Tensile properties of thermally exposed aluminium borate whisker reinforced 6061 aluminium alloy composite

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The effect of thermal exposure on the tensile properties of aluminium borate whisker reinforced 6061 aluminium alloy composite was studied. The interfacial reaction was investigated by TEM and the mechanical properties were studied using tensile tests. The results indicated that the interfacial reaction had an influence on the mechanical properties of the composite, so that the maxima of Young's modulus and ultimate tensile strength of the composite after exposure at 500°C for 10 h were obtained for the optimum degree of interfacial reaction. The yield strength, however, was not only affected by the interfacial state but also by many other factors. MST/4328

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Introduction

Aluminium borate whisker $(Al_{18}B_4O_{33})_w$, (denoted $AlBO_w$) reinforced aluminium composites have been shown to have good mechanical properties, low thermal expansion coefficients, and fairly low cost.[1–5] It is well known, however, that the interfacial state plays an important role in the mechanical properties of the composites. In studies of these composites, previous researches have indicated that the unstable aluminium borate whiskers could react with the matrix, and the reaction products ameliorated or deteriorated the mechanical properties of the composites.[6–10] Hence, study of the effect of thermal exposure on the tensile properties of $Al/AlBO_w$ composites is important in promoting the wider applications of the composite

The present paper aims to investigate the effects of thermal exposure treatments on the interfacial reaction and tensile properties of the aluminium alloy $6061/AlBO_w$ composite.

Experimental

The aluminium alloy $6061/AlBO_w$ composites studied were fabricated by a squeeze casting technique with a whisker volume fraction of 25%. To investigate the effects of thermal exposure temperature and time on the interfacial reaction and tensile properties, experiments were categorised into two groups as follows: one was with thermal exposure treatment performed at 100, 200, 300, 400, and 500°C for 1 h and the other at 500°C for 0, 5, 10, 30, and 50 h, following which all specimens were cooled to room temperature in air.

The dimensions of the tensile specimens are shown in Fig. 1*a*. Tensile tests were carried out on an Instron testing machine. The Young's modulus of the composite was measured by the slope of the unloading curve, which is shown schematically in Fig. 1*b*. As shown in Fig. 1*b*, the specimen was tested to point A, then the load was removed, and the slope of the unloading curve was used to measure the Young's modulus of the composite. All tensile data quoted were the average values of two specimens and the scatter was less than 5%.

Observations of the interface were made using a Philips CM12 TEM with an operating voltage of 120 kV. Specimens for TEM observations were abraded to a thickness of ~20 μm and finally thinned by ion milling.

Results and discussion

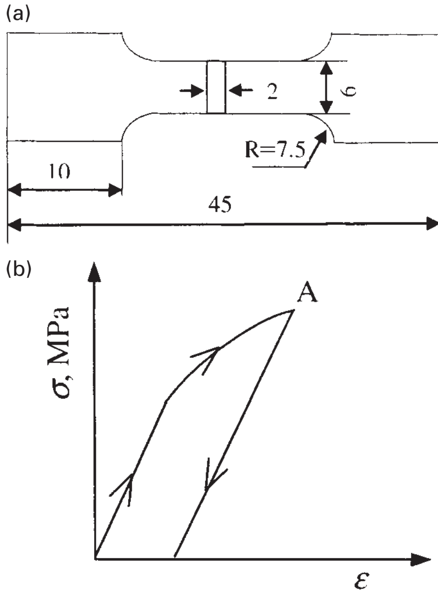
INTERFACIAL REACTION

A TEM micrograph of the microstructure in the squeeze cast condition and corresponding selected area electron diffraction patterns (SADP) are shown in Fig. 2*a* and *b*, respectively. It is clear that interfacial reaction had taken place during the fabrication process of the composites. From indexing of the SADP, the product was identified as $MgAl_2O_4$ with a spinel structure, which agrees well with previous studies.[2–4,8–10]

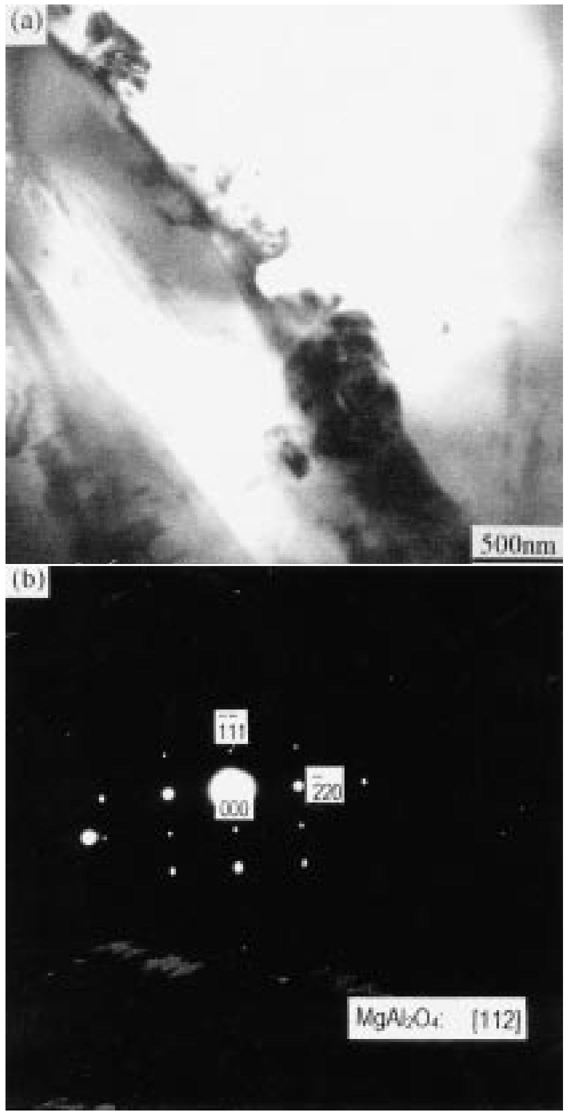
Transmission electron micrographs of microstructures in the specimens exposed at 100 and 300°C for 10 h, and at 500°C for 30 and 50 h are shown in Fig. 3*a–d*, respectively. A few products of the interfacial reaction in the squeeze cast condition are formed and are distributed sparsely around the whiskers, as shown in Fig. 2*a*. With an increase in the thermal exposure temperature, the products increase both in quantity and size. Because the interfacial reaction product is $MgAl_2O_4$ (Refs. 2–4 and 8–10), the reaction is controlled by diffusion of Mg in the matrix. Therefore, it is easy to understand that the products grew predominantly along the surface of the whiskers instead of radially into the whiskers. Thus, diffusion of Mg through the products and into the whiskers to react is very difficult. So the products tend to cover the surface rather than grow much into the depth of the whiskers. On the other hand, the reaction process comprised both the growth and nucleation of the products. As shown in Fig. 3*c*, the products in the specimen exposed at 500°C for 3 h are serrated at the interfaces. With increasing exposure time, the serrated products linked to form a larger bulk to cover most of the whiskers, as is the case in the specimens exposed at 500°C for 50 h.

YOUNG'S MODULUS

The effects of thermal exposure time at 500°C and temperature after 10 h on the Young's modulus of the composite are shown Fig. 4*a* and *b*, respectively. Figure 4*a*



1 Schematic diagrams of *a* tensile specimen: dimensions in mm; *R* radius and *b* unloading curve



2 *a* transmission electron micrograph of as cast 6061/($Al_{18}B_4O_{33}$)$_w$ composite microstrucutre and *b* corresponding selected area diffraction pattern

indicates that the Young's modulus of the composite initially increases with exposure time, but when the exposure time is longer than 10 h, the Young's modulus of the composite gradually decreases. The Young's modulus of the composite exposed at 500°C for 30 h is lower compared with that for 10 h. The Young's modulus of the composite after exposure times longer than 30 h hardly decreases. In Fig. 4*b* the Young's modulus of the composite exposed for 10 h always increases with increasing exposure temperature. The effect of thermal expansion on the Young's modulus of the composite can be understood as follows.

First, the effective volume fraction of reinforcement was increased by the formation of the interfacial reaction product ($MgAl_2O_4$), which results in the Young's modulus increases owing to the mixture law.

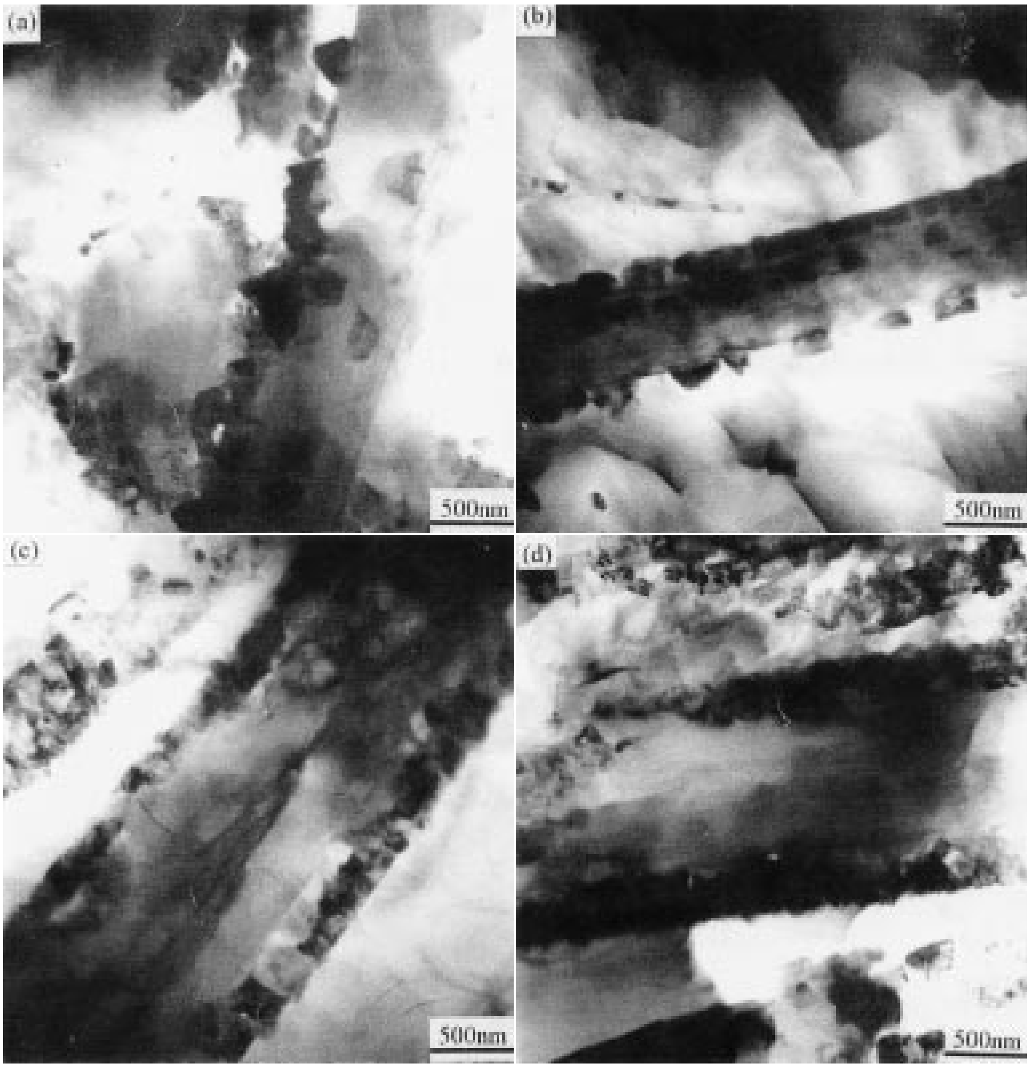
Second, the increase in the amount of serrated reaction products strengthens the mechanical gnawing between the matrix and the whiskers, which makes the load transfer more effective.[10] When the composite was exposed at 500°C for 30 and 50 h, the product was distributed continuously on the surface of the whiskers, so the mechanical gnawing is heavily weakened or disappears completely.

Therefore, the Young's modulus is dependent both on the volume fraction and the morphology of the interfacial reaction product. When the exposure time at 500°C is long, the interfacial reaction is so extensive that the product is continuous and the mechanical gnawing disappears. When the exposure time at 500°C is shorter than 10 h, both the effective volume fraction of reinforcement and the mechanical gnawing resulting from the serrated products was enhanced, which results in an increase in the Young's modulus. When the exposure time is longer than 10 h, more products were formed and distributed continuously on the surface of the whiskers, and this weakened the mechanical gnawing. Thus, the modulus decreases with increasing exposure time. So it can be inferred that the mechanical gnawing between the whiskers and the matrix owing to the formation of the serrated products makes a large contribution to the increase in the elastic modulus and ultimate tensile strength of the composite.[10]

ULTIMATE TENSILE STRENGTH

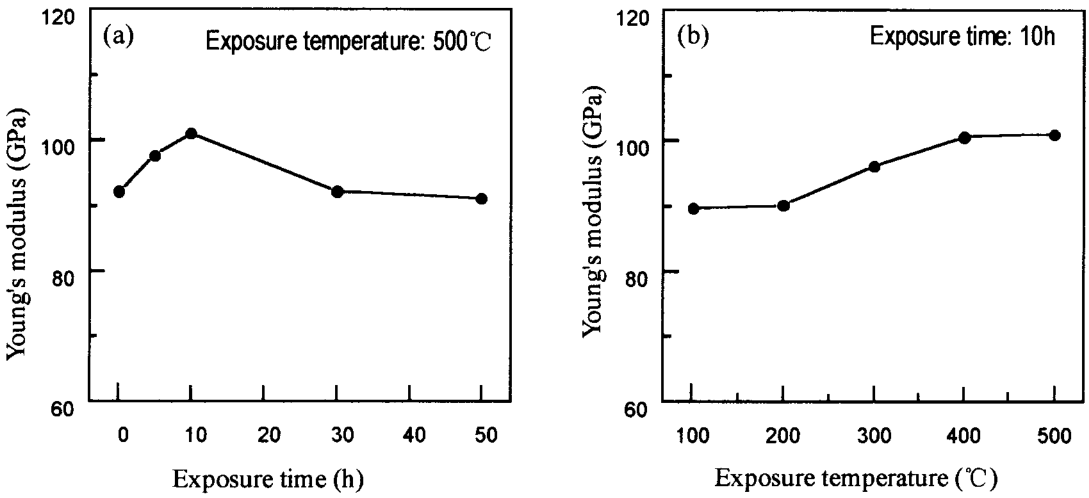
Figure 5*a* and *b* shows the effect of exposure time at 500°C and temperature after 10 h on the ultimate tensile strength of the composite, respectively. Ultimate tensile strength first increases with exposure time, and then decreases, as shown in Fig. 5*a*. It can be seen in Fig. 5*b* that the ultimate tensile strength of the composite exposed for 10 h increases slightly with increasing exposure temperature.

It is well recognised that the interface can affect the mechanical properties of composites. The initial increase in ultimate tensile strength of the composite exposed at 500°C with exposure time was caused mainly by three factors. First, atoms diffuse through the interface and the interfacial reaction at higher temperatures enhances interface bonding. Second, the mechanical gnawing between the whiskers and the matrix owing to the serrated products makes the load transfer more effective.[10] Third, the quantity and volume of products increase the effective volume fraction of reinforcement. Nevertheless, the combined strengthening of the above three factors increases with exposure times shorter than 10 h at 500°C, which gives rise to appearance of the maximum ultimate tensile strength. With further increases in exposure time and temperature, although the increase in the effective volume fraction of the whiskers caused by increase in the quantity of the products enhances the strengthening effect, the small serrated products grow to interconnect into a large bulk. Thus, the mechanical gnawing between the whisker and the matrix is seriously



a 100°C for 10 h; *b* 300°C for 10 h; *c* 500°C for 30 h; *d* 500°C for 50 h

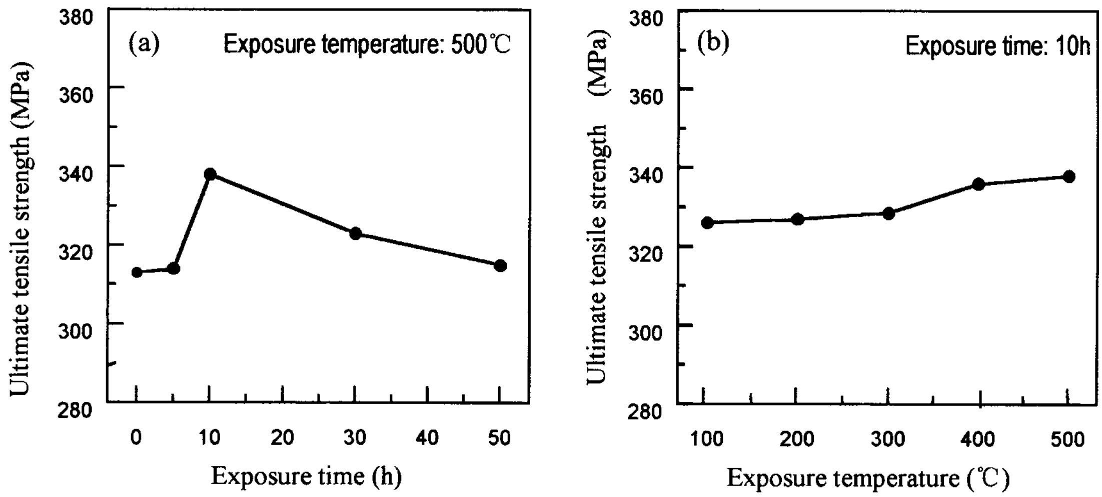
3 Transmission electron micrograph of 6061/$(Al_{18}B_4O_{33})_w$ composites after given thermal exposure treatments



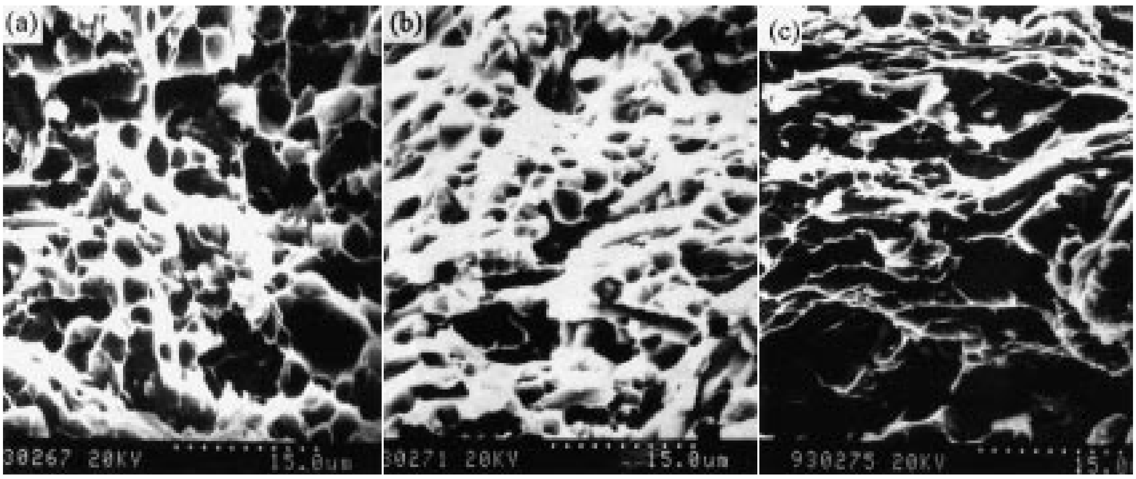
4 Effect of *a* exposure time and *b* exposure temperature on Young's modulus of composite

weakened, which causes the decrease in the ultimate tensile strength. However, when the exposure time is more than 30 h, the products no longer grow owing to the lack of Mg in the zones close to the products and the difficulty of long distance diffusion of Mg atoms. As a result, the Young's modulus and ultimate tensile strength decrease a little. Based on the above discussion and analyses, only when an optimum degree of interfacial reaction is reached, can the maxima Young's modulus and ultimate tensile strength be obtained. This provides a practical way for mechanical property optimisation by properly controlling the degree of interfacial reaction for the Al/$AlBO_w$ composite.

Fractographs of tensile specimens exposed at 500°C for 0, 10, and 50 h are shown in Fig. 6*a*, *b*, and *c*, respectively.

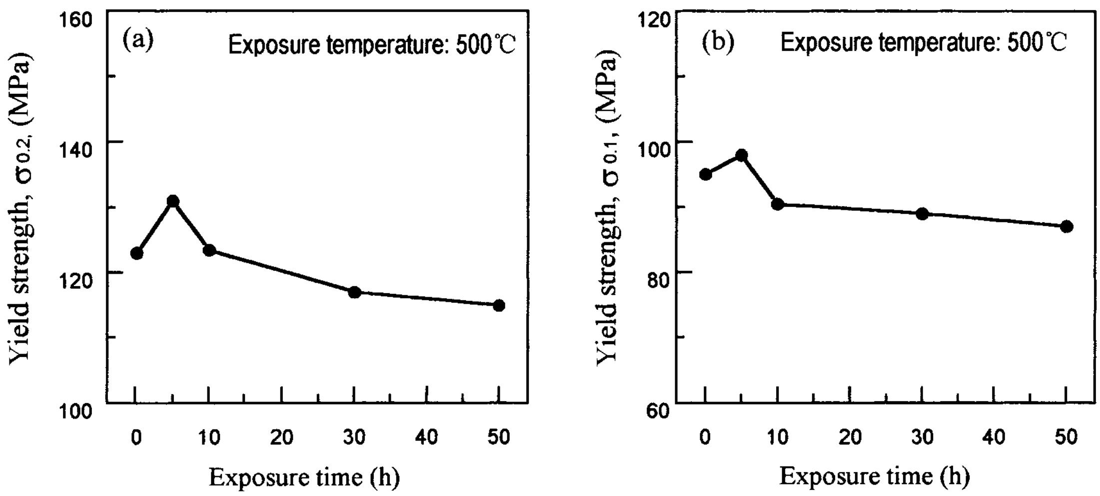


5 Effect of *a* exposure time and *b* exposure temperature on ultimate tensile strength of composite



a 500°C for 0 h; *b* 500°C for 10 h; *c* 500°C for 50 h

6 Fractographs of tensile specimens after given thermal exposure treatments

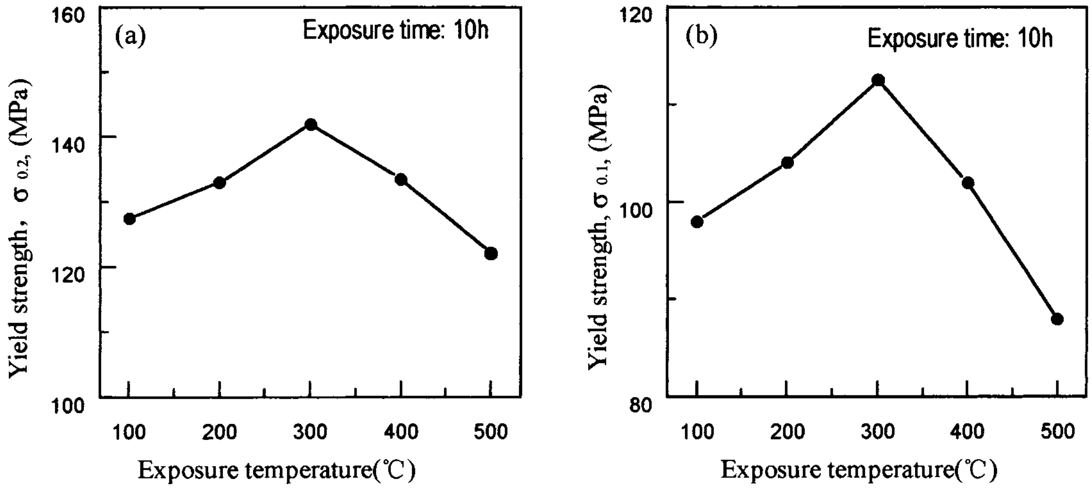


7 Effect of thermal exposure time on yield strength for *a* 0·2% and *b* 0·1% residual strain

It is can be easily seen in Fig. 6*a* that there are some large holes resulting from interfacial debonding, which indicates that the interfacial bonding is weak for the as cast composite. However, larger holes are observed in the fractograph of a tensile specimen exposed at 500°C for 50 h, as shown in Fig. 6*c*, which are formed by fracture of coarse and brittle $MgAl_2O_4$. On the other hand, Fig. 6*b* shows many ductile dimples and no large holes, which suggests that interfacial bonding is strong after exposure at 500°C for 10 h and a higher ultimate tensile strength is obtained.

YIELD STRENGTH

The effects of thermal exposure time on yield strength with 0·2 and 0·1% residual strain for the composite exposed at



8 Effect of thermal exposure temperature on yield strength for *a* 0·2% and *b* 0·1% residual strain

500°C are shown in Fig. 7*a* and *b*, respectively. Yield strengths of the composites exposed for 5 h with 0·2 and 0·1% residual strain both achieve the highest values. Figure 8*a* and *b* shows the effect of exposure temperature on yield strengths with 0·2 and 0·1% residual strain for the composite exposed for 10 h. Yield strengths with 0·2 and 0·1% residual strain both increase as the exposure temperature increases up to 300°C.

According to the above discussion and analysis, the maximum of yield strengths with 0·2 and 0·1% residual strains do not correspond exactly to the optimum degree of interfacial reaction required for maximum Young's modulus and ultimate tensile strength values. Although the interface exerts an effect on yield strength, work hardening of the matrix may make a greater contribution to it. In addition, quantity and distribution of dislocations in the matrix and residual stress may also contribute to the yield strength. The effects of the factors mentioned above on yield strength are complicated and it is very difficult to quantitatively determine their respective contributions.

Conclusions

1. Different degrees of interfacial reaction take place in the aluminium alloy $6061/AlBO_w$ composite under the different thermal exposure conditions. With increasing exposure time at 500°C, the serrated products can become interconnected into large bulks attached to the surface of the whiskers.

2. The interfacial reaction has an important effect on the Young's modulus and ultimate tensile strength. The Young's modulus and ultimate tensile strength of the composite both achieve the maximum values after exposure at 500°C for 10 h.

3. The maximum yield strengths with 0·2 and 0·1% residual strains do not correspond exactly to the optimum degree of interfacial reaction as the yield strength is controlled not only by the interfacial bonding but also by some other factors such as residual stress in composites.

Acknowledgement

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References

1. K. SUGANUMA, T. FUJITA, N. SUZUKI, and K. NIIHARA: *J. Mater. Sci. Lett.*, 1990, **9**, 633.
2. K. SUGANUMA, T. FUJITA, N. SUZUKI, and K. NIIHARA: *Light Met.*, 1991, **40**, 297 (in Japanese).
3. W. D. FEI, X. D. JIANG, S. WU, C. LI, and C. K. YAO: *J. Mater. Res.*, 1993, **1**, 1 (in Chinese).
4. J. HU, W. D. FEI, C. LI, and C. K. YAO: *J. Mater. Sci. Lett.*, 1994, **13**, 1794.
5. L. J. YAO: Doctoral thesis, Harbin Institute of Technology, China, 1996.
6. D. J. LLOYD, I. JIN, and G. C. WEATHERLY: *Scr. Metall. Mater.*, 1994, **31**, (4), 393.
7. K. NAGATOMO and K. SUGANUMA: *J. Jpn Inst. Met.*, 1994, **58**, (1), 78.
8. X. G. NING, J. PAN, K. HU, and H. YE: *Mater. Lett.*, 1992, **13**, 377.
9. W. D. FEI, X. D. JIANG, C. LI, and C. K. YAO: *Mater. Sci. Technol.*, 1997, **13**, 918.
10. W. D. FEI, X. D. JIANG, C. LI, and C. K. YAO: *J. Mater. Sci. Lett.*, 1996, **15**, 19.