The whisker–matrix interfacial reactions in SiC, Si_3N_4 and $Al_{18}B_4O_{33}$ whisker-reinforced aluminium-matrix composites

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Whisker-reinforced aluminium composites have been of great interest for their high specific strength, high modulus, high wear resistance and thermal stability. Among them, SiC [1], Si_3N_4 [2] and $Al_{18}B_4O_{33}$ [3] whisker-reinforced aluminium composites appear to be promising in industry. Recently, systematic investigations of the mechanical properties of these composites have been reported [4], considering the composites in the as-fabricated (F) and T6-treated (T) states, which gave the bending strengths of 760.4 MPa (F) and 893.4 MPa (T) for SiC/6061Al ($V_f = 25.5\%$), 789.6 MPa (F) and 946.2 MPa (T) for Si_3N_4/6061Al ($V_f = 30.0\%$), 649.1 MPa (F) and 636.4 MPa (T) for $Al_{18}B_4O_{33}$/6061Al ($V_f = 28.0\%$). Here V_f represents the volume percentage of whiskers in the composites. In the composites the whisker–matrix interfaces take up a high volume percentage and will influence the mechanical properties of the composites. It has thus been of much interest to study the interface structure and interfacial reactions to obtain a good understanding of the relationship between the interface and the mechanical properties. This letter presents recent research results concerning the characterization of the whisker–matrix interfacial reactions in these composites, which were fabricated by squeeze casting.

High-resolution transmission electron microscopy (HRTEM) observations in previous work showed that there were two kinds of interface structure in whisker-reinforced aluminium-matrix composites [5–7], i.e. directly bonded interface and interface bonded with an amorphous transition layer with width of nm scale. For instance, SiC [5] and Si_3N_4 [6] whisker bonded with aluminium matrix with an amorphous layer, and $Al_{18}B_4O_{33}$ whisker bonded directly with the aluminium matrix [7]. Fig. 1a shows an HRTEM image of the SiC–6061Al (Al–Mg–Si alloy) interface, from which a 1 nm thick amorphous transition layer between SiC and Al matrix can be seen. Fig. 1b and c shows the energy-dispersive spectroscopy (EDS) analysis results in the Al matrix and at the SiC–Al interface, respectively. The atomic ratios of MgAl were 1:27 and 1:15 (Fig. 1c), which indicates Mg segregation at the SiC–Al interface. MgO particles at the SiC–Al interfaces have been observed in SiC whisker-reinforced aluminium alloy-matrix composites [8, 9], which resulted from the Mg segregation at the interfaces. Mg segregation was also found at Si_3N_4–6061Al [10] interfaces and $Al_{18}B_4O_{33}$Al [7] interfaces, which resulted in interfacial reactions. Fig. 2a–c shows the Si_3N_4 whiskers in Si_3N_4–pure Al, Si_3N_4–6061Al as-fabricated and Si_3N_4–6061Al T6-treated composites, respectively. The incident electron beam direction was parallel to the whisker growth axis [0 0 1]. It can be seen from Fig. 2 that no interfacial reaction occurred in Si_3N_4–pure Al composite because of the absence of Mg, but interfacial reactions existed in Si_3N_4–6061Al composite due to

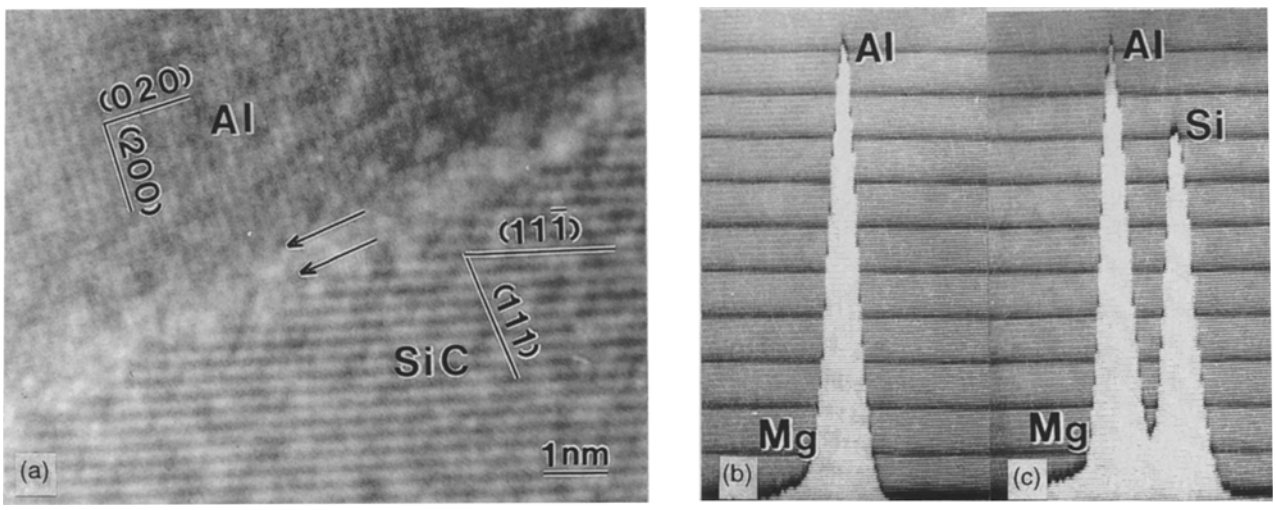

Figure 1 (a) HRTEM image of the SiC–Al interface, and EDS results (b) in the Al matrix and (c) at the SiC–Al interface.

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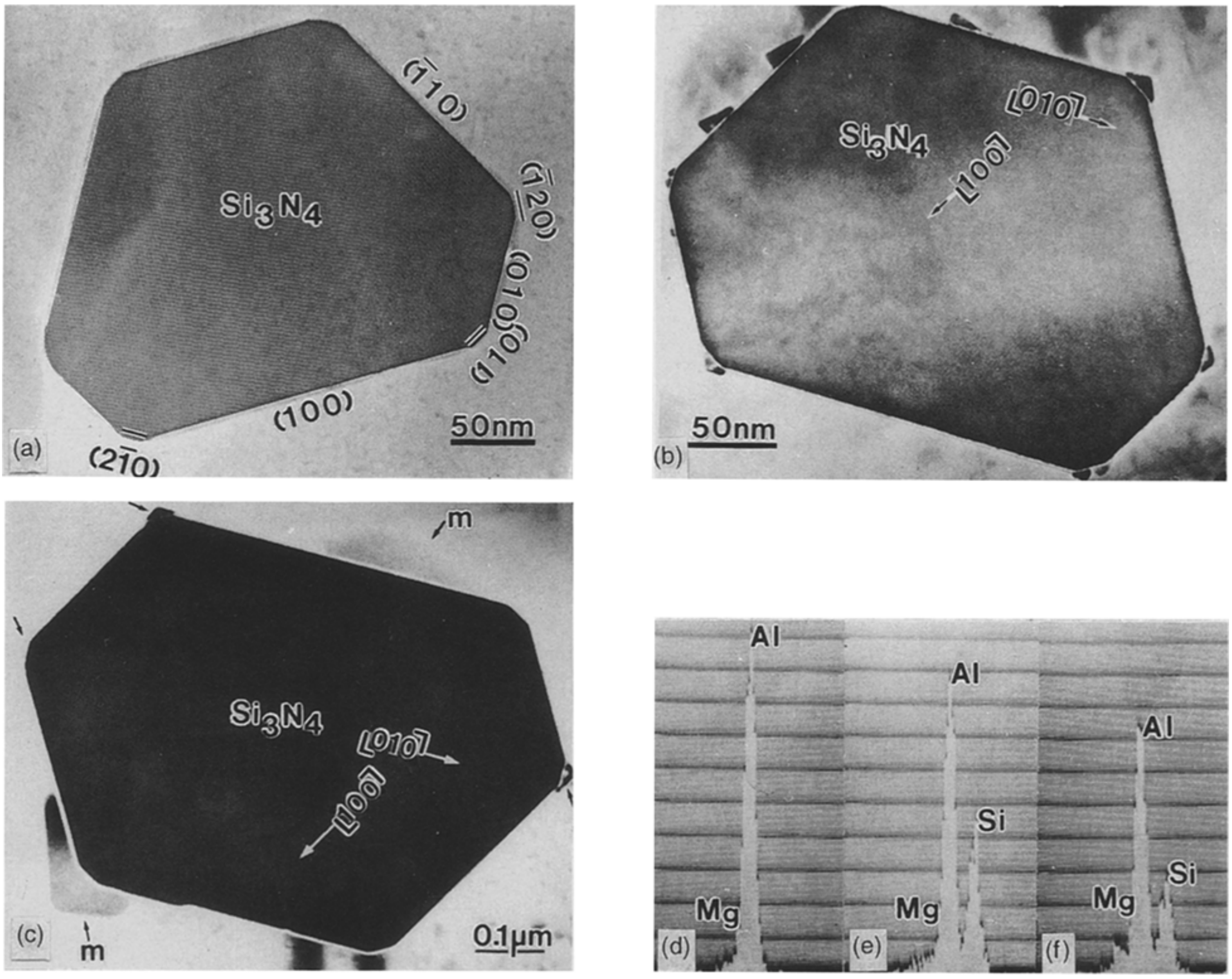

Figure 2 Diffraction contrast images of the Si_3N_4 whiskers in (a) the Si_3N_4–pure Al composite, (b) the Si_3N_4–6061Al as-fabricated composite and (c) the Si_3N_4–6061Al T6-treated composite, viewed along the whisker growth axis. EDS results (d) in the matrix, (e) at the whisker–matrix interface and (f) at the reaction product.

Mg segregation. Fig. 2 also shows the EDS results in the matrix (Fig. 2d), at the whisker–matrix interface (Fig. 2e) and at the interfacial reaction product (Fig. 2f). The atomic ratios of Mg:Al were 1:18 (Fig. 2d), 1:11 (Fig. 2e) and 1:6 (Fig. 2f), from which the Mg segregation at the interface can be found. The EDS results at the interfacial reaction product in Fig. 2f indicated that the reaction products were Mg compounds. Detailed analysis showed that most of the particles at the interface in the as-fabricated composite were $MgAl_2O_4$ and a few were MgO [10], which was different from the case at the SiC–6061Al interfaces [8]. In the T6-treated state the Mg_2Si particles of the strengthening phase in the 6061Al alloy preferred to precipitate at the Si_3N_4–6061Al interfaces, as shown by m in Fig. 2c. This kind of precipitation may be beneficial to the interface strength. Detailed observations showed that in SiC–6061Al and Si_3N_4–6061Al composites the interfacial reactions did not continue to occur during T6 treatment. Therefore, the bending strength of the composites increased after T6 treatment due to the matrix strengthening.

Fig. 3a–c shows the $Al_{18}B_4O_{33}$ whiskers (marked W) in $Al_{18}B_4O_{33}$–pure Al (Fig. 3a), $Al_{18}B_4O_{33}$–6061Al as-fabricated (Fig. 3b) and $Al_{18}B_4O_{33}$–6061Al T6 treated (Fig 3c) composites. It can be seen that no interfacial reaction occurred at the $Al_{18}B_4O_{33}$–Al interfaces in $Al_{18}B_4O_{33}$–pure Al composite. However, serious interfacial reactions existed at the whisker–matrix interfaces in $Al_{18}B_4O_{33}$–6061Al composites. In Fig. 3b and c the reaction products are marked by black dots. It has been found that the $Al_{18}B_4O_{33}$ whiskers themselves take part in the interfacial reactions [8], which may be found by comparing Fig. 3b and c with Fig. 3a. This kind of interfacial reaction certainly eats parts of the whiskers [8]. The interfacial reactions became more serious after T6 treatment (compare Fig. 3b and c, i.e. the reaction products increased in number and became larger in the T6 state than in the as-fabricated state. Fig. 3d and e shows the EDS results at the $Al_{18}B_4O_{33}$–matrix interfaces without interfacial phase in the as-fabricated (Fig. 3d) and T6 (Fig. 3e) states. The Mg:Al atomic ratios were 1:21 (Fig. 3d) and 1:29 (Fig. 3e), which indicates that the Mg segregation decreased in the T6 state due to the continued interfacial reactions. This phenomenon can be used to explain why the bending strength in the T6 state did not increase and even decreased (F649.1 MPa and T636.4 MPa).

It can be seen that the interfacial reaction style depends on the interface structure character. Moreover, the interface structure character depends

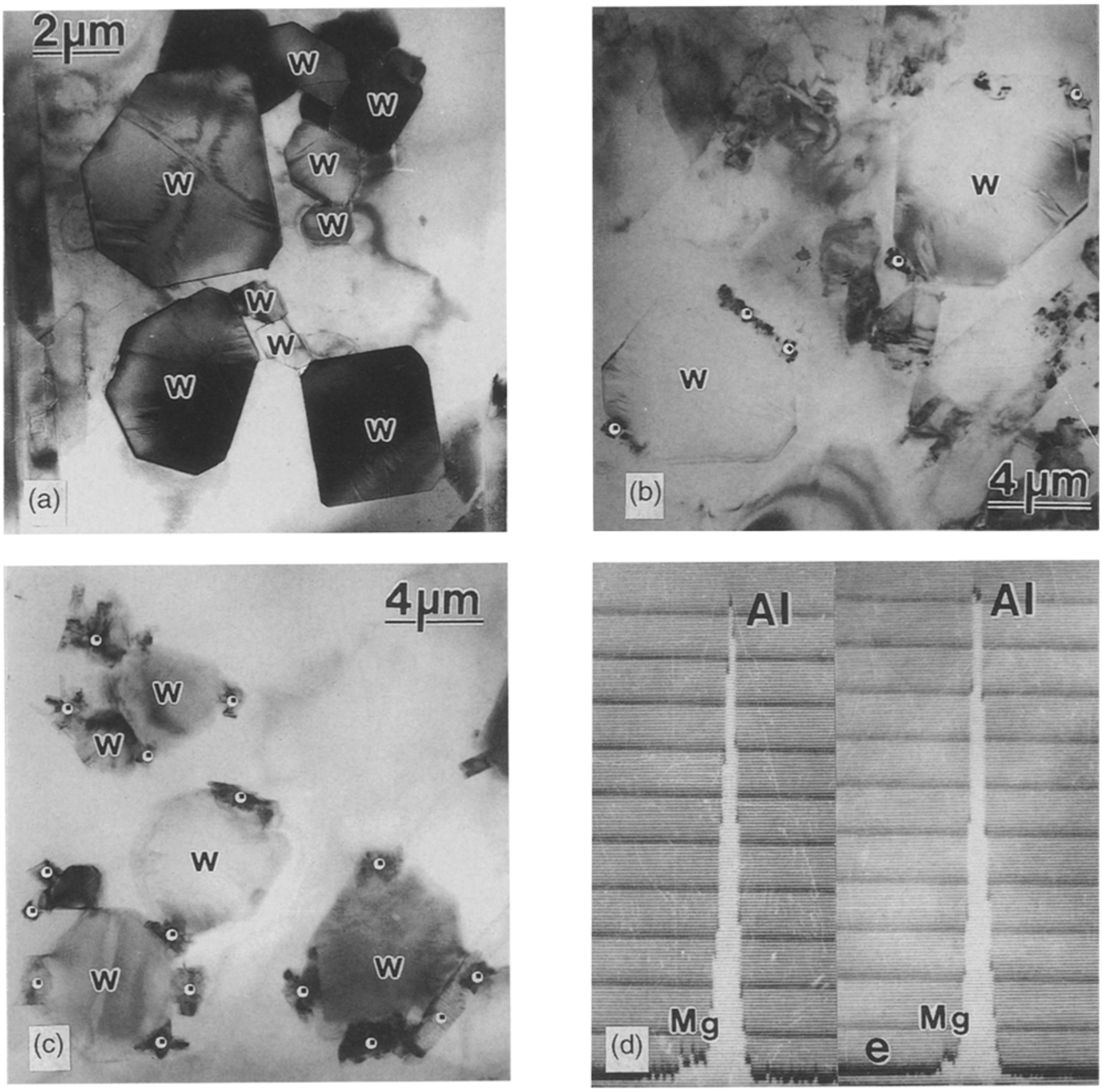

Figure 3 Diffraction contrast images of the $Al_{18}B_4O_{33}$ whiskers in (a) the $Al_{18}B_4O_{33}$–pure Al composite, (b) the $Al_{18}B_4O_{33}$–6061Al as-fabricated composite and (c) the $Al_{18}B_4O_{33}$–6061Al T6-treated composite. EDS results at the whisker–matrix interfaces in the (d) as-fabricated and (e) T6-treated states.

on the surface state of the isolated whiskers. The amorphous layers existed on the surfaces of isolated SiC [12] and Si_3N_4 whiskers [6], and the surfaces of the isolated $Al_{18}B_4O_{33}$ whiskers were very clean [7], which resulted in the existence of amorphous transition layer at the SiC- and Si_3N_4–Al interfaces and the directly bonded $Al_{18}B_4O_{33}$–Al interface. Moreover, the unstable character of the $Al_{18}B_4O_{33}$ surfaces [7] showed that the whiskers took part in the interfacial reactions.

In conclusion, it was found that the Mg segregation at the whisker–matrix interfaces was the important factor resulting in the interfacial reactions. There were two kinds of interfacial reactions: the segregated Mg atoms reacted with the interface transition layers and the whiskers themeselves did not take part in the reactions; and the segregated Mg atoms reacted directly with the whiskers in the composites without interface transition layers. The latter case may be harmful to the mechanical properties of the composites, due to the decreasing of the bending strength after T6 treatment.

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