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Letter

Subsurface damage of ceramic paticulate reinforced Al–Li alloy composite induced by scratching at an elevated temperature

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Abstract

The wear resistance mechanisms of a silicon carbide (SiC) paticulate reinforced Al–Li alloy composite at 250°C by a pyramidal indenter have been studied. It is found that the subsurface damages that control the wear resistance are: generation of dislocations and cracks in the SiC particles, interface debonding between matrix and reinforcements and plastic deformation of the matrix.

Keywords: Alloy; Al–Li alloy; Composite; Ceramic particulate

Wear resistance of particle reinforced metal matrix composites depends on the matrix property, particle strength and particle–matrix interface characteristics. Significant modifications of the material underneath the sliding contact area may take place due to the local stress intensity and heat produced. It has been found that particle fracture, interface voiding and matrix deformation would occur under repeated sliding [1–3], which favour delamination wear [4]. However, detailed evidence of subsurface damage in the case of single-pass sliding, which otherwise would offer insight into the formation mechanisms of sliding wear, is lacking. The present work aims to investigate such subsurface damage by means of scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The composite material used was an Al–Li alloy reinforced with 10% (by weight) SiC particles with an average diameter of 13 μm. The composite was prepared by hot isostatic pressing (HIPping) method using Al–Li powder smaller than 105 μm. Its nominal chemical composition by weight (%) is Li: 2.5, Cu: 2.0, Mg: 1.0, Zr: 0.15 and Al: balance. The material tested was solution treated at 530°C for 0.5 h and artificially aged at 190°C for 6 h. Within this temperature range, the coefficient of thermal expansion (CTE) of the SiC particle is 4.63×10^{-6} K^{-1} [5] and that of the Al–Li matrix is 23.5×10^{-6} K^{-1} [6]. The effect of differential thermal expansion on the microstructure of the composite will be discussed later in this communication. Adding lithium to aluminium not only lowers the density but also increases the elastic modulus and the strength [7]. Also, copper and magnesium improve the strength of Al–Li alloys through solid solution and precipitate strengthening and minimise the formation of precipitate-free zones near the grain boundaries. Zirconium, which forms the cubic Al_3Zr coherent dispersoid, suppresses recrystallization and stabilizes subgrain structures [8].

The sliding wear experiments were carried out on a reciprocating scratch machine with a pyramidal indenter having an apex angle of 136° at a temperature of 250°C. The indenter was oriented with one of the pyramidal surfaces as the leading plane to simulate the wear process. Rectangular samples were polished down to 1 μm with diamond paste and etched by a Graff/Sargent reagent. A normal load of 10 N and an average linear velocity of 6 mm s^{-1} were used over a wear track

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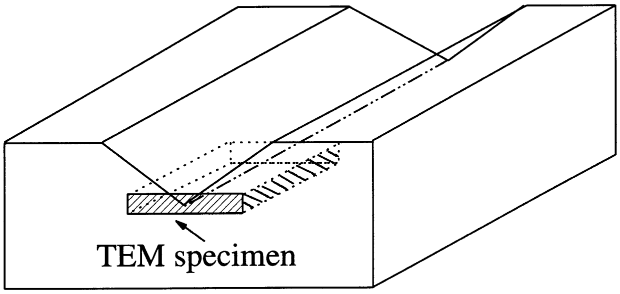

Fig. 1. Preparation of TEM specimen.

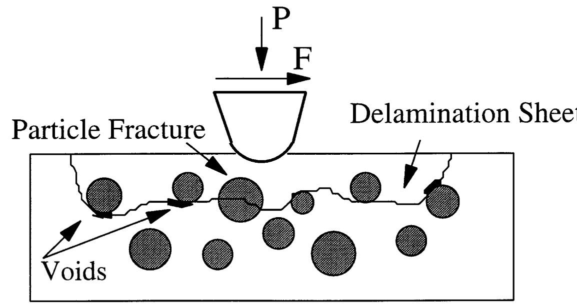

Fig. 3. Illustration of a wear sheet formed by delamination.

6 mm long. Although the sliding speed is high compared to previous work on scratching [9,10], the purpose of the present study is to simulate practical working conditions such as a piston-cylinder sliding pair in an engine, and to investigate the subsurface damage produced. The TEM specimen was prepared by slicing the scratched sample parallel to the scratching surface and then thinning mechanically and finally ion-milling to a thickness of 400 D as shown in Fig. 1. It contained the groove bottom so that both surface and subsurface damage could be examined.

The scratched samples were first examined by SEM. Fig. 2 is a SEM micrograph showing fractured particles. Particles in the path of the indenter were seen to be pushed into the matrix hence causing further deformation of the subsurface material. Matrix–particle debonding and voiding can also be seen clearly in this micrograph. While the initiation of interface debonding and subsequent voiding could be caused by the different CTE's of the SiC particulate and the Al–Li matrix, this seems unlikely in this case. Simple calculations of the theoretical residual stresses in the particle and in the matrix at ambient temperature according to references [11–14] give values of 276 and 30 MPa, respectively. Sun et al. [13] using X-ray diffraction confirmed that the residual stress in the matrix of a SiC/Al composite is of the order 25 MPa after the low temperature treatment (kept in liquid nitrogen for 14 h and then warmed up to ambient temperature). However, at the test temperature of 250°C these residual stresses would become negligible. Arsenault and Taya [11] and Zahl and McMeeking [12] both showed that at temperatures above 200°C the residual stresses in similar MMCs are fully relaxed. Hence we believe that the thermal residual stresses are insignificant at the scratching temperature of 250°C and therefore not responsible for interface debonding/voiding observed in Fig. 2. However, it is important to realise that once such interface debonding and voids were initiated they would extend by the repeated application of shear and tensile stresses induced by scratching. Void formation is an integral part of the crack initiation and propagation process. Thus, in a real wear system with multiple contact sliding, voids would link up and produce large delamination sheets [1,4]. This process is illustrated in Fig. 3. Compared to single phase metals without particulate reinforcements, interface voiding and linkage is an important process that affects the wear of particulate MMCs [15].

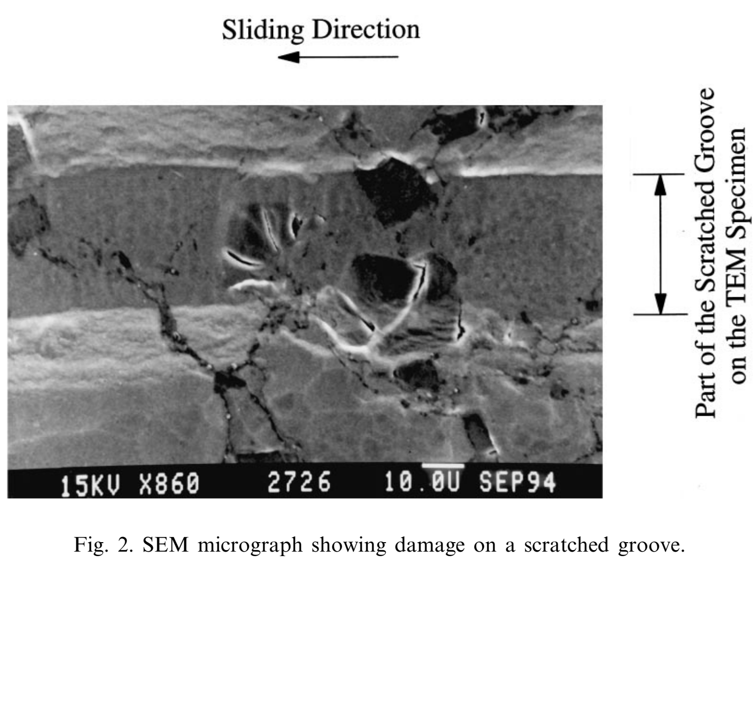

Fig. 2. SEM micrograph showing damage on a scratched groove.

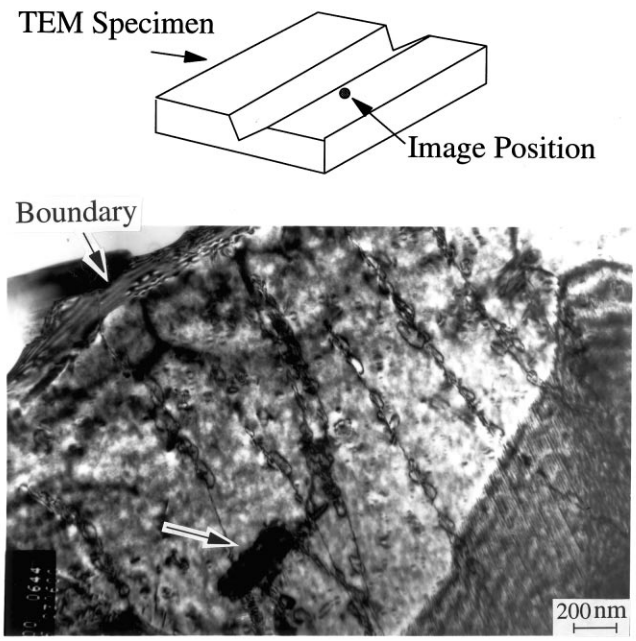

Fig. 4. TEM micrograph of the subsurface structure after scratching showing precipitates and dislocations in a grain.

Detailed information on the subsurface damage of the matrix and the particles was investigated by TEM. Dislocations in the matrix region underneath the scratch in the position indicated by an arrow can be clearly seen in Fig. 4. Nearly parallel slip lines generated in the matrix due to scratching suggest that the matrix material can be sheared or fractured along these slip lines, inside the grain, if further sliding is applied. The dislocation may cut through the coherent precipitates during plastic deformation (see arrow in Fig. 4), thus reducing the flow stress on the slip plane and making it prone to subsequent deformation. Therefore, delamination of the matrix material is likely in the wear process.

Dislocations and cracks (see arrows) in a small particle after scratching are shown in Fig. 5, which indicate that the particles can be fractured if a critical fracture stress is reached. (Fractured SiC particles were indeed found on the scratched surface, Fig. 2). Because the particles outside the scratched groove are free of dislocations, Fig. 6, the dislocation found here must be caused by scratching rather than formed during fabrication of the composite. Fig. 5 also shows the interface between a SiC particle and the matrix. No reaction products were found along the interface due to the powder metallurgy fabrication method. Under moderate applied loads, the particles in the matrix not only strengthen the material but also wear out the abrasives (or hard asperities on the counterpart). However, if the particles were fractured, the wear resistance of the composite would drop.

Based on the information from Figs. 2 and 5 and Fig. 6, it is quite clear that the stresses generated by the frictional force at the contact surface are largely responsible for the particle fracture and particle–matrix debonding/voiding at the interface. The release of residual thermal stresses is not the main cause of interface debonding/voiding because such damage was not formed in the region outside the scratch, as shown in Fig. 6. It can therefore be inferred that the damage zone with cracks would be extended under repeated sliding thus contributing to increased wear.

In summary, the subsurface damage induced by scratching at an elevated temperature (250°C) on the

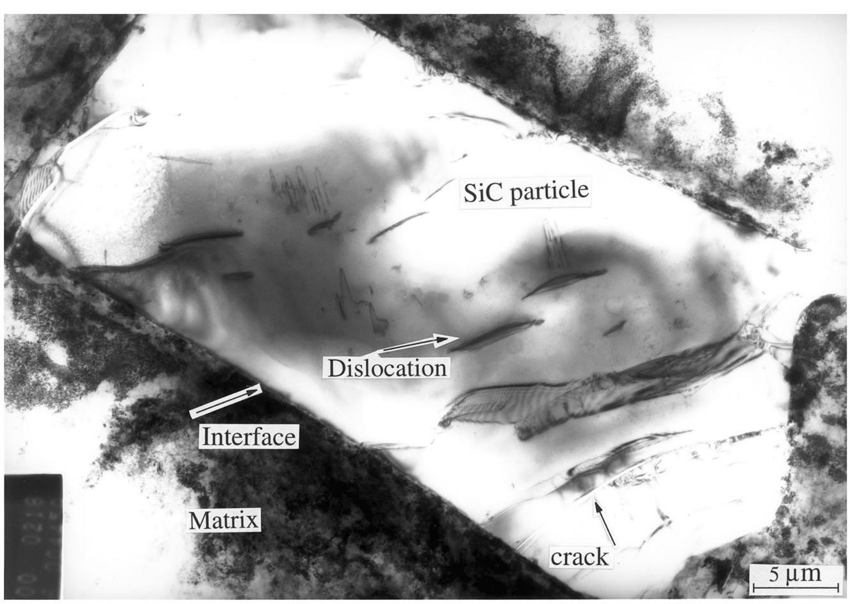

Fig. 5. TEM micrograph showing interface and response of the matrix and a particle by scratching.

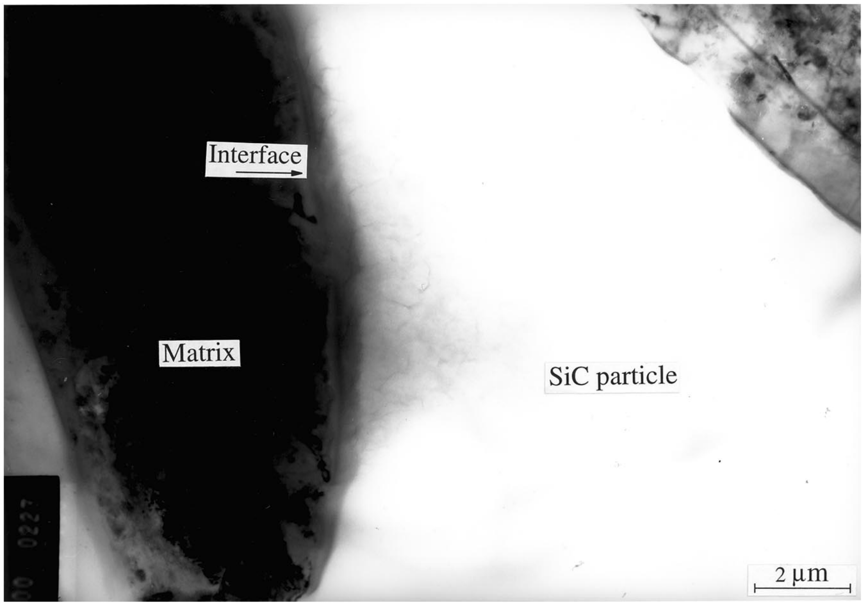

Fig. 6. TEM micrograph showing no dislocation in a particle outside the scratch.

SiC particulate reinforced Al-Li composite consists of: (1) dislocations and cracks in the reinforced particles; (2) debonding at the interface between matrix and reinforcements; and (3) plastic deformation of matrix characterised by parallel (dislocation) slip lines. These damage mechanisms will control the wear resistance of the metal matrix composite.

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