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Effect of interfacial reactions on solid erosion of $Al_{18}B_4O_{33}$ whisker-reinforced AC4C Al alloy matrix composites①

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Abstract: Solid erosion of as-cast and treated 19.5%(volume fraction) $Al_{18}B_4O_{33}$ whisker/AC4C Al composites was investigated at room temperature under steady-state conditions. The results indicated that the interfacial reaction between the whisker and matrix alloy have an effect on the erosion characteristics of the composites. The erosion resistance of the composites with a strongly bonded whisker-matrix interface and the higher whisker strength resulted from suitable reaction treatment can be improved at high impact angles and is the same as the as-cast composites at low angle. For the composites after excessive reaction treatment, the weak and brittle interface fractures easily at small strains, and the whiskers with relative low strength and low hardness at the specimen surface can not effectively resist the microcutting or microploughing action, thus the composites exhibit reduced erosion resistance.

Key words: interfacial reactions; solid erosion; metal matrix composites **Document code:** A

1 INTRODUCTION

Whisker-reinforced aluminum composites have been of great interest for their high specific strength, high modulus and high wear resistance. Several studies[1~5] on the erosion of metal-matrix composites (MMCs) have shown that these advanced engineering materials erode more rapidly than the unreinforced matrix metals do. The improvement in mechanical properties due to secondary processing does not lead to a proportionate increase in erosion resistance. During the erosion by solid-particle impingement, it has a higher tendency for cracking and fragmentation of the reinforced materials. The decrease of erosion resistance was attributed to the reduced ductility imposed by increasing the reinforcement phase. The solid erosion mechanism of the composites involve not only the basic ductile or brittle mechanism operative in single-phase materials, but also effects of the characterization related to microstructure[6]. The adhesion between reinforcer and matrix plays an important role in the erosion behavior of composite materials. According to Hutchings[7], the most important parameter in deciding the performance of the composites in erosive conditions is whether the reinforcement particle or fiber undergoes fracture or not. If the erodents do not cause fracture of reinforcement phase, then the protection by reinforcement phase can be expected.

Interfaces constitute an important microstructural feature of composite materials[8]. In the case of MMCs, improvements in wetting and bonding at the whisker-matrix interface can be achieved by a chemical reaction that yields chemical compound which forms strong bonds with both metals and ceramics. However, an excessive interfacial reaction would degrade the reinforcement phase strength. Thus, the matrix-whisker interface interactions and the whisker properties must all be considered in composite design to modify the erosion characteristics of the composites.

This work is concerned with the erosion behavior of 19.5%(volume fraction) $Al_{18}B_4O_{33}$ whisker/AC4C Al composites under steady-state conditions. The influence of interfacial reactions between the matrix and whisker on the erosion resistance of the composites is also discussed.

2 EXPERIMENTAL

Composite containing 19.5%(volume fraction) randomly dispersive aluminum borate ($Al_{18}B_4O_{33}$) whisker $d(0.5\sim1.0)\ \mu m\times(10\sim30)\ \mu m$, density $2.93\ g\cdot cm^{-3}$, elastic modulus 400 GPa, tensile strength 8 GPa and Moh's hardness 7) was fabricated by squeeze casting technique at the molten pouring metal temperature of 760 ℃ and preform temperature of 700 ℃. The AC4C Al (Si 6.5%~7.5%, Mg 0.2%~0.45%, Fe < 0.55%, Zn < 0.35%, Cu <

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0.25 %, Al balance) was selected as the matrix alloy. In the reaction treatment, the specimens were treated at 500 ℃ for 4 h, 10 h and 36 h, respectively, then water quenched to room temperature, aged at 160 ℃ for 6 h and air cooled. After extraction from the composites, the whisker surfaces were examined using scanning electron microscopy and X-ray diffraction. Before erosion testing, the surfaces of the specimens (40 mm × 40 mm × 5 mm) were polished with 1 000 grit SiC emery paper and degreased with acetone.

Solid erosion tests were conducted at room temperature using an air-stream rig which has been described previously[9]. The specimen was mounted inside a test chamber and the distance between the specimen surface and the end of the nozzle was 10 mm. For these tests, angular silica sand (HV 1 280) with size of 106 ~ 149 μm was used as erodent. The erodent particle velocity in this work was 140 $m \cdot s^{-1}$ and the constant particle feed rate was 0.23 $g \cdot s^{-1}$. Experiments at this particle velocity were carried out for impact angle from 15° to 90°.

All measurements were conducted at the steady-state condition. The steady-state erosion was determined by plotting the volume loss (mass loss/density) from the specimen against total mass of the erodents, and the gradients of these plots were calculated to determine the erosion rates. The eroded surfaces and cross-section of the specimens were observed by scanning electron microscopy (SEM).

3 RESULTS AND DISCUSSION

Under the squeeze-casting condition, the interaction time for the whisker and the matrix alloy at high temperature was very short, no interfacial reaction product formed in the as-cast composites. From the X-ray diffraction pattern of the extracted whiskers from the treated $Al_{18}B_4O_{33w}$/AC4C Al composites, there were other substances being found after heat treatments compared with the as-received whisker pattern, indicating that interfacial reaction occurs between $Al_{18}B_4O_{33}$ whisker and Al matrix alloy under the reaction treatment conditions. The reaction product was identified as spinel $MgAl_2O_4$. According to Suganuma et al[10], the interfacial reaction in the composites may be as follows:

$$Al_{18}B_4O_{33} + 4Al \rightarrow 11\ \gamma\text{-}Al_2O_3 + 4B \quad (1)$$

$$\gamma\text{-}Al_2O_3 + Mg + [O] \rightarrow MgAl_2O_4 \quad (2)$$

The interfacial reaction in the composites is a coupling reaction. The presence of Mg in the matrix alloy is one of the essential conditions under which the interfacial reaction can occur during the heat treatment. The scanning electron micrographs showing the morphology of whiskers in various states are present in Fig.1. On the surfaces of the whiskers extracted from the treated $Al_{18}B_4O_{33w}$/AC4C Al composites, a lot of interfacial products can be seen (Figs.1 (b), (c) and (d)). As the treatment time increases, the interfacial reactions become more serious, i.e. the reaction products increase and interface reaction layer becomes thicker.

The interaction between the whisker and matrix alloy has an influence on the microstructure and properties of the whisker. Severe interfacial reaction damages the whisker and results in degradation of the whisker strength and hardness[11]. The interfaces rely on the combination of the mechanical interlocking and chemical bonding. As a result of chemical reaction, the tensile strength, fracture strain and hardness of the composites have varied significantly with increasing reaction time. The mechanical properties of the as-cast and treated composites are listed in Table 1. In the case of the composites treated for short time, the reaction zone is very thin, and the effect of intrinsic defects in the whisker is very small. Because some circumferential notches formed around the whiskers and the whiskers are able to maintain their full strength, the tensile strength of the composites is not reduced while the fracture strain increases slightly. However, as the interaction zone thickens, the interface begins to dominate the mechanical behavior. As seen in this table, with further increasing reaction time, the tensile and hardness test date are consistent with thicker reaction zones being weakened, resulting in the tensile properties and hardness of the composites being far less than those of the as-cast composites.

The steady-state erosion rates of the $Al_{18}B_4O_{33w}$/AC4C Al composites for various impact angles at a particle velocity of 140 $m \cdot s^{-1}$ are shown in Fig.2. At the constant particle velocity, the steady-state erosion rates of the composites increases slightly with impact angle at low angles, and reaches maximum between 20° ~ 30°, then decreases with further increasing impact angle. This result is in agreement with previous studies[1,3]. At low impact angle, the erosion rate of the as-cast composites is similar to that of the composites treated for suitable time, and lower than those of the composites treated for long times. Above 30° impingement angle, for every set of conditions, the composites treated for suitable time has the highest erosion resistance while the composites treated for longest time has the greatest erosion rate.

The eroded surfaces of the specimens were examined by scanning electron microscopy in order to understand the erosion mechanisms and characteristic features of erosion. As seen in Fig.3, the eroded surfaces of the composites at normal impact angle represent craters and a high degree of flake formation under the high-velocity particle impact condition. The flake formation occurs when the surface suffers plastic deformation and a strain-hardened layer is produced on the surface because of the repeated impacts of erodent particles. The detachment of the flakes by

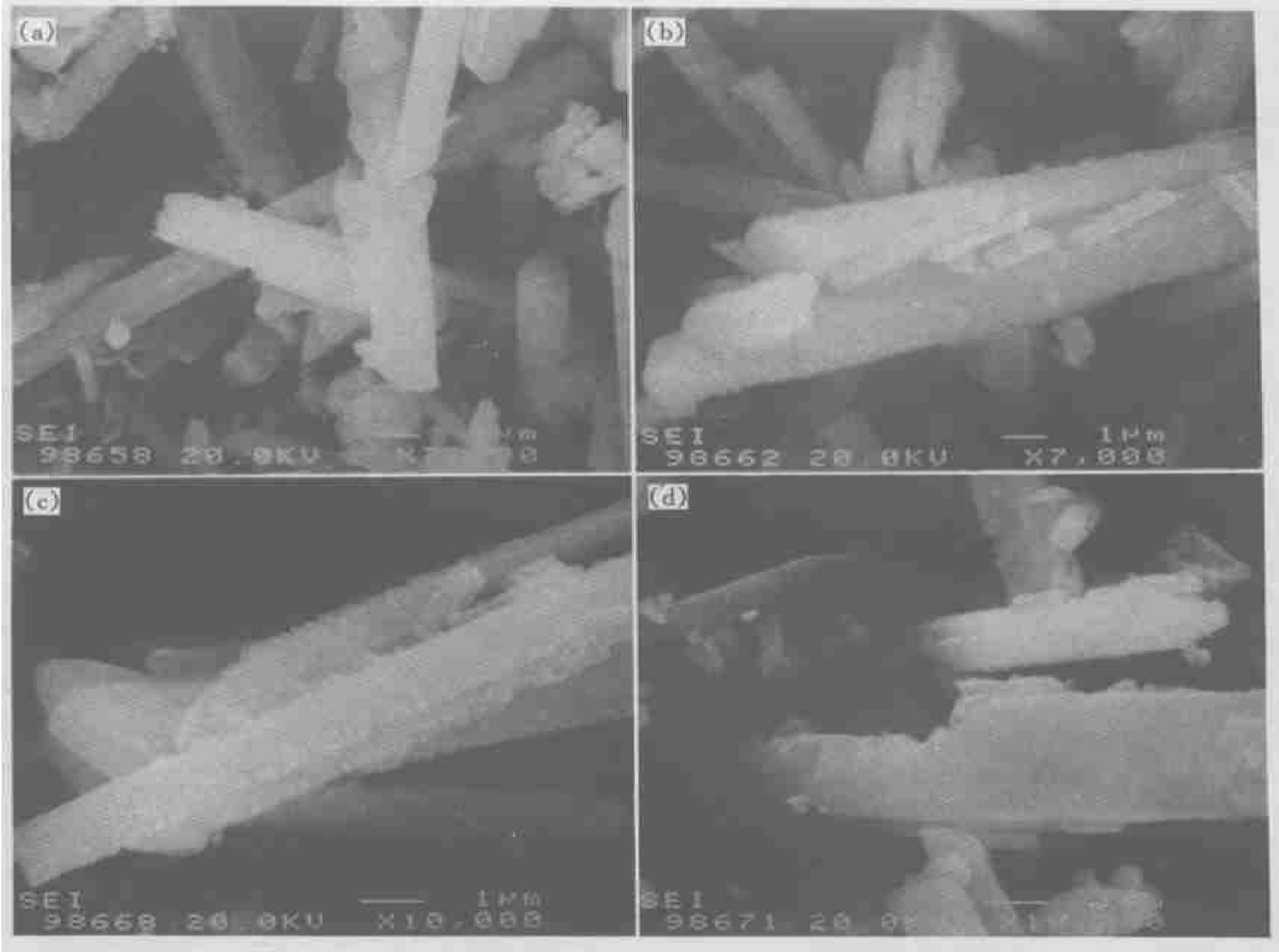

Fig.1 SEM micrographs of whiskers extracted from as-cast composite (a), composite treated at 500 ℃ for 4 h (b), composite treated at 500 ℃ for 10 h (c) and composite treated at 500 ℃ for 36 h (d)

Table 1 Mechanical properties of as-cast and treated $Al_{18}B_4O_{33\,W}$/ AC4C Al composites

Composite	Ultimate stress / MPa	Fracture strain / %	Elastic modulus / GPa	Hardness HV
As-cast	302.3	2.3	96.1	126
Treated, 500 ℃, 4 h	298.6	2.5	94.8	123
Treated, 500 ℃, 10 h	279.5	2.1	92.7	119
Treated, 500 ℃, 36 h	248.2	1.9	87.9	114

ductile fracture appears to be one of the main mechanisms of material loss during steady-state particle erosion. Furthermore, except the plastic flow, interfacial cracking, fragmenting and dislodging of $Al_{18}B_4O_{33}$ whisker occurred under the high-velocity particle impact. In contrast, interfacial cracking and fragmenting and dislodging of $Al_{18}B_4O_{33}$ whisker easily occur on the excessively treated composites. It is observed that the reinforcement whisker is dislodged on the eroded surface. (Fig.3(c), shown by arrows).

Because of severe localized fracture and dislodge-

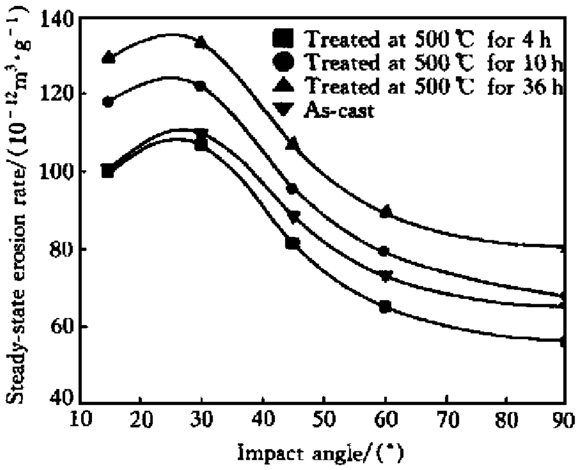

Fig.2 Steady-state erosion rates of as-cast and treated composites as a function of impact angle

ment of $Al_{18}B_4O_{33}$ whisker, no correlation was found between the erosion rates and hardness of the composites although hardness determines the resistance to plastic deformation. For a series of composites tested by Srinivasan et al[12], an inverse relation between erosion rate and mechanical properties was provided

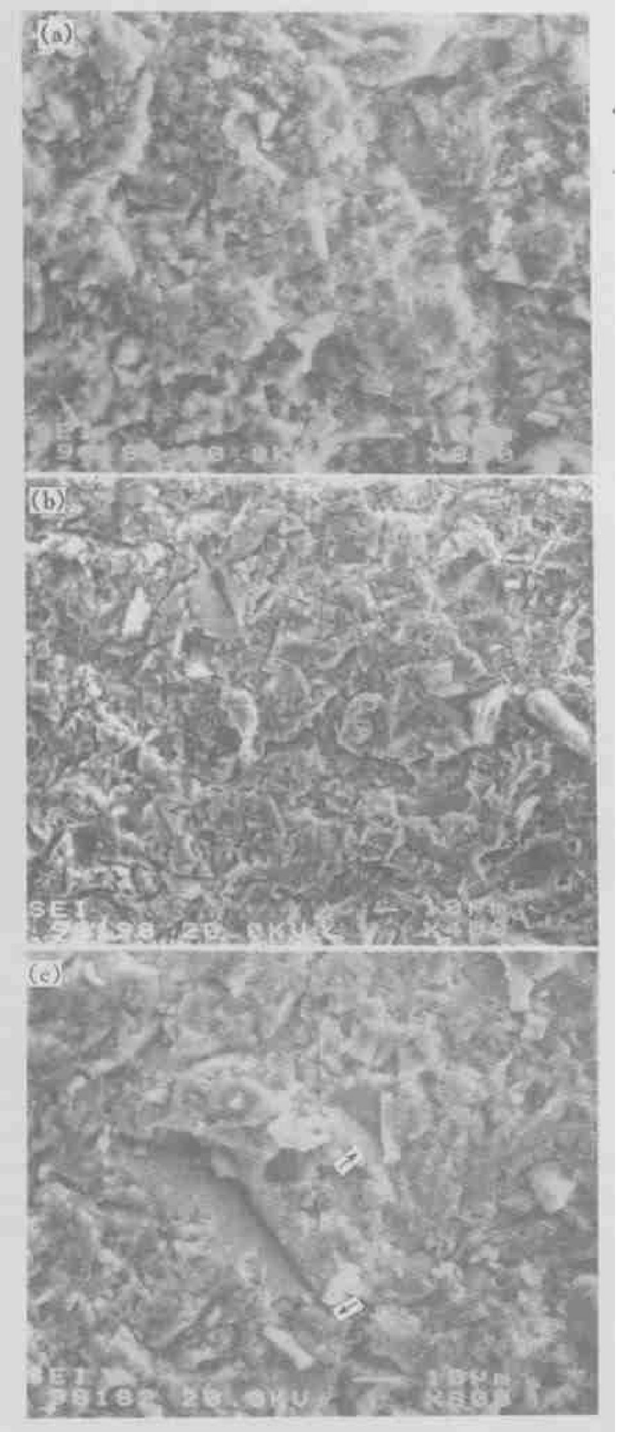

Fig.3 SEM micrographs of eroded surfaces of composites at normal impact angle
(a) —As-cast composite;
(b) —Composite treated at 500 ℃ for 4 h;
(c) —Composite treated at 500 ℃ for 36 h

by the parameter $\sigma_b \varepsilon_f$, which includes both flow stress σ_b and fracture strain ε_f. In this work, the interfacial reaction drastically changes the bonding strength of the interface and the mechanical properties of the composites. Compared with the mechanical property of the composites, the value of $\sigma_b \varepsilon_f$ increases after heat treatment for short time, but reduces as the treatment time further increases. During successive particle impact at high impact angles, the dislocation density at the reinforcer/matrix interface further increased, which resulted in strain localization around the reinforcer[6].

Fig. 4 shows the typical micrographs of the cross-section perpendicular to the eroded surfaces of the treated composite. The weak and brittle reaction layer formed at the whisker-matrix interface due to an excessive reaction easily fractures at small strains, resulting in relatively larger number of cracks on the subsurface of the composites (Fig.4 (b)). The whisker in the excessively treated composite can promote the rate of material removal process by crack growth through the interface of the whisker-matrix decohesion. Therefore, the excessively treated composite reveals a reduced erosion resistance. Because of the increase in fracture strain and the maintenance in strength, the composite after suitable heat treatment exhibits lower erosion rate as compared to the as-cast and the excessively treated composites at high impingement angles.

At the constant particle velocity, the resistance to fragmentation and dislodgement of $Al_{18}B_4O_{33}$

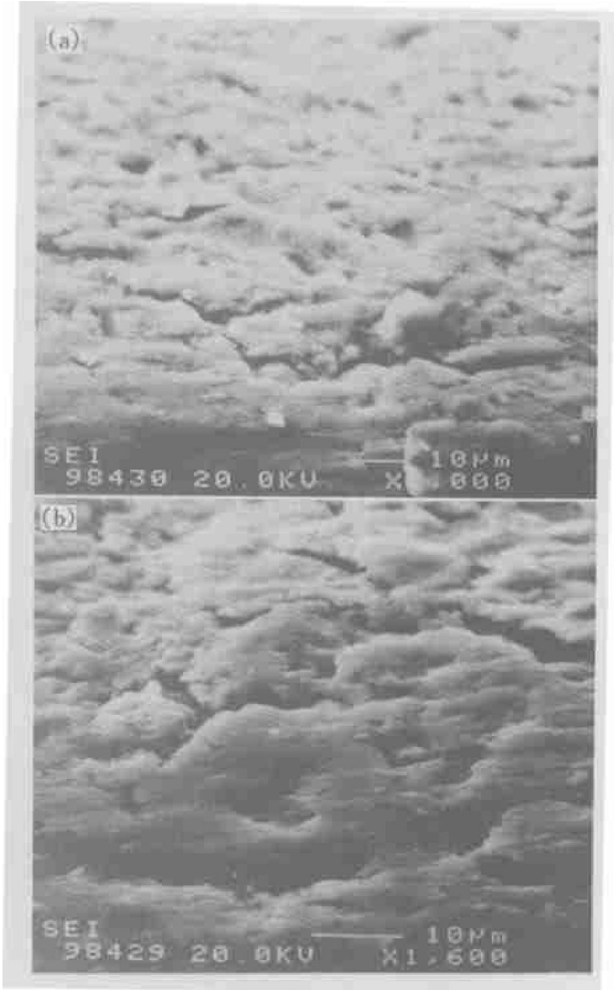

Fig.4 SEM micrographs of cross-section of eroded surfaces of composites after various treatment
(a) —Treated at 500 ℃ for 4 h;
(b) —Treated at 500 ℃ for 36 h

whisker is also a function of impact angle. When the composites were eroded at low impact angles, the erosion processes observed in the composites are associated with their corresponding plastic deformation, microcutting and gouging. But in the case of high particle velocity, the normal part of the impact energy at low angle can also produce a strain-hardened layer and flake on the eroded surface of the composites. During the solid erosion at low impact angle, the whisker with relative high strength at the surface of the specimen can act as protective reinforcement to resist the microcutting or microploughing action. However, a high extent of interfacial interaction would be expected to degrade the whisker strength and hardness. Therefore, an excessive reaction treatment for the composites was harmful to the erosion resistance at low impact angles.

4 CONCLUSIONS

The interfacial reaction between the whisker and matrix alloy results in change in mechanical properties and erosion characteristics of the composites. The erosion mechanism for the as-cast and treated composites involves flaking, interfacial cracking, cutting and gouging. Furthermore, fragmentation and dislodgement of whisker also occurs on the eroded surface of the composites under high velocity particle impact conditions. Through suitable reaction treatment, the erosion resistance of the composites with a strong interfacial bond and better whisker strength can be improved at high impact angles and is the same as the as-cast composites at low angle. The excessive reaction treatment has a deleterious effect on the erosion resistance of the composites.

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