Effect of Volume Fraction Whiskers on Tensile and Thermal Expansion Properties of Mg$_2$B$_2$O$_5$ Whisker-reinforced Aluminum Composite

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Abstract. This paper prepared magnesium borate whisker reinforced aluminum matrix composites by extrusion casting, and studied the effects of the volume fraction of the reinforced phase on the mechanical properties, thermal expansion properties and microstructure of the composites. The test results show that the reinforced magnesium borate whisker in the composite can be uniformly dispersed in the aluminum matrix to improve the strength. With the increase of the volume fraction, the strength of the composite material increases and the plasticity decreases. When the whisker volume fraction is 30%, the strength of the composite material reaches the maximum, with its tensile strength reaching 244 MPa and elastic modulus 107.6 GPA. When the whisker volume fraction is 20%, the composite has the best plasticity and the fracture elongation is 0.47%. The thermal expansion curve of the composite shows that the increase of whisker volume fraction will reduce the thermal expansion coefficient of the composite.

1. Introduction
Whisker reinforced aluminum matrix composites have a wide application prospect in the field of national defense and civil manufacturing due to their excellent mechanical and thermal expansion properties. Magnesium borate whisker (Mg$_2$B$_2$O$_5$, or MBO for short) has been widely concerned by researchers due to its good performance and low price, but its application as the reinforced phase of aluminum matrix composite is not in-depth enough [1,2].

Magnesium borate whisker reinforced aluminum matrix composite has excellent properties, but its preparation technology still has great difficulties. Powder metallurgy method can realize the preparation of the reinforced phase content in the composite system in a large range, but the whisker material with a certain aspect ratio is easy to break and damage during the ball grinding mixing process. Meanwhile, the powder metallurgy process is complex and the cost is high, which is not suitable in the actual production promotion. The agitation casting method developed on the basis of alloy melting preparation has the advantages of mature technology and high production efficiency. However, restricted by the uniformity of the dispersion of the reinforced phase, it is difficult to prepare the composite with whisker volume fraction above 5%, which is prone to the phenomenon of partial polymerization of the reinforced phase. In the whisker reinforced aluminum matrix composites prepared by extrusion casting method, good microstructure properties can be obtained due to the uniform dispersion of whisker in the reinforced phase [3]. However, subject to the preparation process of whisker prefabrication, the volume fraction of reinforced phase of extrusion casting is generally
around 25% at present [4]. This paper prepared magnesium borate whisker prefabricated with different volume fraction by dry pressing method, and prepared whisker reinforced aluminum matrix composite (MBOw/Al) by extrusion casting method. At the same time, this paper studied the influence of whisker volume fraction on the microstructure and properties of composite, and discussed the influence mechanism of whisker on the mechanical properties and thermal expansion properties of composite.

2. Experimental method

The morphology of magnesium borate whiskers in the reinforced phase of MBOw/Al composites is shown in Fig. 1, with a length of 10~50 μm and a diameter of 0.2~2 μm. The matrix of the composite material was industrial pure aluminum.

In order to change the volume fraction of magnesium borate whisker in aluminum matrix composites and simplify the process, the whisker preforms were prepared by dry pressing. First, magnesium borate whisker was placed in distilled water and dispersed by ultrasound. It was then filtered, dried and pressed into a mold to produce porous whisker preforms with whisker volume fraction of 15%, 20%, 25% and 30%, respectively. The preform was sintered at 900 °C for 2h, and the magnesium borate whisker reinforced aluminum matrix composites were prepared by squeeze casting method. The casting temperature was 800 °C, and the preheating temperature of the mold was 560 °C. The distribution uniformity and morphology of whiskers in the composites were observed by OLYMPAS PMG3 metallographic microscope. H-3000 scanning electron microscope (SEM) produced by Hitachi Company was used to observe the original morphology of the whisker and the morphology of the tensile port of the composite material.

The tensile tests of the composites were carried out by Instron-1186 mechanical tester at room temperature. The tensile rate was 0.5mm/min, and the tensile direction was perpendicular to the direction of squeeze casting. The thermal expansion experiment of the composite material was carried out with DIL402C thermal expansion instrument produced by Netzch Company in Germany. The experimental parameters are shown in Table 1.

| Composite material | MBOw/Al |
|--------------------|---------|
| Sample size        | Φ6×25 mm|
| Experimental temperature | Indoor temperature ~450 °C |
| Data selection temperature | 50~400 °C |
| Heating rate       | 5 °C/min |
| Cooling method     | Furnace cooling |
3. Experimental results and analysis

3.1. Micro-morphology of magnesium borate whisker reinforced aluminum matrix composites

Fig. 2 is the metallographic photograph of magnesium borate whisker reinforced aluminum matrix composites. The photographing plane is the vertical direction of the extrusion casting direction. As can be seen from Fig. 2, the whisker reinforced phase in the composites prepared by the process described in this paper is uniformly dispersed, without a large number of whiskers being entwined or agglomerated together. This indicates that ultrasonic treatment can disperse the whiskers. The long axis direction of magnesium borate whisker is basically perpendicular to the direction of squeeze casting. This is due to the characteristics of the whisker geometry and the prefabrication process. In this plane, the whiskers show a random and chaotic distribution, which is isotropic in this plane. In addition, the density of aluminum matrix composites is good, without obvious holes, cracks and other defects.

![Fig. 2 The metallograph photo of MBOw/Al composite](image)

3.2. The tensile strength and fracture structure of composite materials

Table 2 shows the mechanical properties of aluminum matrix composites with different whisker volume fractions. The parameter values in Table 2 are plotted in Fig. 2. The composite materials with 25% and 30% whisker volume fraction had broken before the plastic deformation reached 0.2%, so the tensile strength of these two materials was used to replace the yield strength in Fig. 2 (b). It can be seen from Fig. 2 that the tensile strength, yield strength and elastic modulus of composites all increased with the increase of whisker volume fraction, while the value of plastic deformation ability, namely fracture elongation, decreased with the increase of whisker volume fraction. The results show that the whisker content is an important factor to determine the mechanical properties of aluminum matrix composites.

| Whisker volume fraction | Material number | Tensile strength (σt)/MPa | Yield strength (σ0.2)/MPa | Elasticity modulus/GPa | Elongation at break/% |
|------------------------|----------------|--------------------------|--------------------------|-----------------------|-----------------------|
| 15%                    | 15%MBOw/Al     | 141                      | 118                      | 84.1                  | 0.38                  |
| 20%                    | 20%MBOw/Al     | 176                      | 131                      | 85.7                  | 0.47                  |
| 25%                    | 25%MBOw/Al     | 184                      | -                        | 89.0                  | 0.16                  |
| 30%                    | 30%MBOw/Al     | 244                      | -                        | 107.6                 | 0.12                  |

In Fig. 2(d), the fracture elongation of 15% MBOw/Al composite was 0.38%, lower than that of 20% MBOw/Al composite, which was not consistent with the predicted trend. After analysis, we believed that the composite with 15% whisker volume fraction broke in advance during the tensile test. This is due to the low volume fraction of whiskers, which lead to the defect of insufficient strength in
the prefabrication process and the formation of microdefects in the extrusion casting process, which reduced the plasticity of the composite material.

![Graph a](image1.png)

![Graph b](image2.png)

![Graph c](image3.png)

![Graph d](image4.png)

Fig. 3 The room temperature tensile strength of MBOw/Al composites reinforced by different volume fraction whiskers (a) Ultimate tensile strength, (b) Yield strength ($\sigma_{0.2}$), (c) Elasticity modulus, (d) Elongation at break.

Fig. 4 shows the SEM photos of tensile fracture of MBOw/Al composites. As can be seen from the figure, there were a large number of whiskers perpendicular to the extrusion casting direction and a small number of whiskers parallel to the extrusion casting direction (perpendicular to the stretching direction) on the tensile fracture. As the volume fraction of whiskers in the composites increased, the number of whiskers parallel to the extrusion casting direction also increased gradually. In the tensile fracture of the 30% MBOw/Al composite, we could also see coarse whiskers parallel to the direction of squeeze casting. Studies have shown that when whiskers are parallel to the tensile direction, the pullout or fracture behavior of whiskers from the matrix during deformation plays a major role in the enhancement of mechanical properties of composites [5].
Fig. 4 The SEM photos of tensile fracture surface of MBOw/Al composite materials (a) 15%MBOw/Al, (b) 20%MBOw/Al, (c) 25%MBOw/Al, (d) 30%MBOw/Al.

3.3. Thermal expansion behavior

Fig. 5 and Fig. 6 show the test results of thermal expansion coefficient of magnesium borate whisker reinforced aluminum matrix composites with different whisker volume fraction. The first measurement data of the as-cast sample is defined as the initial state, and the second measurement data is defined as the cycle state. As can be seen from Fig. 5, in the direction of squeeze casting, the thermal expansion coefficient curves of the three groups of materials with whisker volume fraction less than 30% basically coincide. The initial engineering thermal expansion coefficient is about $18 \times 10^{-6}$/°C at 100 °C and about $23 \times 10^{-6}$/°C at 350 °C. This indicates that the external pressure in the extrusion casting process acts in this direction, making the whisker densities of the first three groups of samples basically the same in this direction. The thermal expansion curves of the composites coincide because the whiskers have the same influence on the thermal expansion properties of the composites. Due to the high density of whiskers in the extrusion casting direction of 30% MBOw/Al composites during the preparation of preforms, therefore the pressure of squeeze casting has little influence on it, and the thermal expansion coefficient of this group of materials is the lowest. Its initial engineering thermal expansion coefficient is $14 \times 10^{-6}$/°C at 100 °C and $19 \times 10^{-6}$/°C at 350 °C, which indicates that the larger the whisker volume fraction is, the lower the thermal expansion coefficient of the composites will be.
Fig. 5 The thermal expansion curves of composite materials with different volume fraction preforms (squeeze casting direction) (a) Initial state engineering thermal expansion coefficient, (b) Cycle state engineering thermal expansion coefficient.

As can be seen from Fig. 6, in the direction perpendicular to squeeze casting, the thermal expansion coefficient of the four magnesium borate whiskers with different whisker volume fractions changed slightly. With the increase of whisker volume fraction of magnesium borate, the thermal expansion coefficient of the composites decreased gradually, which also proved that the thermal expansion coefficient of the composites decreased with the increase of whisker volume fraction of the reinforcement. Among them, the initial engineering thermal expansion coefficient of 30% MBOw/Al composites is about $14 \times 10^{-6}/°C$ at 100°C and $19 \times 10^{-6}/°C$ at 350°C.

Fig. 6 The thermal expansion curves of composite materials with different volume fraction preforms (radial direction) (a) Initial state engineering thermal expansion coefficient, (b) Cycle state engineering thermal expansion coefficient.

3.4. Discussion

According to the mixing law and the experimental results of researchers, the higher the volume fraction of the reinforced phase in the composite, the higher the strength and the lower the coefficient of thermal expansion. However, due to the high elastic modulus of ceramic whiskers, it is difficult to prepare composites with high volume fraction of whiskers due to the influence of whisker prefabrication process. At the same time, when the volume fraction of reinforced phase is too high, the preheating temperature and permeability pressure of squeeze casting will be increased, which will
affect the quality of composites. Studies have shown that the change of thermal expansion coefficient of metal matrix composites is mainly affected by the relaxation rate of internal residual stress [5]. It can be seen that in the composites with different volume fraction of whiskers prepared, the higher the volume fraction is, the faster the relaxation rate of residual tensile stress will be during the heating process.

4. Conclusion
(1) The influence of whisker volume fraction on the mechanical properties of the composites is reflected in that the strength of the composites increases while the plasticity decreases with the increase of whisker volume fraction. Aluminum matrix composites with magnesium borate whisker content of 30% have tensile strength of 244 MPa and elastic modulus of 107.6 GPa at room temperature.
(2) Through the observation of microstructure of magnesium borate whisker reinforced aluminum matrix composites, it was found that the whisker preforms prepared by ultrasonic-dispersed dry pressing process could achieve better whisker dispersion in the composites.
(3) The thermal expansion test results show that in the direction perpendicular to squeeze casting, the thermal expansion coefficient of the composite decreases with the increase of whisker volume fraction. In the direction of squeeze casting, the thermal expansion coefficient curves of 15% MBOw/Al, 20% MBOw/Al and 25% MBOw/Al groups basically coincide. The thermal expansion coefficient of 30% MBOw/Al composite is the lowest, and its initial engineering thermal expansion coefficient is $14 \times 10^{-6}/^\circ C$ at 100°C and $19 \times 10^{-6}/^\circ C$ at 350°C.

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