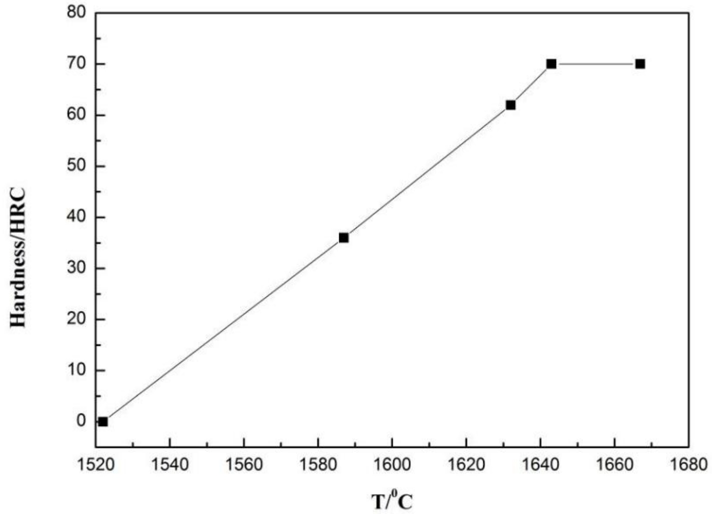

Figure 2: Hardness of ZTA ceramic materials with the addition of 0.5% MgO for sintering at different temperatures

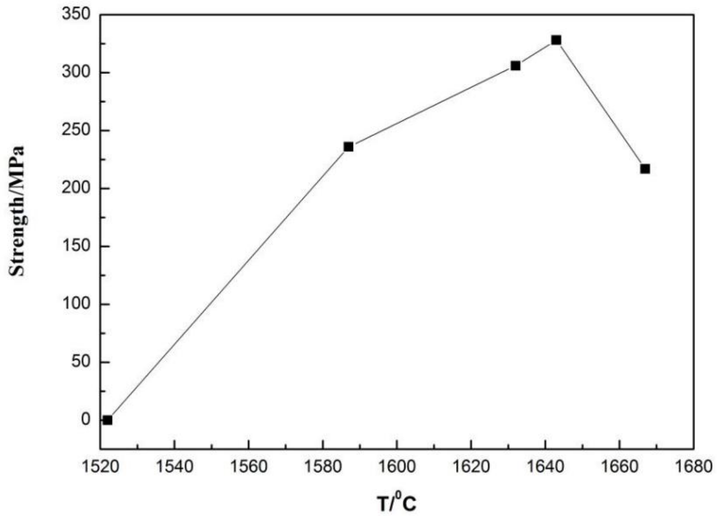

Figure 3: Flexural strength of ZTA ceramic materials with the addition of 0.5% MgO for sintering at different temperatures.

3.2. Effect of the content of the additive MgO on the properties of ZTA composites

The mechanical properties of the ZTA composites obtained by increasing the content of the additive MgO from 0 wt% to 2 wt% and sintering at 1643 °C are shown in Figure 4, Figure 5, and Figure 6. The sintered density of the ZTA composites was increased to 4.16 g.cm^{-3} at the additive amount of 0.5 wt% of MgO, which is higher as compared to that of the composites without added MgO (3.80 g.cm^{-3}) , the degree of densification was increased. An appropriate amount of MgO can promote sintering, reduce internal pores in the material, and facilitate grain growth. When the temperature is suitable part of the MgO can dissolve in ZTA to form a solid solution, enhancing the material's density, hardness, and flexural strength. When the addition of MgO exceeded 0.5 wt%, the density showed a gradual decreasing trend (Figure 4), which could be attributed to the fact that too much MgO formed the $MgO{\cdot}Al_2O_3$ spinel phase with Al_2O_3 in ZTA composites, which would lead to the formation of certain defects inside the material due to the mismatch of the coefficients of thermal expansion of the two and thus cause a decrease in the density. Hardness and flexural strength are also decrease. The hardness measured under the same conditions was 70 HRC (Figure 5) and the flexural strength was 328 MPa (Figure 6). Therefore, the addition of 0.5 wt% MgO can increase the densification of ZTA ceramics and improve the flexural strength and hardness of ZTA composites.

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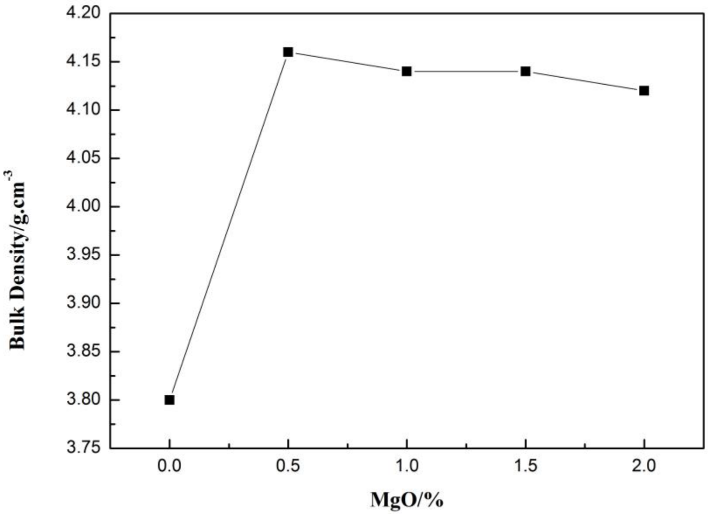

Figure 4: Effects of different content of MgO on the density of ZTA ceramic materials.

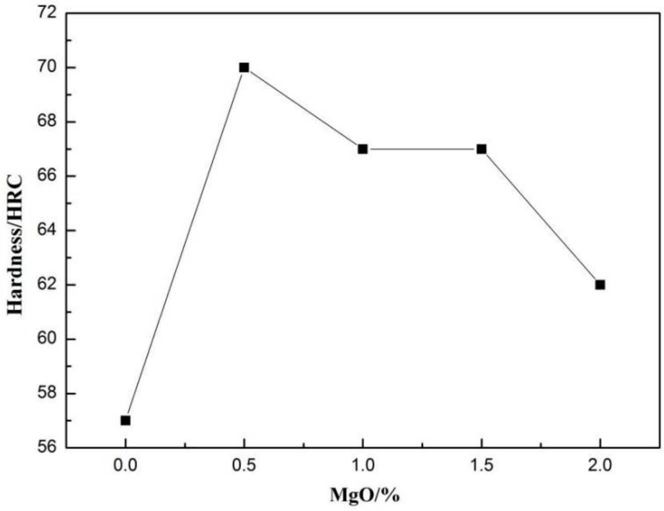

Figure 5: Effect of different content of MgO on the hardness of ZTA ceramic materials.

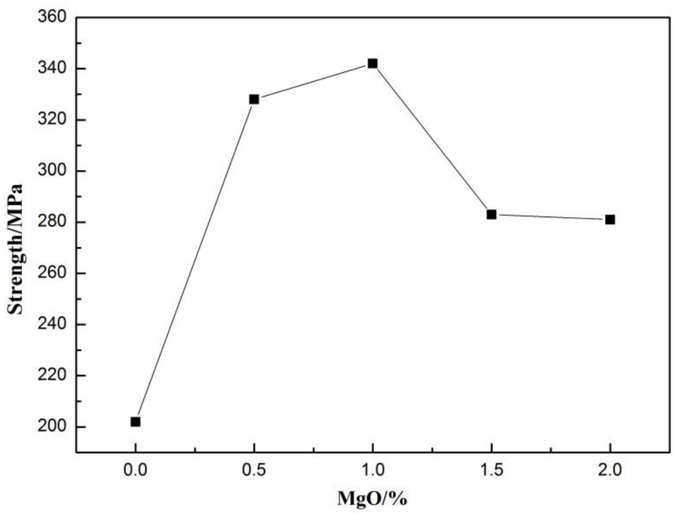

Figure 6: Effect of a different content of MgO on the flexural strength of the ZTA ceramic materials.

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3.3 Effect of the content of the additive TiO_2 on the properties of ZTA composites

The content of additive TiO_2 was increased from 0 wt% to 2 wt%, and the mechanical properties of the ZTA composites obtained by sintering at 1643 ^{O}C are shown in Figure. 7, Figure. 8, and Figure. 9. The sintered density, hardness, and strength of the ZTA composites all showed a trend of increasing and then decreasing with the increase of the TiO_2 additive, which may be attributed to the fact that a small amount of TiO_2 is capable of solid-solution substitution with Al_2O_3. This may be due to the fact that a small amount of TiO_2 can be exchanged with Al_2O_3 in solid solution, which promotes the sintering rate of Al_2O_3。Thus, the density of the material is increased, thereby enhancing its hardness and strength. But too much TiO_2 can easily lead to the abnormal growth of Al_2O_3 grains, which affects the mechanical properties of the material. Stress concentration at grain boundaries can lead to a decrease in the mechanical properties of materials. When the addition of TiO_2 is 0.5 wt%, the ZTA composite material has the best overall performance, with a density of 4.14 g.cm^{-3}, a hardness of 67 HRC, and a flexural strength of 311 MPa .

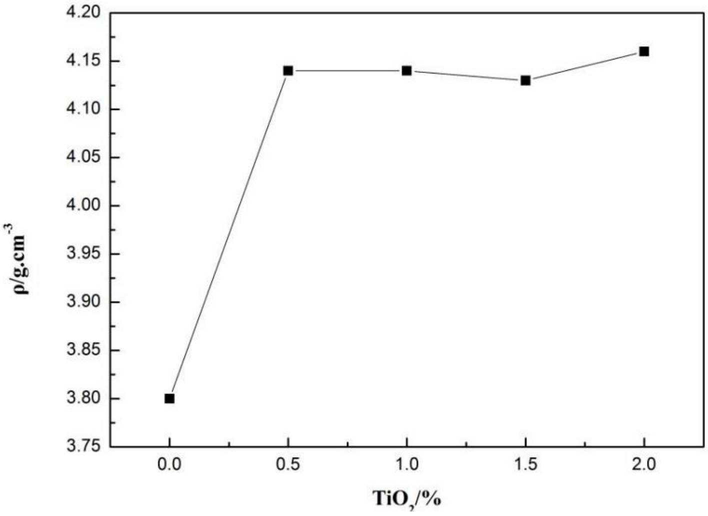

Figure 7: Effect of different content of TiO_2 on the density of ZTA ceramic materials.

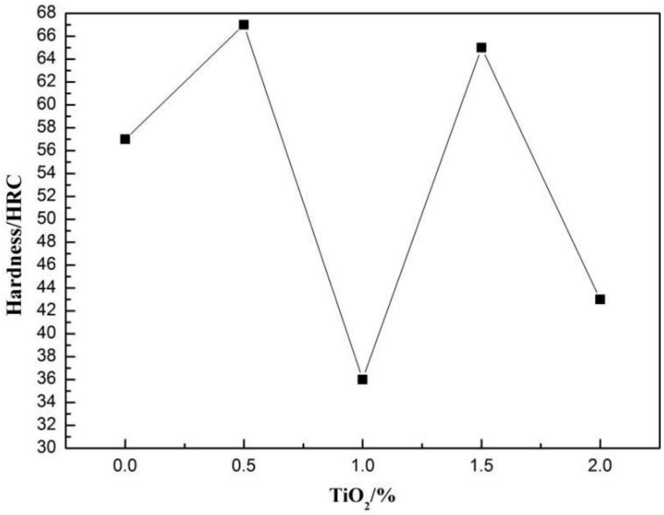

Figure 8: Effect of different content of TiO_2 on the hardness of ZTA ceramic materials.

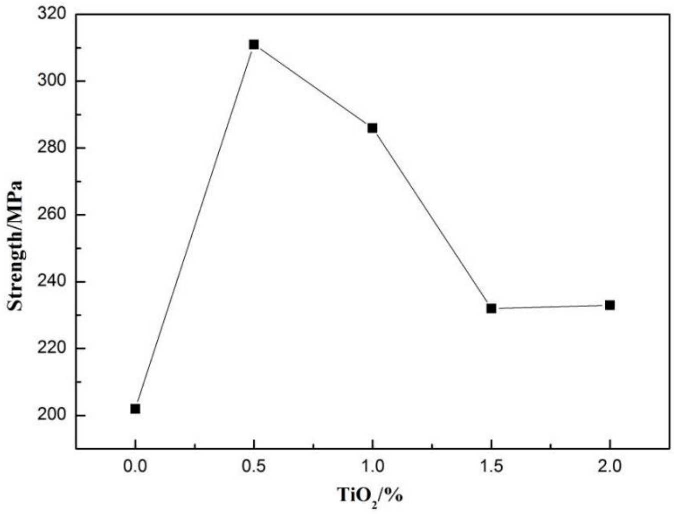

Figure 9: Effects of different content of TiO_2 on the flexural strength of the ZTA ceramic materials.

3.4. Effect of the content of composite additives MgO and TiO_2 on the properties of ZTA composites

On the basis of clarifying the effect of single additive on the comprehensive performance of ZTA composites, we have done the experiment on the effect of composite additives MgO and TiO_2 on the mechanical properties of the composites, and the results were shown in Table 1. The mechanical properties of ZTA composites with the total amount of 1 wt% of MgO and TiO_2 were improved in density, hardness and strength than those of the composites with a single additive. The addition of MgO can promote the sintering of the material, reducing the pores within the ZTA and increasing the density, thereby mechanical properties such as flexural strength and hardness. The addition of TiO_2 can inhibit grain growth, refine the grains, and react with the ZTA matrix to a second phase, not only providing dispersion strengthening but also altering the crack propagation path and increasing the resistance to crack propagation, thus enhancing the material's toughness. Theistic effect of these two additives jointly improves the mechanical properties of the material.

Table 1: Effect of composite additives on the physical properties of ZTA ceramic materials.

MgO/%	TiO_2/%	Density/g·cm^3	Hardness/HRC	Strength/MPa
0.5	0.5	4.19	59	350

Then we did the experiment of constant content and grinding the prepared powder through sand mill for 1 h to investigate the effect of sanding process on the mechanical properties of ZTA composites experiment, the results are shown in Table 2. The ZTA composites with the addition of a total amount of 1 wt% of MgO and TiO_2 showed a substantial increase in density, strength and hardness after sand milling.

Table 2: Influence of sand grinding process on the physical properties of ZTA ceramic materials.

MgO/%	TiO_2/%	Density/g·cm^3	Hardness/HRC	Strength/MPa
0.5	0.5	4.36	73	391

Therefore, it is inferred that the sand grinding process can make the components in the mixture more refined, and the small particles make the microstructure the material more compact, with fewer pores in the material after sintering and more uniform structure; the refined ZTA can effectively prevent the generation and propagation of in the material under external force, absorbing more deformation energy, thus improving the comprehensive mechanical properties of the material. The ZTA composite with the addition of 0.5 wt% of MgO, 0.5 wt% of TiO_2 and sand milled for 1h had the best overall performance with a density of 4.36 g.cm^{-3}, hardness of 73 HRC, and flexural strength of 391 MPa.

3.5. SEM analysis

The microstructures of the ZTA composites before and after sand-grinding for 1 h with the addition of 0.5 wt% MgO and 0.5 wt% TiO_2 are shown in Figs. 10 and 11. As can be seen from the figures, the average grain size of the composites after sanding is around 1 μm, which is much smaller than the average grain size before sanding, which is more favorable for sintering and improving the

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densification of the materials. Therefore, the overall mechanical properties of the ZTA composite materials have been improved. This also confirms the previous speculation about the synergistic effect of the two additives.

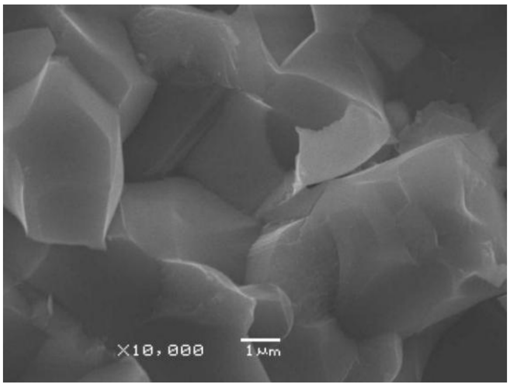

Figure 10: SEM diagram of ZTA composite ceramic material before sand grinding.

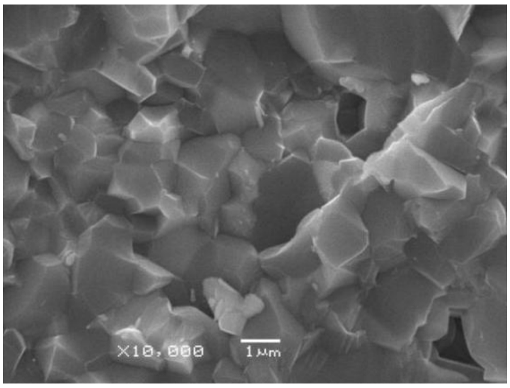

Figure 11: SEM diagram of ZTA composite ceramic material after sand grinding.

3.6. XRD analysis

A certain amount of yttria is often added to the ZTA matrix to enhance the stability of the material. Figure 12 shows the XRD pattern of the ZTA specimen after sanding. From the figure, it can be seen that there are a large number of tetragonal phases of zirconium dioxide in the specimen, which is due to the fact that the ionic radius of Y^{3+} (0.09 nm) is larger than that of Zr^{4+} (0.072 nm), which meets the condition of replacement solid solution, then Y^{3+} partially replaces Zr^{4+}, stabilizes the tetragonal phase t-ZrO_2 to room temperature, and enhances the comprehensive performance of ZTA ceramic composites.

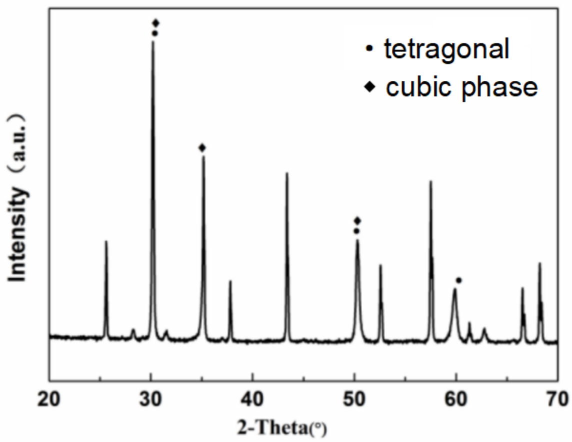

Figure 12: Atlas of the XRD of the Z T A ceramic sample.

3.7. Abrasion resistance

The test results of wear resistance of ZTA composites with adding 0.5 wt% of MgO, 0.5 wt% of TiO_2 after sanding for 1 h are shown in Table 3. In 30 min, the wear amount of the ZTA composite is only 0.02 mg, which is better compared with chemical zirconium ZTA composites (the wear amount is 0.07 mg).

Table 3: Wear resistance test results of ZTA composite ceramic materials after sand grinding.

Samples	Coefficient of Friction	rubbing time	attrition rate
Composite ZTA	0.397	30min	0.02mg
Chemical Zirconia ZTA	0.398	30min	0.07mg

4. Conclusions

In this paper, the effect of single additive MgO content and TiO_2 content and the addition of both composite additives on the mechanical properties of ZTA ceramic composites was investigated separately. We also studied the effect of sand grinding process on the properties of the material. It was found that at 1643 ^{0}C:

(1) The densification, strength and hardness of ZTA ceramics can be improved with a single addition of MgO or TiO_2 content of 0.5 wt%;

(2) The densification, strength and hardness of ZTA ceramics are higher than single additive when the total content of composite additives MgO and TiO_2 is 1 wt%;

(3) The addition of MgO can promote the sintering of the material, reducing the pores within the ZTA and increasing the density, thereby mechanical properties such as flexural strength and hardness. The addition of TiO_2 can inhibit grain growth, refine the grains, and react with the ZTA matrix to a second phase, not only providing dispersion strengthening but also altering the crack propagation path and increasing the resistance to crack propagation, thus enhancing the material's toughness. Theistic effect of these two additives jointly improves the mechanical properties of the material.

(4) The density, hardness and flexural strength of the ZTA composite ceramic material with 1 wt% composite additives were increased to a greater extent after sand-grinding for 1 h. The density, hardness and flexural strength of the ZTA composite ceramic material with 1 wt% composite additives were 4.36 g.cm^{-3}, hardness of 73 HRC, and flexural strength of 391 MPa, respectively.

(5) The sand grinding process can make the components in the mixture more refined, and the small particles make the microstructure the material more compact, with fewer pores in the material after sintering and more uniform structure; the refined ZTA can effectively prevent the generation and propagation of in the material under external force, absorbing more deformation energy, thus improving the comprehensive mechanical properties of the material. And sanding for a certain time can reduce the wear of electro-fused zirconia ZTA composites compared to chemical zirconia ZTA composites.

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