Effect of thermomagnetic treatment on microstructure and tensile properties of aluminum borate whisker reinforced aluminum composite containing Fe_3O_4 particles

G. LI
School of Materials Science and Engineering, Harbin Institute of Technology, P.O. Box 405, Harbin 150001, People's Republic of China; Department of Chemistry, Harbin Normal University, Harbin 150080, People's Republic of China

W. D. FEI*
School of Materials Science and Engineering, Harbin Institute of Technology, P.O. Box 405, Harbin 150001, People's Republic of China
E-mail: wdfei@hit.edu.cn

Y. LI
Centre for Composite Materials, Harbin Institute of Technology, Harbin 150001, People's Republic of China

Aluminum borate whisker ($Al_{18}B_4O_{33}$, denoted by ABO) reinforced aluminum composite (denoted by ABO/Al) has been extensively investigated on account of good mechanical properties and fairly low cost [1–3]. The thermal mismatch stress (TMS) caused by mismatch of coefficients of thermal expansion (CTE) between the reinforcement and matrix is one of inherent characteristics of metal matrix composites [4–6], and has some undesirable effects on the properties of composites, such as yield strength, fatigue life, and dimensional stability [7–9]. The low tensile yield strength resulting from the residual stress limits the application of composites in many precision structural parts.

It is very important to find a technique to reduce the TMS and to maintain a higher density of dislocation in the matrix for the optimization of the tensile properties of ABO/Al composite, which is the main aim of the present study.

The authors [10] have successfully developed an aluminum matrix composite reinforced by both aluminum borate whisker and Fe_3O_4 particles [denoted by (ABO+FO)/Al], and a higher tensile strength was attained in the composite after thermomagnetic treatment.

In the present study, the dislocations in the matrix for as-cast and thermomagneticially treated composites were observed using a transmission electron microscope (TEM), and the effect of thermomagnetic treatment on microstructure and tensile properties of (ABO+FO)/Al composite is discussed.

The (ABO+FO)/Al composite used was fabricated using a squeeze casting method with the whisker and particle volume fraction of 24%, and the volume ratio between ABO whisker and Fe_3O_4 particle was about 4:1. The matrix used was pure aluminum, together with ABO whiskers with a diameter of 0.5–1 μm and a length of 10–30 μm and Fe_3O_4 particles with a diameter of 40–60 μm. To prevent the interaction between Fe_3O_4 particles and aluminum, the Fe_3O_4 particles were coated using a chemical method [10].

The specimens were thermomagneticially treated at 100° for 1 hr with a pulsed magnetic field of about 400 kA/m perpendicular to the section plane of the tensile specimen. The microstructures of (ABO+FO)/Al composite before and after thermomagnetic treatment were evaluated on a type CM-12 TEM. Thin foils for TEM observation were prepared by ion milling.

The dimensions of the tensile specimens are shown in Fig. 1. The tensile tests were performed on an INSTRON type 5569 tensile machine with a tensile rate of 0.5 mm/min.

The comparison of ultimate tensile strength (UTS) and elongation of as-cast, and thermomagneticially treated (ABO+FO)/Al composite is shown in Fig. 2. It can be seen that the UTS of as-cast composite is about 240 MPa, and after thermomagnetic treatment, the UTS is enhanced to about 320 MPa. As shown in Fig. 2b, the elongation of the composite is clearly increased after thermomagnetic treatment. Thermomagnetic treatment is a very effective technique for improving the tensile properties of (ABO+FO)/Al composite.

To analyze the mechanism of the effect of thermomagntic treatment on the UTS, TEM observation of the dislocations in the matrix was carried out.

Fig. 3a shows the dislocation configuration in the matrix of the as-cast composite remote from ABO

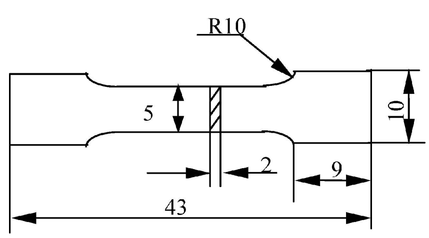

Figure 1 Dimension of a tensile specimen (in mm).

*Author to whom all correspondence should be addressed.

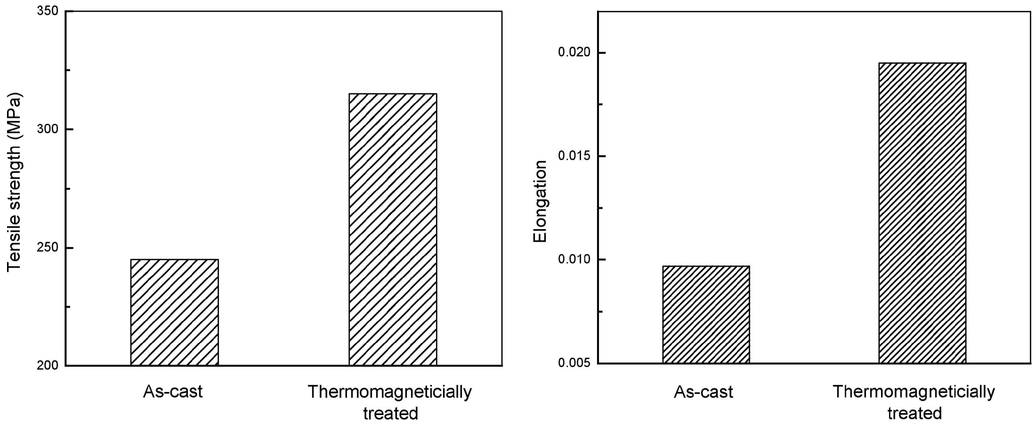

Figure 2 UTS and elongation of as-cast and thermomagneticially treated (ABO+FO)/Al composite.

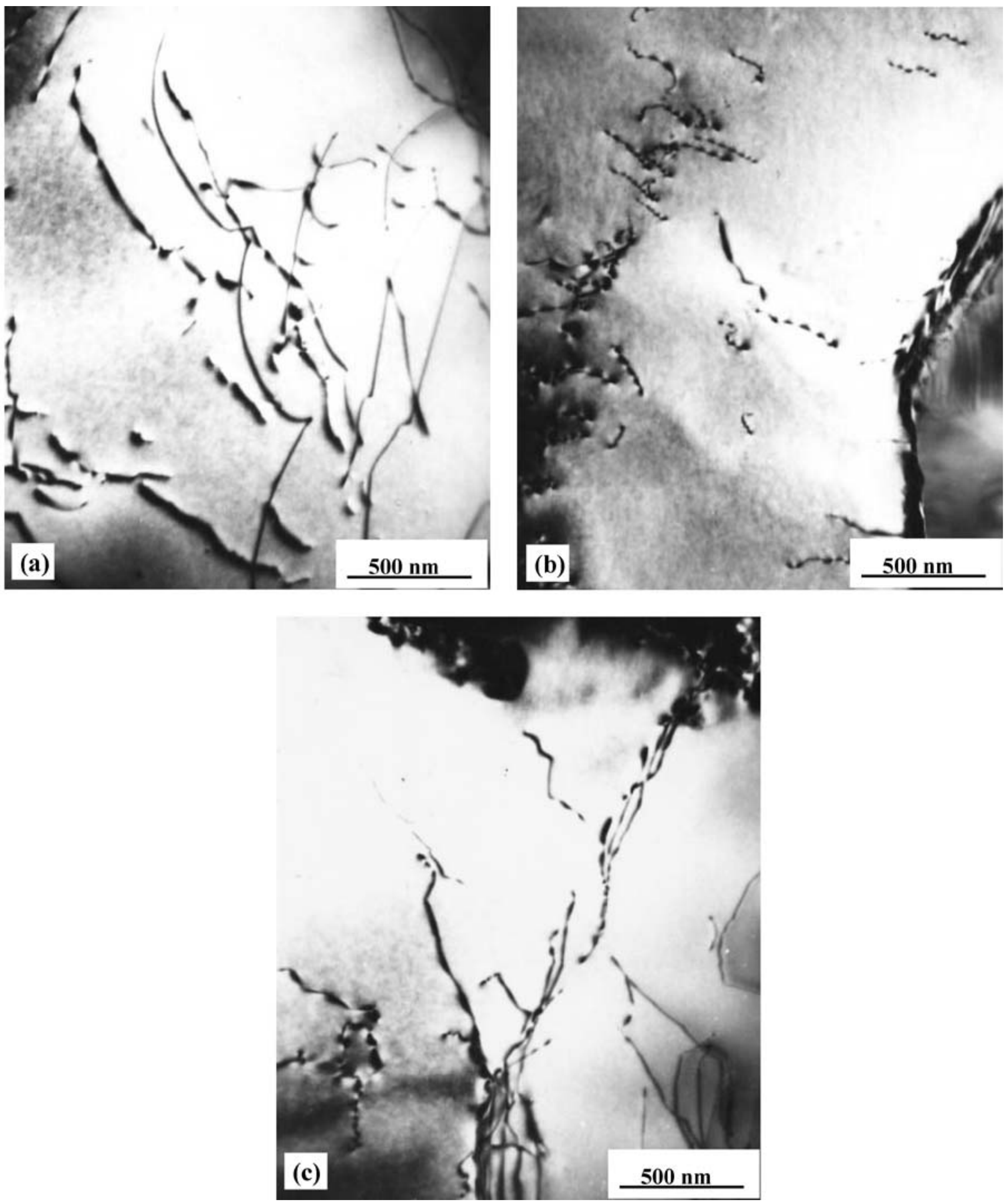

Figure 3 TEM micrographs of dislocation configuration in the matrix of the as-cast composite, (a) remote from ABO and Fe_3O_4, (b) and (c) adjacent to ABO-Al and Fe_3O_4-Al interfaces.

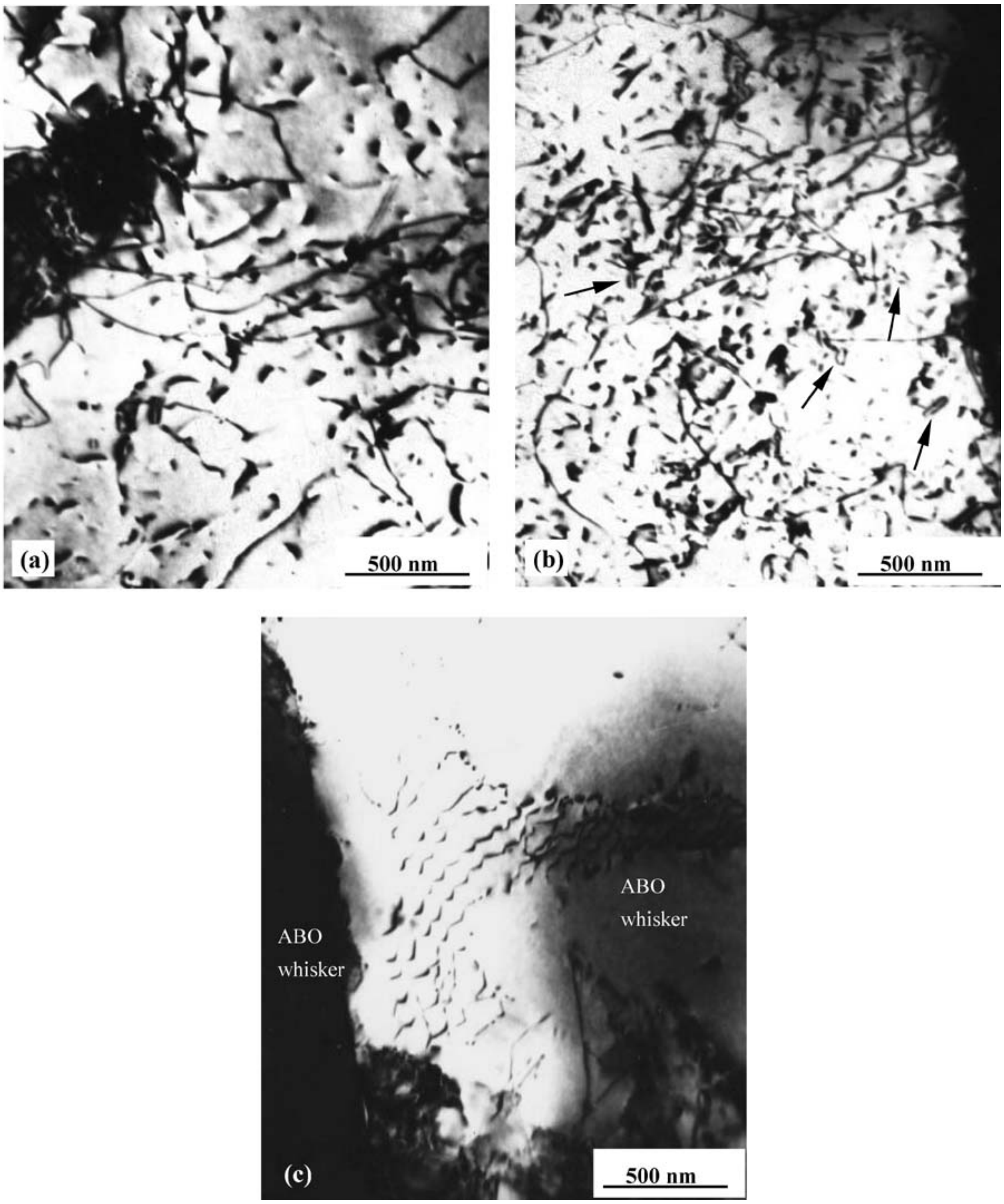

Figure 4 TEM micrographs of dislocation configurations in the matrix of the thermomagneticially treated composite: (a) adjacent to ABO-Al interface, (b) adjacent to Fe_3O_4-Al interface, and (c) in the region between two whiskers.

whiskers and Fe_3O_4 particles. It can be seen that the dislocation density is low, and the main state of dislocations is straight.

Fig. 3b and c give the dislocation configurations adjacent to ABO whiskers and Fe_3O_4 particles in the matrix of the as-cast composite, respectively. It can be seen that the dislocation density is also not high, in the meantime, some helical dislocations are found, which result from vacancies absorbed by screw dislocations.

Fig. 4a shows the dislocation configuration adjacent to an ABO-Al interface in the matrix of the composite thermomagneticially treated. A high density of curved dislocations is observed in the region.

Fig. 4b gives the microstructure adjacent to an Fe_3O_4-Al interface in the matrix of the composite thermomagneticially treated. It can be seen that there are many curved dislocations in the matrix. In the region of the matrix, many dislocation loops can also be found (shown by arrows). The formation of the dislocation loop may result from vacancy concentration.

Fig. 4c shows the dislocation configuration in the matrix of the composite in the region between two whiskers in the composite after thermomagnetic treatment. Many helical dislocations which result from vacancies absorbed by screw dislocations are found.

Comparing Fig. 3 with Fig. 4, one can conclude that the dislocation density in the matrix of composite thermomagneticially treated is much higher than that of the as-cast composite. It is found that the dislocation loop and helical dislocation densities in the matrix of composite after thermomagnetic treatment are much higher than those of the as-cast composite.

On the basis of this study, the nature of the effect of thermomagnetic treatment on the microstructure and tensile properties of (ABO+FO)/Al composite can be discussed. Because of the magnetostrictive properties of Fe_3O_4 particles, the size of Fe_3O_4 particles may alter periodically with changing external magnetic field, which results in a lot of vacancies being produced at the interface between Fe_3O_4 and matrix, and the interface between the whisker and matrix. Because the specimens were thermomagneticially treated at 100 °C, vacancies can diffuse from the interface to the interior of the matrix, which results in the volume of the matrix increasing. Vacancies induced by thermomagnetic treatment can be confirmed by the observation of higher density dislocation loops and helical dislocations in the matrix of thermomagneticially treated composite. Hence, the TMS of the composite was reduced, which leads to the increase of the elongation and UTS of the composite. On the other hand, the dislocation density in the matrix of composite thermomagneticially treated was enhanced, which suggests that the TMS can be relaxed through the plastic deformation of the matrix during thermomagnetic treatment. A high density of dislocations is also beneficial in increasing the UTS of the composite.

According to this study, the main conclusions are as follows. Firstly, the tensile strength and elongation of (ABO+FO)/Al composite are enhanced, and the UTS of (ABO+FO)/Al composite can reach 320 MPa after the thermomagnetic treatment. Secondly, the dislocation density in the matrix of the composite after thermomagnetic treatment is higher than that of as-cast composite. Thirdly, vacancies can be produced during the themomagnetic treatment and some vacancies are absorbed by screw dislocations or form dislocation loops, which increases the tensile strength of the composite. Finally, one can conclude that thermomagnetic treatment is a very effective technique to improve the tensile properties of whisker reinforced aluminum composite containing magnetostrictive particles.

References

1. K. SUGANUMA, G. SASAKI, T. FUJITA and N. SUZUKI, *J. Jpn. Inst. Light Met.* **41** (1991) 297. (in Japanese)
2. J. HU, W. D. FEI, C. LI and C. K. YAO, *J. Mater. Sci. Lett.* **13** (1994) 1797.
3. W. D. FEI, X. D. JIANG, C. LI and C. K. YAO, *Mater. Sci. Technol.* **13**(1997) 918.
4. W. D. FEI, Q. Y. LIU, N. G. LIANG and C. K. YAO, *ibid.* **17** (2001) 912.
5. C. T. KIM, J. K. LEE and M. R. PLICHTA, *Metall. Trans.* **21A** (1990) 673.
6. M. VOGELSANG, R. J. ARSENAULT and R. M. FISHER, *ibid.* **17A** (1986) 379.
7. H. Y. ZHANG, P. M. ANDERSON and G. S. DAEHN, *Metall. Mater. Trans.* **25A** (1994) 415.
8. J. M. PAPAZIAN and P. N. ADLER, *Metall. Trans.* **21A** (1990) 401.
9. G. L. POVIRK, A. NEEDLEMAN and S. R. NUTT, *Mater. Sci. Eng.* A **132** (1991) 31.
10. G. LI, Y. SUN and W. D. FEI, *Mater. Lett.* **57** (2003) 3217.

Received 20 November 2003
and accepted 3 June 2004