MICROSTRUCTURE AND WEAR RESISTANCE OF A COMPOSITE Gr/Al₂O₃/Al PRODUCED BY RECIPROCATING EXTRUSION

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A reciprocating extrusion process was used to produce graphite and alumina reinforced pure aluminium composite. The graphite particles (0~5vol%), alumina particles (10 vol%) and pure aluminium particles (balanced) were dehydrated separately at 70°C in vacuum for 3 hours, and then mixed together. A round billet with 50 mm in diameter was prepared by hot pressing at 350°C with the mixed particles and then extruded to a fully-consolidated goblet-like sample at 480°C and 430MPa by reciprocating extrusion. The results showed that all reinforced particles were refined and uniformly distributed in the matrix by reciprocation extrusion severe plastic deformation. The presence of graphite particles caused the reduction in the friction coefficient and wear rate of the Gr/Al₂O₃/Al composite. Compared with the composite prepared only by alumina particles (10 vol%) and pure aluminium particles, the friction coefficient and wear rate of the Gr/Al₂O₃/Al composite, which contains 5vol% graphite and 10vol% alumina particles, decreased 45.3% and 33.5%, respectively, and thereafter it displays an excellent combination of low friction coefficient (0.37) and wear rate ($2.2 \times 10^{-7} \text{mm}^3/(\text{N.m})$), and appears to be more promising.

Keywords: Metal matrix composites; Graphite particle; Alumina particle; Particle-reinforced composite; Wear

1. Introduction

Particle reinforced aluminum-matrix composites possess excellent properties, such as low density, high specific stiffness, high strength, high wear resistance and good seizure resistance, they are promising in using in aero-space structure, automobile engine and semiconductor parts casing, etc¹. The reinforced particles in composites are usually ceramic with high mechanical properties, including SiC, Al₂O₃, TiC and TiB₂ particles, etc². Particulate-reinforced Al-matrix composites are usually synthesized using particle metallurgy or various methods involving molten metals³, and they are receiving more and more attention than any other metal-matrix composites in recent years because of lower density and cheaper cost.

Considerable works have been done on the graphite particle reinforced metal-matrix composites which exhibit low friction, low wear rate, and excellent seizure resistance. In

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the composites, graphite presumably imparts improved wear resistance through the formation of a graphite-rich film on the wear surface⁴. Graphite/aluminum metal-matrix composites have been used⁵ in aerospace vehicles and are candidate materials for aeronautical, automotive and electro-mechanical machinery industries due to their potentially excellent specific mechanical properties. Gibson et al studied⁶ the effects of 2wt. % graphite particulate on the wear rate of aluminum alloy. The result showed that the wear rate of the alloy was significantly reduced. However, when the amount of graphite content was above to 8wt. %, the wear rate increased due to the low bonding strength at the interface between graphite particulates and Al based alloy. Jha et al found⁷ that graphite particulates in the graphite/ aluminum alloy composite prepared by powder metallurgy technique distributed non-uniformly and segregated as clusters. The clusters acted as porosity in the composite and made the composites brittle, resulted in the nucleation of crack in the composite, and therefore reduced the fracture toughness and elongation of matrix material and led to the severe wear. Das and Prasad discovered⁸ that 3wt. % of graphite could increase the seizure resistance for the Al-Si-Cu alloy.

In comparison with other preparation methods, reciprocating extrusion is one of the new processes with broad application prospect because of its easy process, low manufacturing cost and uniformly dense microstructure. In the present study, a reciprocating extrusion process was used to produce graphite and alumina reinforced pure aluminium composite (Gr/Al₂O₃/Al) from pure Al particle, Al₂O₃ particles and graphite particles. The effects of reciprocating extrusion and content of graphite on microstructure and wear properties of the composites were investigated.

2. Experimental

2.1 Experimental materials

The experimental Al₂O₃/Al composite and Gr/Al₂O₃/Al composites were produced from pure Al particle, Al₂O₃ particle and graphite particle. The purity of Al particle is 99%, the average size of the particle is about 29μm. The purities of Al₂O₃ particle and graphite particle are 99% and 99.85%, the average sizes of the particles are 44μm and 30μm, respectively. The graphite particles (1~5vol%), alumina particles (fixed at 10 vol%) and pure aluminium particles (balanced) were dehydrated separately at 70°C in a vacuum chamber with 1.3×10⁻⁵MPa for 3 hours. Then the particles were mixed with certain amount of ethanol and polyethylene glycol for 24 hours. The mixed particles were put into a mold and pressed as a billet 75mm long and 50mm in diameter at room temperature, and then the billet was put in the vacuum chamber which was heated at 80°C for 24h, so that any atmosphere in the billet was drew out. Subsequently, the billet was compacted under 320MPa pressure at 350°C for 25minutes and then extruded to a fully-consolidated goblet-like billet at 480°C by reciprocating extrusion.

Fig. 1 shows the schematic diagram of the reciprocating extrusion apparatus. The apparatus basically consists of a die and two sets of a container with a ram. Each set is located on one side of the die. The extrusion ratio is 12.76:1. For each extrusion pass

operation, a billet is put in one container and extruded by a ram into the opposite container. At the same time, a back pressure is applied by another ram so as to recover the billet in an original shape. By this method, the billet can be repetitively extruded between two containers and undergo severe plastic deformation. Fig.2 shows the morphology of one of the billets prepared by reciprocating extrusion for 2 passes in the experiment.

Fig.1. The schematic diagram of the reciprocating extrusion apparatus.

Fig.2. The morphology of the reciprocating extrusion billet.

2.2 Microstructure examination

The morphologies of the particles were examined by using AMRAY-1000B scanning electron microscope. The microstructure, especially the distribution of the reinforced particles in the composites, was analyzed by using Olympus-GX71 optical microscopy and the scanning electron microscope.

2.3 Wear resistance test

The wear resistance was performed on a MMW-2 high temperature pin-on-disc wear resistance tester under dry sliding condition at room temperature. The composite wear specimens with the dimensions of $\phi 43 \times 3$ mm were cleaned by ultrasonic cleaning and vacuum degassing. The basic process of the wear resistance tester is that the friction specimens slide on a rotating 45-steel disc with HB235. The applied load on the specimens was 40N, the relative sliding velocity of the specimen was 136r/min and the sliding time was limited to 30min. The wear resistance was evaluated by friction coefficient and wear rate. The friction coefficient was obtained by dividing the measured friction force by the applied load. The average weight loss of the specimens was measured by a precision balance with an accuracy of 10^{-4} g. Moreover, the morphologies of wear surface of the composites were examined by means of AMRAY-1000B scanning electron microscope.

3. Results

3.1 Microstructures of the composites

Fig.3 shows the SEM micrographs of the pure Al particles, Al₂O₃ particles and graphite particles. The pure Al particles were spherical; the Al₂O₃ particles look irregular and have a rough surface morphology; the graphite particles were polygonal and with a lamellar structure.

(a) pure Al particle

(b) Al₂O₃ particle

(c) graphite particle

Fig. 3. SEM micrographs of pure Al particle, Al₂O₃ particle and graphite particle.

Fig.4 showed the as-extruded microstructures of the Gr/Al₂O₃/Al composites. The results revealed that the composites were completely densified by reciprocation extrusion. Moreover, the reinforced particles Al₂O₃ and graphite were refined and uniformly distributed in the matrix.

Reciprocating extrusion process involves the direct extrusion and mushrooming deformation at one pass. Direct extrusion makes the particles huddle together closely and flow longitudinally, whereas, the mushroom deformation makes them move transversely⁹. During the processing by reciprocating extrusion, pores among the particles

can close up because of high pressure and severe deformation in aluminum; at the same time, the reinforced graphite and alumina particles collide with each other and are segmented into pieces. Consequently, the particles are refined gradually and their distribution becomes uniform.

Fig. 4. The optical microstructures of as-extruded Gr/Al₂O₃/Al composites with different amount of graphite: (a) no graphite, (b) 1vol% Gr, (c) 3vol% Gr, and (d) 5vol% Gr. The alumina particles in the composites are account for 10 vol%.

3.2. Wear resistance

Fig. 5 shows the variation of the friction coefficient with the volume fraction of graphite in the composites. Noticeably, the presence of graphite particles resulted in the reduction of friction coefficient. The friction coefficient of the composite containing 5vol% graphite was 0.37, which was 45.3% lower than that of Al₂O₃/Al composite.

The variation of the wear rate with the graphite content in the composite is showed in Fig.6. It could be noted that there was a critical value 1% for the graphite content. While the graphite content was lower than 1%, the wear rate increased with the graphite. However the wear rate decreased with the graphite when the graphite content was higher than 1%. Graphite is soft and always tends to soften the composites. The more the graphite was, the lower the strength of the composites.

Graphite has a hexagonal structure, which consists of carbon atoms arranged in a layer-like structure. The bonding within the layer is quite strong, but layers are weakly bonded with each other. When small amount of graphite (lower than 1% graphite) was

added in the composite, it was not enough to form a lubrication film on the friction surface, and the discontinuation of the composite, which results from the addition of small amount of graphite, causes the desquamation of Al₂O₃ particles during the wear process, thus a heavy plastic deformation occurred on the surface of composites, and this deteriorated the friction and wear action. So the composite that contains 1% graphite has a higher wear rate.

Fig. 5 The variation of the friction coefficient of the composites with the graphite content.

Fig.6 The variation of the wear rate with the graphite content.

While when the amount of graphite was above the critical value(1% graphite), a graphite lubrication film was formed on the friction surface. The film was beneficial for the formation of smooth contacting surface and therefore the friction and wear action between the friction pairs could be relieved. So the wear capacity improves with the increase of the volume of graphite. The wear rate was as low as $2.2 \times 10^{-7} \text{ mm}^3/(\text{N.m})$ when the graphite content was 5%.

Fig.7 shows the typical SEM micrographs of the wear surfaces of Gr/Al₂O₃/Al composites. It could be clearly seen that plastic deformation occurred on the surface of

the $\text{Al}_2\text{O}_3/\text{Al}$ composite in which no graphite added (Fig. 7(a)). More seriously, part of the composite wear sample was scraped off from the contacting surface during the sliding process. It was noticed that some scraped materials adhered to the steel friction counterface, which indicated clearly that adhesive wear played a main role for the composites. However, as the graphite content increased, the wear surface of the $\text{Gr}/\text{Al}_2\text{O}_3/\text{Al}$ composites became smoother (Fig. 7(b),(c)), and materials adhered to the friction counterface was less. This phenomenon suggested that the wear surface of the composite was rich in graphite which served as solid lubricant and alleviated friction. When the graphite content increased to 5vol% in the composites, a thin integrate graphite film formed and no substance adhered on the friction counterface (Fig. 7(d)). It indicated that the higher graphite content yielded a smoother wear surface.

Fig.7 The typical SEM micrographs of the wear surfaces of $\text{Gr}/\text{Al}_2\text{O}_3/\text{Al}$ composites: (a) no graphite, (b) 1vol % Gr, (c) 3vol % Gr and (d) 5vol % Gr. The alumina particles in the composites are account for 10 vol%.

For the $\text{Gr}/\text{Al}_2\text{O}_3/\text{Al}$ composite, the graphite particles in subsurface region could form solid lubricant film on the wear surfaces, therefore alleviated the mutual wear action of $\text{Gr}/\text{Al}_2\text{O}_3/\text{Al}$ composite and 45 steel counterface. The fine graphite granules were mixed with the other wear debris and then a smooth graphite-rich tribo-layer was formed on the worn surface¹⁰. To sum up, the addition of graphite particles as the second reinforcement in $\text{Al}_2\text{O}_3/\text{Al}$ composite was effective to improve the wear properties of the composite, thus the lifespan of $\text{Gr}/\text{Al}_2\text{O}_3/\text{Al}$ composite was much higher than that of $\text{Al}_2\text{O}_3/\text{Al}$ composite.

In consideration of the combined properties of wear rate and friction coefficient, the Gr/Al₂O₃/Al composite with 5vol% graphite appears to be the best of all the composites in the present study. This is expected since the composite contains a suitable amount of graphite for lubrication.

4. Conclusions

(1) Reciprocating extrusion can be used to prepare graphite and alumina reinforced pure aluminium composite Gr/Al₂O₃/Al from graphite particles (1~5vol%), alumina particles (10 vol%) and pure aluminium particles. The tightness of the composites is high, and the reinforced particles Al₂O₃ and graphite were refined and uniformly distributed in the matrix.

(2) Graphite can effectively reduce the friction coefficients of Gr/Al₂O₃/Al composites. As the graphite content increases, the wear rate firstly increases and then decreases. The friction coefficient and wear rate of the Al₂O₃/Al composite is 0.6750 and $3.3 \times 10^{-7} \text{ mm}^3/(\text{N.m})$, respectively. The friction coefficient and wear rate of the Gr/Al₂O₃/Al composite containing 5vol % graphite is 0.37 and $2.2 \times 10^{-7} \text{ mm}^3/(\text{N.m})$, which is 45.3% and 33.5% lower than that of the Al₂O₃/Al composite.

(3) The Gr/Al₂O₃/Al composite, which contains 5vol% graphite and 10vol% alumina, displays an excellent combination of low friction coefficient and wear rate, and appears to be more promising in application.

Acknowledgments

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References

1. H. S. Chu, K. S. Liu and J. W. Yeh, *Scripta Materialia*, **45**, 541 (2001).
2. Y. Z. Zhan and G. D. Zhang, *Materials and Design*, **27**, 79(2005).
3. H. S. Chu, K. S. Liu and J. W. Yeh, *Metallurgical and materials transactions* **31A:10**, 2587(2000).
4. J. F. Lin, M. G. Shih and Y. W. Chen, *Wear*, **198**, 58(1996).
5. A. Daoud, *Materials Letters*, **58**, 3206(2004).
6. P. R. Gibson, A. J. Clegg and A. A. Das, *Wear*, **95**, 193(1984).
7. A.K. Jha, S.V. Prasad and G.S. Upadhyaya, *Wear*, **133**, 163 (1989).
8. T.F. Stephenson and J.A.E. Bell, In *Advances in production and fabrication of light metals and metal matrix composites*, ed. M.M. Avedesian, et al. (The Metallurgical Society of CIM, Alberta, Canada, 1992), pp. 511–520.
9. Z. M. Zhang, C. J. Xu, X. F. Guo, S. Z. Jia, *Acta Metallurgica Sinica (English Letters)*, **21**, 169(2008).
10. S. Basavarajappa, G. Chandramohan, Arjun Mahadevan, Mukundan Thangavelu, R. Subramanian and P. Gopalakrishnan, *Wear*, **262**, 1007(2007).