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Micro-X-ray diffraction study of thermal residual stresses in some model aluminum matrix composites

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Because of large difference in coefficients of thermal expansion (ΔCTE) between reinforcement and matrix, metal matrix composites (MMCs) would always present high thermal residual stresses (TRS) in microstructure after cooling down from fabricating or heat-treating temperature. Various theoretical models have been developed to study the TRS distribution in MMCs [1–4]. Their results indicated that the TRS distribution near reinforcement/matrix interface was not uniform and with increase in distance to the interface the TRS decreased. As so far, however, this gradient distribution feature of TRS in MMCs has not been confirmed in experimental investigations. This is because the diameter of X-ray or neutron beam is millimeter scale (mm) and only mean values of TRS in matrix or reinforcement could be obtained [5–8]. We consider that understanding the maximum residual stress near interface instead of mean stress is much important to explain some micro-processes such as crack nucleation, crack propagation and plastic relaxation in matrix which often take place near the interface. So it is necessary to employ the testing apparatus with higher resolving power. Tanaka investigated TRS distribution of welding interface in Si_3N_4/steel composite by a micro-X-ray diffractometer with a 100 μm of resolving power [9]. Adachi measured microscopic stress distribution in a multilayered ceramic matrix composite by a X-ray diffractometer with a 150 μm of resolving power [10]. In this work, a micro-X-ray diffractometer with a 30 μm of resolving power is used to investigate the TRS distribution near interface in several aluminum matrix composites.

In order to be suitable to the resolving power of the used diffractometer three model composites are fabricated in this work. The first is a single SiC fiber (114 μm in diameter) reinforced 1100Al composite (SiC_f(s)/1100Al). The second is a bundle of 11 SiC fibers (476 μm in diameter) reinforced 1100Al composite (SiC_f(b)/1100Al). For the two model composites, the cylinder specimens with 12 mm in diameter and 6 mm in height are casted at 670 °C. The SiC fiber and bundle locate at the central position of the cylinders. The third material is (SiCp-6061Al) composite bars reinforced 6061Al composite (SiCp-6061Al/6061Al). This composite is fabricated by a vacuum pressure infiltration method and has dual microstructure as shown in Fig. 1. The volume fraction of SiCp within the bars is 45% and nominal volume fraction of SiCp in the overall composite is about 15%. The diameter of bars is 560 μm and the interspacing between the bars is in the range of 200–320 μm.

A Jeol JDX-3530M X-ray diffractometer system is used in this work. The dispersed X-ray from a point source is collimated to a beam of 30 μm in diameter. Stress as a function of distance to interface on surface of specimens can be measured by altering x, y and z coordinates of a sample holder. The image of tested area is amplified by an optical microscope and observed by a monitor. In this study all tests are conducted on the cross section perpendicular to the fiber and bars. Two directional residual stresses in the matrix are measured. One is hoop residual stress perpendicular to the radius of the SiC fiber and reinforcing bars, and the other is radial residual stress parallel to the radius of the fiber and bars. The parameters of the XRD experiment are listed in Table I. The (422) reflection of Al, the elastic modulus of 72 GPa and the Poisson's ratio of 0.33 are used to calculate the residual stresses by a conventional $\sin^2\Psi$ method.

Fig. 2 shows experimental results of the TRS in the matrix of the SiC_f (s)/1100Al composite. The abscissa is the distance from the interface to the margin of measurement area, the ordinate is the mean value of the testing point area (30 μm). As predicted by theoretical models, the hoop residual stress is tensile whereas the radial residual stress is compressive. The TRS distribution has a gradient, and the absolute values of the TRS decrease with increase in the distance to the interface. In our experiment the obtained maximum hoop residual stress is 29.9 MPa, the maximum radial residual stress is −25.6 MPa. It can also be seen from Fig. 2 that the dimension of the stress gradient distribution region (DSGDR) is about 70 μm. If we use the ratio between DSGDR and the reinforcement size to denote the relative dimension of stress gradient distribution region

TABLE I The experimental parameters of Jeol JDX-3530M micro X-ray diffraction

Radiation	Filter	Voltage	Current	$2\theta^0$	Scan in steps
Cu K_{α_1}	Ni	40 kV	40 mA	137.3°	0.084°

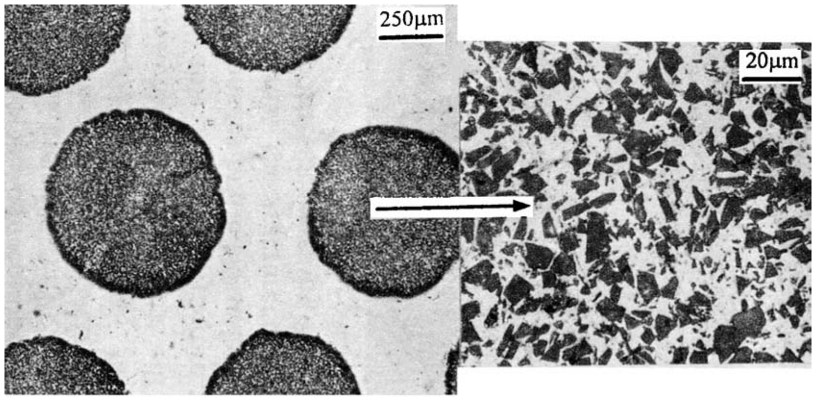

Figure 1 Optical microstructure of SiCp-6061Al/6061Al composite.

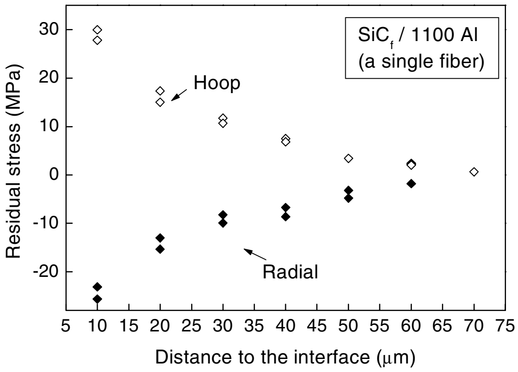

Figure 2 Thermal residual stresses distribution near interface in matrix of the SiC_f (s)/1100Al composite.

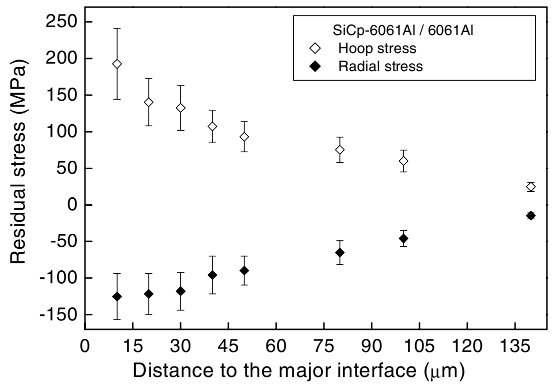

Figure 4 The residual stresses distribution near a (SiCp-6061Al) bar in the SiCp-6061Al/6061Al composite.

(RDSGDR), then in this case the RDSGDR is slightly more than 0.6. This value is lower than that predicted by theoretical models in which the RDSGDR were in a range of 1.5 to 2.0 [1–4].

Fig. 3 demonstrates the TRS distribution near interface in matrix of the SiC_f (b)/1100Al composite. The TRS distribution feature is exactly same as that in the SiC_f (s)/1100Al composite. But due to its large size of reinforcement (560 μm) the maximum stresses and ADSGDR are higher than that in the SiC_f (s)/1100Al composite. The obtained maximum hoop and radial residual stresses are 51.9 and –40.9 MPa respectively, and the DSGDR is 270 μm. However, the RDSGDR is slightly lower than 0.5.

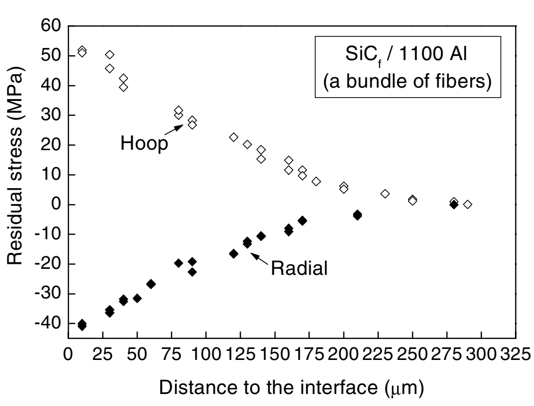

Figure 3 Thermal residual stresses distribution near interface in matrix of the SiC_f (s)/1100Al composite.

Fig. 4 shows the TRS distribution near a (SiCp-6061Al) bar in the matrix of the SiC-6061Al/6061Al composite. It is evident that the TRS distribution is the same as above two model composites. But the maximum stresses are much higher than that in the two model composites. The obtained maximum hoop and radial stresses are 192.5 and –125.2 MPa respectively. This might be related to the interaction of the reinforcing bars. Unlike above two model composites in which only single reinforcement is embedded into infinite matrix, the SiCp-6061Al/6061Al composite has a large number of the reinforcing bars and the interspacing between bars is smaller. So upon early cooling stage the thermal mismatch stresses have induced the plastic relaxation in overall matrix area and led to increase in yield strength of the matrix. Thus the plastic relaxation upon further cooling stage becomes difficult and leaves a relatively higher residual stresses. It can also be deduced from Fig. 4 that the DSGDR is about 150 μm, so the RDSGDR is 0.27 which is lower than that in the above two model composites. This is because the ΔCTE between (SiCp-6061Al) bar and 6061Al matrix is lower than that between the SiC fiber and 1100Al matrix in the two model composites.

In closing, our experimental results can be summarized as follows:

1. The hoop and radial residual stresses in the matrix near a continuous reinforcement in SiC/Al composites are tensile and compressive respectively.

2. The thermal residual stresses (TRS) in the matrix present as a gradient distribution feature. The absolute values of the TRS decrease with increase in the distance to the reinforcement/matrix interface. The maximum TRS at interface is dependant on the reinforcement size, reinforcement interspace and the difference in coefficients of thermal expansion (ΔCTE) between reinforcement and matrix.

3. The TRS gradient distribution area is quite small. The ratio between demension of stress gradient distribution range and reinforcement size is lower than 1 and is dependant to the ΔCTE between reinforcement and matrix.

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