Effect of TiB Content on the Properties of Al-TiB Composites

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Abstract:
In this study, titanium boride (TiB) was used to make Al-TiB composites. The contents of TiB added into Al matrix were 1 wt.%., 5 wt.% and 10 wt.%, respectively. The composites were pressed at a pressure of 382 MPa and sintered at 600 °C for 4 hours. The microstructures and properties of density, hardness and wear were investigated. Experimental results indicated that, the composite with 5 wt.% TiB owned the highest relative density and hardness among the three parameters. In addition, TiB particles dramatically improved the wear resistance of the Al matrix and the more TiB content the better of the wear resistance. That is, the composite with 10 wt.% TiB owned the best wear resistance.

Keywords: Titanium boride (TiB); Al-TiB composites; Density; Hardness; Wear

1. Introduction

Due to the high specific strength, good ductility, excellent thermal and electrical conductivity, fine corrosion resistance, aluminum (Al) and its alloys have been widely used in various industries such as chemistry, food, automobile, aerospace and transportation, etc. However, some poor surface properties (in particular hardness and wear resistance) severely restrict their further applications in many fields [1-3]. In order to solve this problem, aluminum matrix composites (AMCs) reinforced with hard ceramic particles begins to be valued by researches, because of their high stiffness, high elastic modulus and superior wear resistance [4-6].

Compared with some other ceramic reinforcements, TiB has been identified as owning the most appropriate balance of thermochemical stability, good mechanical properties and thermal expansion [3]. Hu et al. through boronizing the Ti powder synthesized face centered cubic (fcc) structure TiB powder and used this TiB powder as hardening materials for laser coating [7, 8]. Guo et al. used this TiB powder made Cu-TiB composites by powder metallurgy method and obtained the composite with good mechanical properties and high conductivity [9]. Besides, although AMCs reinforced with TiB have been studied by a few researchers [10, 11], Al-TiB composites were rarely reported.

Hence in this study, we take TiB powder which also fabricated by Hu et al. as additive to produce Al-TiB composites through powder metallurgy method. The detailed reasons for the change of density, hardness and wear resistance along with TiB content are investigated.

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2. Experimental materials and procedures

Al powder and TiB powder were used as raw materials for making Al-TiB composites. The structures are shown in Fig.1. The preparation process of the samples was divided into four steps: Firstly, the contents of TiB powders selected to mix with Al powders were 1 wt.%, 5 wt.%, and 10 wt.%, respectively. Then these kinds of powders were put into an automatic mixer with a rotated speed of 60 RPM for 2 hours. Secondly, the mixed powders were pressed into cylinders with size of $\Phi$ 14 mm $\times$ 10 mm under the pressure of 382 MPa. Thirdly, the samples were sintered in a furnace protected with $N_2$ at a heating speed of 20 $^\circ$C/min. The sintering temperature was selected as 600 $^\circ$C.

After heat preservation at 600 $^\circ$C for 4 hours, the samples were cooled inside the furnace to room temperature. Lastly, one side of round surfaces was grounded with sand papers and mirror polished as the initial state.

![Fig. 1. Particle morphologies of Al powders (a) and TiB powders (b).](image)

X-ray diffraction (XRD) analysis was carried out with CuKα radiation in a Rigaku D/Max-2500/pc X-ray diffractometer. Scanning speed and range were 4°/min and 10°-90°. Microstructures of the powders and sintered samples were characterized by using a Zeiss EVO18 scanning electron microscopy (SEM). Densities of the composites were measured according to Archimedes' principle. Hardness test was carried out using a HVS-1000 microhardness measurement device. The applied load was 0.49 N (50 g) with a load time of 15 s. And the average of 5 indentations was taken for each sample. To ensure the accuracy of hardness test results, 7 indentations were tested for each experiment parameter. The maximum and minimum values were removed, and the average value of residual 5 indentations was taken for each experiment parameter.

Dry sliding wear test was conducted with a pin-on-disc type tribometer (MG-2000). Before testing, specific size ($\Phi$ 6 mm $\times$ 12 mm) samples were processed as pins and the disc was made of YG6 cemented carbide with a hardness of 64 HRC. The tests were performed under the loads of 40 N and 60 N with a rotating velocity of 100 rpm and the sliding time of 25 min. All wear tests were carried out at room temperature. Contact surfaces of pins were grounded and polished as well before testing. An AL104 electronic balance that gave readings to 0.1 mg was used to weigh the pins before and after wear test. Then the mass loss during wear test can be calculated. Eventually, the morphologies of worn surfaces were examined by using scanning electron microscopy (SEM).
3. Results and Discussion
3.1. XRD analysis

Fig. 2. XRD pattern of the composite containing 5 wt.% TiB.

Fig. 2 shows the XRD pattern of the composite containing 5 wt.% TiB. It can be seen clearly that there only exist Al phase and TiB phase, no any new phase was found. That is, during the process of sintering, neither the decomposition reaction of TiB nor the interfacial reaction between Al and TiB occurred.

3.2. Surface morphologies analysis

Fig. 3 shows the surface morphologies of the composites with different contents of TiB. Seen from Fig. 3(a)-(c), the morphology of original Al powder particles was disappeared. Fig. 3(a) shows the surface morphology of composite with the least content (1 wt.%) of TiB. During the process of sintering, low content of TiB particles played fewer roles in hindering the small Al grains from merging with each other to grow larger. Finally, the grains of Al matrix were relatively large with plenty of pores distributed inside them. When the content of TiB reached 5 wt.%, as shown in Fig. 3(b), hindrance effect for the merge of small Al grains was enhanced. Therefore, the size of matrix grains decreased, which supplied more grain boundaries that can act as fast paths for the pores to be eliminated. Meanwhile, the pores can also be filled by TiB particles. Thus, the number of pores in the matrix was lower than the 1 wt.% TiB content one. Besides, the interfacial bonding between Al matrix and TiB particles looked better.

From Fig. 3(c) we can see that, due to the reason discussed above, when with high content of TiB (10 wt.%), the number of pores in the Al matrix was far below than the composites with 1 wt.% and 5 wt.% TiB content. On the contrary, there existed a lot of hollows distributed around the TiB particles. This is mainly because, the more content of TiB particles, the more contact area between TiB particles and Al matrix, and the harder to make TiB particles and Al matrix contact well during the process of compaction. That is, the interfacial bonding between Al matrix and these TiB particles was poor. Therefore, quit a few pores were persisted in the interface between Al matrix and these TiB particles.
Next, during the process of sintering, these pores gathered mutually and swallowed small pores around, then large pores formed around these TiB particles eventually.

3.3. Density analysis

| TiB percentage (wt %) | Measured density (g/cm$^3$) | Theoretical density (g/cm$^3$) | Relative density (%) |
|-----------------------|-----------------------------|-------------------------------|---------------------|
| 1                     | 2.62                        | 2.71                          | 96.68               |
| 5                     | 2.68                        | 2.76                          | 97.10               |
| 10                    | 2.60                        | 2.81                          | 92.53               |

Table I shows the density of composites with different TiB content. The densities of Al and TiB are 2.7 g/cm$^3$ and 4.51 g/cm$^3$ [12], respectively. That is the density of TiB is about 1.67 times than Al. So, the theoretical density of composites increased with the TiB content. But in fact, the composite with 10 wt.% TiB owned the minimum measured density. Correspondingly, its relative density was no doubt the lowest. According to Fig. 3(c), it was not hard to comprehend that the generation of massive large pores caused by the excessive TiB particles led to the expansion of composite which finally reduced the relative density of 10 wt.% TiB content composite. In addition, the composite with 5 wt.% TiB owned the maximum relative density, even a little higher than 1 wt.% TiB content one. Generally speaking, the increase of reinforced particles will more or less reduce the relative density. Therefore, apart from the reduced number of pores, this result also further evidenced the better interfacial bonding between Al matrix and TiB particles.
3.4. Hardness analysis

Fig. 4. Surface hardness of composites with different TiB content.

Fig. 4 shows the surface hardness of composites with different TiB content. It can be seen that, compared with the original sintered sample, the hardness of the Al-TiB composites increased obviously. The increase of hardness was mainly caused by dispersion strengthening effect of TiB [13]. Hence the hardness should be increased with the TiB content. Nevertheless, when the content of TiB reached 10 wt.%, the hardness was lower than the composite with 5 wt.% TiB. This is because the relative density of the composites also had important influence on the hardness. The decrease of relative density would no doubt reduce the hardness [9]. As shown in Table I, when the content of TiB reached 10 wt.%, the relative density was reduced dramatically, which finally caused its hardness lower than the composite with 5 wt.% TiB.

3.5. Wear analysis
3.5.1. Wear loss analysis

Fig. 5. Wear loss of the composites with different TiB content under the load of 40 N and 60 N.
Fig. 5 shows the wear loss of the composites with different TiB content under the load of 40 N and 60 N. As can be seen, no matter under which load, the wear loss of composites was reduced with the increase of TiB content. Meanwhile, compared with the composite with 1 wt.% TiB, the wear loss of the composite with 10 wt.% TiB all reduced over 50 % under the two kinds of loads. When under the same content of TiB particles, the wear loss of the composites was increased with the load among which 10 wt.% TiB content composite changed least. All the experimental data indicated that TiB particles dramatically improved the wear resistance of the Al matrix and the more TiB content the better of the wear resistance. This is mainly because the hardness of TiB particles is much higher than Al matrix, during the process of friction, they can improve the ability of composites to resist exterior force, which finally lightened the wear loss of composites.

3.5.2. Worn surface morphologies analysis

Fig. 6. Worn surface morphologies of the composites with 1 wt.% (a), 5 wt.% (b) and 10 wt.% (c) TiB under the load of 40 N.

Fig. 6 and Fig. 7 show the worn surface morphologies of Al-TiB composites under the load of 40N and 60N, respectively.

When the applied load was 40 N, as can be seen from Fig. 6(a)-(c), plough grooves were found on all the worn surfaces, which indicated that abrasive wear occurred. Meanwhile, as shown in Fig. 6(a), cracks and adhesive marks were observed on the worn surface of 1 wt.% TiB content composite, which indicated that delamination wear and adhesive wear occurred along with abrasive wear, which accelerated the wear rate of 1 wt.% TiB content composite [14]. Besides, small quantities of cracks were also found on the worn surface of 5 wt.% TiB content composite, as shown in Fig. 6(b). Nevertheless, for the composite with 10 wt.% TiB content (Fig. 6(c)), except for relatively shallow plough grooves, there were no other surface damage marks existed on the worn surface, which manifested that masses of TiB reinforced particles dramatically weaken the damage degree of worn surface and finally reduced the wear loss.
When the applied load reached 60 N, as can be seen from Fig. 7(a)-(c), the degree of wear increased obviously. And it is evident from Fig. 7(a) that under the higher load, the effect of adhesive wear mechanism was further enhanced for the composite with 1 wt.% TiB content. Meanwhile, the wear process of the composite with 5 wt.% TiB content (Fig. 7(b)) began to be governed by the combining effect of abrasive wear, delamination wear and adhesive wear mechanism. However, as shown in Fig. 7(c), although under the high load, because of the high content of TiB particles, other wear mechanism had little effect to the 10 wt.% TiB content composite and its major wear mechanism was still abrasive wear.

4. Conclusions

Al-TiB composites were successfully produced with TiB content of 1 wt.%, 5 wt.% and 10 wt.%, respectively. During the process of sintering, neither the decomposition reaction of TiB nor the interfacial reaction between Al and TiB occurred. When the content of TiB was 5 wt.%, the composite owned the highest relative density among the three parameters. Compared with the original sintered sample, the hardness of the Al-TiB composites increased obviously. Dispersion strengthening effect of TiB was the main reason for the improvement of surface hardness. However, for the composite with 10 wt.% TiB, the low relative density finally caused its hardness lower than the composite with 5 wt.% TiB. TiB particles dramatically improved the wear resistance of the Al matrix and the more TiB content the better of the wear resistance. In other words, the composite with 10 wt.% TiB owned the best wear resistance.

Acknowledgments

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