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Fatigue Crack Growth Resistance of SiC_p Reinforced Al Alloys: Effects of Particle Size, Particle Volume Fraction, and Matrix Strength

M.T. Milan and P. Bowen

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The main aim of this work was to study the effects of particle size, particle volume fraction, and matrix strength on the long fatigue crack growth resistance of two different grades of Al alloys (Al2124-T1 and Al6061-T1) reinforced with SiC particles. Basically, it was found that an increase in particle volume fraction and particle size increases the fatigue crack growth resistance at near threshold and Paris regimen, with matrix strength having a smaller effect. Near final failure, the stronger and more brittle composites are affected more by static modes of failure as the applied maximum stress intensity factor (K_{max}) approaches mode I plane strain fracture toughness (K_{IC}).

Keywords composite, fatigue crack growth, matrix strength, particle size, volume fraction

1. Introduction

The addition of high-strength ceramic phases to metallic materials has led to the development of a series of metal matrix composites that have provided an alternative to conventional engineering alloys. Discontinuously reinforced metal matrix composites exhibit higher stiffness, strength, and wear resistance than the matrix. However, their poor ductility and fracture toughness have inhibited designers from using this class of materials more extensively. In this sense, a complete understanding of the monotonic and fatigue properties of such composites is essential if they are to be used in structural applications. The present work studied the effects of particle size, particle volume fraction, and matrix strength on the long fatigue crack growth resistance of SiC_p-reinforced Al alloys.

2. Long Fatigue Crack Growth Resistance of Metal Matrix Composites

2.1 Effects of Particle Volume Fraction

Healy et al.[1] found that threshold values and fatigue crack growth resistance in the Paris regimen are higher for Al8090 alloys reinforced with 14% of particles than for the composite reinforced with 3% of particles. After closure effects were considered, Shang and Ritchie[2] found no significant difference on the effective fatigue threshold, $\Delta K_{th,eff}$, for Al-Zn-Mg-Cu + SiC when particle volume fraction increased from 15-20% for three different aging conditions. Mason and Ritchie[3] found that Al2124 + 30% SiC has a higher applied threshold stress intensity factor range (ΔK_{th}) than Al2124 + 20% SiC due to the higher closure levels (due to the higher stiffness) of the composite reinforced with 30% SiC. When closure effects were removed, $\Delta K_{th,eff}$ was also higher for the larger volume fraction composite. A similar result was obtained by Tanaka et al.[4] when studying the data of Kobayashi et al.[5]; which showed that Al6061 + 30% SiC had a higher $\Delta K_{th,eff}$ than did Al6061 + 10% SiC. However, when $\Delta K_{th,eff}$ was divided by Young's modulus (E), no difference was found in the values. This suggests that ΔK_{th} is predominantly correlated to E and closure levels. In fact, Wasen and Heier[6] found for a wide range of metallic and composite materials that $\Delta K_{th,eff}$ was directly proportional to E.

Pippan and Weinert[7] also found that $\Delta K_{th,eff}$ increased with increasing particle volume fraction in Al6061 + Al_2O_3. They used a zone-shielding concept to explain the effect of E on

M.T. Milan and **P. Bowen,** Department of Materials, Aeronautics, Automotive Engineering, Engineering School of São Carlos, University of São Paulo, Brazil. Contact e-mail: mtmilan@sc.usp.br.

Nomenclature	
CTOD	crack tip opening displacement
da/dN	fatigue crack growth rate
E	Young's modulus
K	applied stress intensity factor
K'	effective stress intensity factor
K_{cl}	closure stress intensity factor
K_{IC}	mode I plane strain fracture toughness
K_{max}	applied maximum stress intensity factor
K_{min}	applied minimum stress intensity factor
l	length
R	stress ratio
t	thickness
w	width
ΔK	applied stress intensity factor range
ΔK_{th}	applied threshold stress intensity factor range
$\Delta K_{th,eff}$	effective threshold stress intensity factor range
ε	total elongation
ν	Poisson's ratio
σ_{ys}	0.2% offset yield stress

$\Delta K_{th,eff}$. Since the crack propagated mainly in the matrix, thereby avoiding the particles, the authors suggested that E in the immediate vicinity of the crack tip was smaller than in the surrounding composite and caused "shielding" of the crack tip. This is based on the fact that when the crack grows from a weaker/less-stiff material toward a stronger/stiffer material, there is a reduction of the local crack-driving force and, consequently, a reduction of crack speed.[8-11] Based on this concept, an increase in particle volume fraction increases the long-range E, and the crack-driving force is further reduced. It is important to mention that for the two particle volume fractions studied (16% and 21%), the authors assumed that shielding caused by crack tip deflection/branching was the same and that the increase in $\Delta K_{th,eff}$ was solely caused by the zone shielding.[7] This effect was called "stiffness shielding" and is analogous to microcrack shielding in ceramics where microcracks cause an apparent reduction in E in the vicinity of the crack tip.

The increase in particle volume fraction reduces the interparticle spacing and increases the levels of particle clustering and matrix residual stress/triaxial stress state. This is particularly important for the higher applied stress intensity factor range, ΔK, where the contribution of monotonic modes of fracture increases, resulting in higher fatigue crack growth rates.[12] Boselli et al.[13] highlighted the importance of interparticle spacing and clustering levels on the fatigue crack growth rates of Al + SiC composites by modeling the particle distribution. They showed that the crack accelerated as it propagated through closely spaced pairs of particles. Niklas et al.[14] found that the number of acoustic emission events in Al6061 + SiC increased with an increase in the SiC content and so did the number of SiC particles on the fracture surface. The work of Sugimura and Suresh[15] in Al-Cu with 6%, 13%, and 20% SiC particles, and that of Kumai et al.[16] in Al6061 with 15% and 30% SiC particles, showed that particle fracture was more prevalent with larger volume fractions of particles. This was attributed to higher constraint levels in the matrix as a result of the increased volume fraction of particles. Hall et al.[17] also suggested that the probability of particle fracture, normalized for the particle volume fraction, increases because the higher particle content increases the matrix strength (due to a higher dislocation density), and this in turn results in higher maximum tensile stresses ahead of the crack tip.

2.2 Effects of Particle Size

Several authors have observed that increasing particle size, in general, increases the fatigue crack growth resistance and threshold levels. Shang and Ritchie[18] observed that Al7091 + 20% SiC (10 μm) exhibits higher ΔK_{th} and higher fatigue crack growth resistance than does Al7091 + 20% SiC (6 μm). They noted that the coarse particle distribution induces more crack meandering and, hence, is more effective in promoting higher levels of closure at low ΔK levels and/or low stress ratio (R). When the closure contribution was removed, it was found that large particle-reinforced composites had smaller $\Delta K_{th,eff}$, however, the authors did not offer an explanation for this phenomenon.

Doel,[19] studying Al7075 reinforced with particles that were 5, 13, and 60 μm in size, found that the levels of surface roughness and fatigue crack growth resistance in the Paris regimen increased with increasing particle size. This observation suggested that closure can be important even at a high ΔK. However, it was also observed that the difference in fatigue crack growth resistance is less significant between the 13 and 60 μm particle-reinforced composites, and it was suggested that a contribution of monotonic modes of failure due to particle fracture counterbalances the higher closure levels of the 60 μm particle-reinforced composite. Shang and Ritchie,[2] Kumai et al.,[16] and Tokaji et al.[20] also observed that composites reinforced with large particles exhibited a higher frequency of fractured particles. Couch[21] studied the fatigue crack growth resistance of Al8090 reinforced with 3, 7, and 20 μm particles. It was found that larger particles increased the fatigue crack growth resistance and the frequency of fracture particles. These results are in agreement with the fact that a larger particle is more likely to contain a critical size defect.

2.3 Effects of Matrix Strength

The matrix strength of Al matrix composites can be changed by aging heat treatments or by modifying the chemical composition. Christman and Suresh[22] and You et al.[23] found no effect of aging treatment on the fatigue crack growth resistance of particle-reinforced Al2124. Knowles and King,[24] studying the influence of aging on the fatigue crack growth of Al8090 + SiC, found that threshold values are very similar regardless of the aging treatment applied. However, Paris regimen crack growth rates increased with aging due to the formation of weak points in the microstructure and an increase of the triaxial stresses on the matrix. Additionally, it was suggested that higher matrix strength increases the maximum stresses ahead of the crack tip and at stress-concentrating features such as particles (i.e., the ends or corners). These effects resulted in a stronger monotonic fracture component during fatigue. Pippan[25] found no effect from the microstructure, yield stress, or chemical composition on the $\Delta K_{th,eff}$ of Al6061, Al7020, and Al7075. Tanaka et al.[4] found that ΔK_{th} tended to decrease with the increasing tensile strength of particle-reinforced aluminum alloys. However, the $\Delta K_{th,eff}$ is fairly constant and independent of the composite strength.

Couch[21] studied the fatigue crack growth resistance of Al8090 + SiC at room temperature and at high temperature. At high temperature, fewer fractured particles were observed on the fracture surface, and it was suggested that at high temperature the contribution of monotonic modes of failure is less significant because the matrix yield stress is lower. Consequently, the maximum stress ahead of the crack tip is also lower, although this maximum stress extends over a longer distance. A comparison of the works of Shang et al.,[26] Sugimura and Suresh,[15] and Kumai et al.[16] indicates that a stronger matrix increases the particle fracture probability in fatigue. Similar to the work of Couch,[21] Hall et al.[17] attributed this effect to the increase in the maximum stress ahead of the crack tip, although the plastic zone size or process zone is smaller. In summary, if the crack tip plastic zone size were the main factor controlling the probability of particle fracture ahead of the crack tip, then composites with lower matrix yield stress would exhibit a larger number of fractured particles because the plastic zone size is larger. However, as the literature shows, the opposite occurs, and therefore, as Crawford and Griffiths[27] had already suggested, the maximum stress and the stress distribution ahead of the crack tip are indeed the main factors controlling particle damage.

3. Materials and Experimental Procedures

The materials used in this study were prepared by Aerospace Metal Composites (AMC, Farnborough, UK) via a powder metallurgy-processing route. The SiC particles were blended with the Al alloy powder by mechanical alloying. Hot isostatic pressing (i.e., HIPping) was used to consolidate the bimaterial cylinder at 500 °C for 1 h. After consolidation, the ingot was cooled to room temperature (i.e., the T1 heat treatment) with no subsequent heat treatment. Several composite systems were available for testing with different matrix compositions. The nominal particle volume fractions (%) and average particle sizes as supplied by AMC were:

- Al2124 + 17% SiC (3 μm),
- Al2124 + 25% SiC (3 μm),
- Al2124 + 35% SiC (3 μm),
- Al2124 + 25% SiC (20 μm), and
- Al6061 + 25% SiC (3 μm)

The nominal chemical composition (wt.%) of the Al2124 is 4% Cu, 1.5% Mg, and 0.6% Mn, with the balance in Al. For the Al6061, the chemical composition (wt.%) was 0.3% Cu, 1% Mg, and 0.6% Si, with the balance Al. Four-point bend fatigue testpieces (inner span, 10 mm; outer span, 40 mm) were cut using electrodischarge machining (Fig. 1). A fatigue precrack then was introduced in the testpieces using load-shedding techniques. All fatigue tests were performed under ambient conditions using a constant load range ($R = 0.3$) and a frequency of ~110 Hz. Cracks were monitored using direct current potential drop and replication techniques. The fatigue crack growth rate, da/dN, was calculated using the five-point secant method and was plotted against ΔK.

4. Results and Discussion

4.1 Tensile Results

Tensile data is presented in Table 1. The results are an average taken from three specimens of each material. It can be seen that an increase in the SiC content increases both the yield stress and E while reducing ductility. Also, it is observed that for composites of the same volume fraction of particles, an increase in particle size and/or a decrease in the matrix strength reduced the yield strength while increasing the ductility.

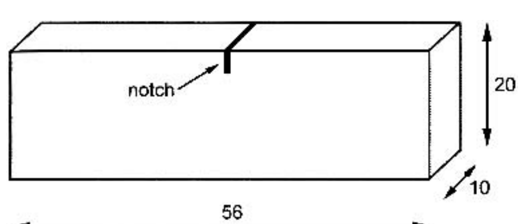

Fig. 1 Fatigue testpiece geometry. All dimensions are in millimeters.

Table 1 Tensile properties

Al alloy/composite	Young's modulus (E), GPa	Yield stress, 0.2% offset (σ_{ys}), MPa	Total elongation (ε), %
Al2124	70.2	159	16.1
Al2124 + 17% SiC (3 μm)	101.0	181	5.4
Al2124 + 25% SiC (3 μm)	115.8	272	2.7
Al2124 + 35% SiC (3 μm)	135.5	395	1.7
Al2124 + 25% SiC (20 μm)	114.9	170	3.3
Al6061 + 25% SiC (3 μm)	114.0	225	5.1

4.2 Long Fatigue Crack Growth Resistance

The addition of SiC particles affects the fatigue crack growth rate of the composites in all three regions of fatigue crack growth (i.e., near-threshold, Paris region, and fast fracture). The effects of particle volume fraction, particle size, and matrix composition on each stage of fatigue crack growth are discussed in further detail below.

4.2.1 Effects of Particle Volume Fraction. Near the threshold, the results presented in Fig. 2 show that the addition of SiC particles increased the ΔK_{th} of the composites when compared with the unreinforced matrix. The presence of SiC particles changed the intrinsic properties of the material, for example, the microstructure, ultimate tensile strength or yield stress, and the E. Also, it was found that a higher volume fraction of SiC particles increases ΔK_{th}. This suggests that microstructure affects ΔK_{th} by means of crack tip deflection and/or crack closure mechanisms. SiC particles act as obstacles to the crack propagation. When a crack approaches a particle, it either cuts through the particle or bypasses it completely. If the crack is deflected, there can be a local reduction of the mode I crack-driving force, and both the applied maximum stress intensity factor (K_{max}) and the applied minimum stress intensity factor (K_{min}) are effectively reduced. Because the Al alloy/SiC interfacial bonding is strong, and particle fracture is minimal (especially in the composites with small particles), the fatigue crack tends to grow around the reinforcement. Furthermore, the presence of clusters and sharp particle corners results in stress concentrators that may provide a weaker fracture path and, consequently, increase the crack path tortuosity. The increase in the surface roughness may cause premature contact of the crack faces as the applied K is reduced in the fatigue cycle. Therefore, the effective ΔK is reduced by effectively increasing K_{min}. This process is favored near ΔK_{th} levels at which crack opening displacements are smaller and the crack faces are closer. Although closure measurements were not performed in this work, the literature supports this interpretation.

In composites, the ratio between K_{cl} (closure stress intensity factor) and K_{max} (i.e., K_{cl}/K_{max}) is increased compared to the matrix alloy, not only by the increase in surface roughness, but also by the increase in stiffness and strength, since crack tip opening displacement (CTOD) is reduced because it is in-

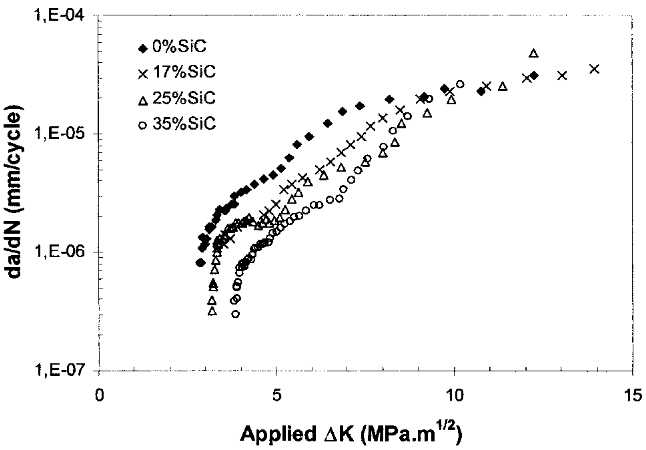

Fig. 2 Effects of particle volume fraction on the fatigue crack growth resistance of Al2124-based composites

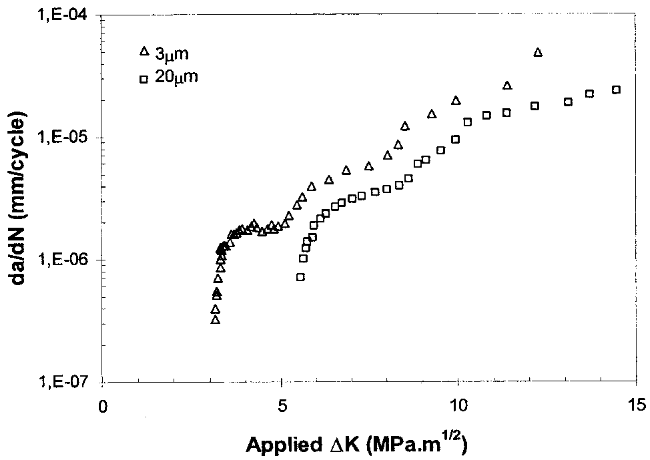

Fig. 3 Effects of particle size on the fatigue crack growth resistance of Al2124-based composites

Table 2 CTOD calculated for different applied K values

Material	CTOD, μm		
	K = 5.0 MPa$\sqrt{m}^{1/2}$	K = 7.0 MPa$\sqrt{m}^{1/2}$	K = 10.0 MPa$\sqrt{m}^{1/2}$
Al2124	2.00	3.92	8.01
Al2124 + 17% SiC (3 μm)	1.23	2.41	4.92
Al2124 + 25% SiC (3 μm)	0.71	1.40	2.86
Al2124 + 35% SiC (3 μm)	0.42	0.82	1.67
Al2124 + 25% SiC (20 μm)	1.14	2.23	4.56
Al6061 + 25% SiC (3 μm)	0.87	1.70	3.45

versely proportional to E and 2% offset yield stress (σ_{ys}), as given by Hertzberg[28]:

$$\text{CTOD} = \frac{K^2(1 - \upsilon^2)}{\sigma_{ys}E} \text{ under plane strain} \quad \text{(Eq 1)}$$

Table 2 shows CTOD values for all materials studied at different applied K values. It is clear that an increase in the particle volume fraction reduces the calculated CTOD. Besides the increase in closure levels, the increase in strength and stiffness also results in lower plastic strain ahead of the crack tip, which is expected to contribute to an increase in the fatigue crack growth resistance of the composites.

In the Paris regimen, the applied K is higher, and the effects of closure are expected to be less significant (i.e., K_{cl}/K_{max} decreases). Nevertheless, results show that increasing the SiC volume fraction increases fatigue crack growth resistance (Fig. 2). From Table 2, it is possible to observe that even at an applied K = 10.0 MPa$\sqrt{m}^{1/2}$, CTOD levels for the composites are small and comparable to the particle size, suggesting that crack closure may still be operative.

Near final failure, it was observed that the fatigue crack growth resistance was superior for the unreinforced matrix and for the low-volume fraction composites (Fig. 2). At high-ΔK, the K_{max} approached the fracture toughness of the material, K_{IC}, and static fracture modes were more likely to occur. The

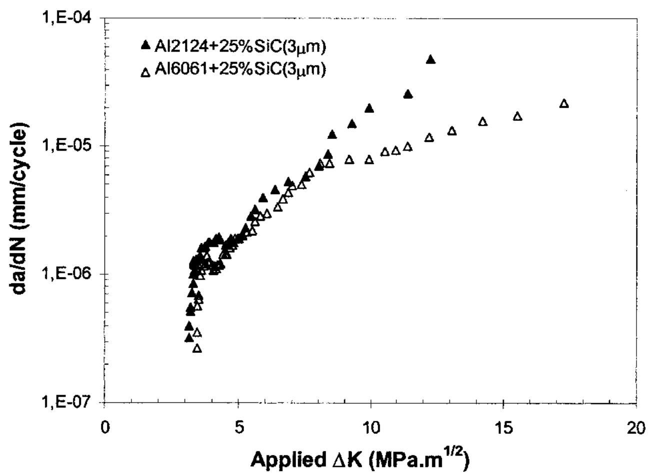

Fig. 4 Effects of matrix strength on the fatigue crack growth resistance of Al alloys reinforced with SiC particles

high-volume fraction composites exhibit higher strength/lower toughness and, consequently, much stronger dependence on K_{max}, leading to characteristically accelerated fatigue crack growth rates in this region.

4.2.2 Effects of Particle Size. The effects of particle size on the fatigue crack growth resistance of the Al2124-based composites can be seen in Fig. 3. The large particle composites exhibit higher fatigue thresholds and fatigue crack growth resistance. Because the volume fraction is kept constant, the stiffness is not expected to be responsible for differences in the fatigue properties of the composites. The height of crack deflection is expected to be higher in the 20 μm composites than in the 3 μm composites. Therefore, the present results suggest that the closure levels (i.e., K_{cl}/K_{max} ratio) are greater for the large-particle composite, although the CTOD levels are also higher (Table 2).

Near final failure, closure effects are expected to be less significant and fatigue crack growth rates more strongly dependent on K_{max}. At this stage, as seen in Fig. 3, the Al2124 +

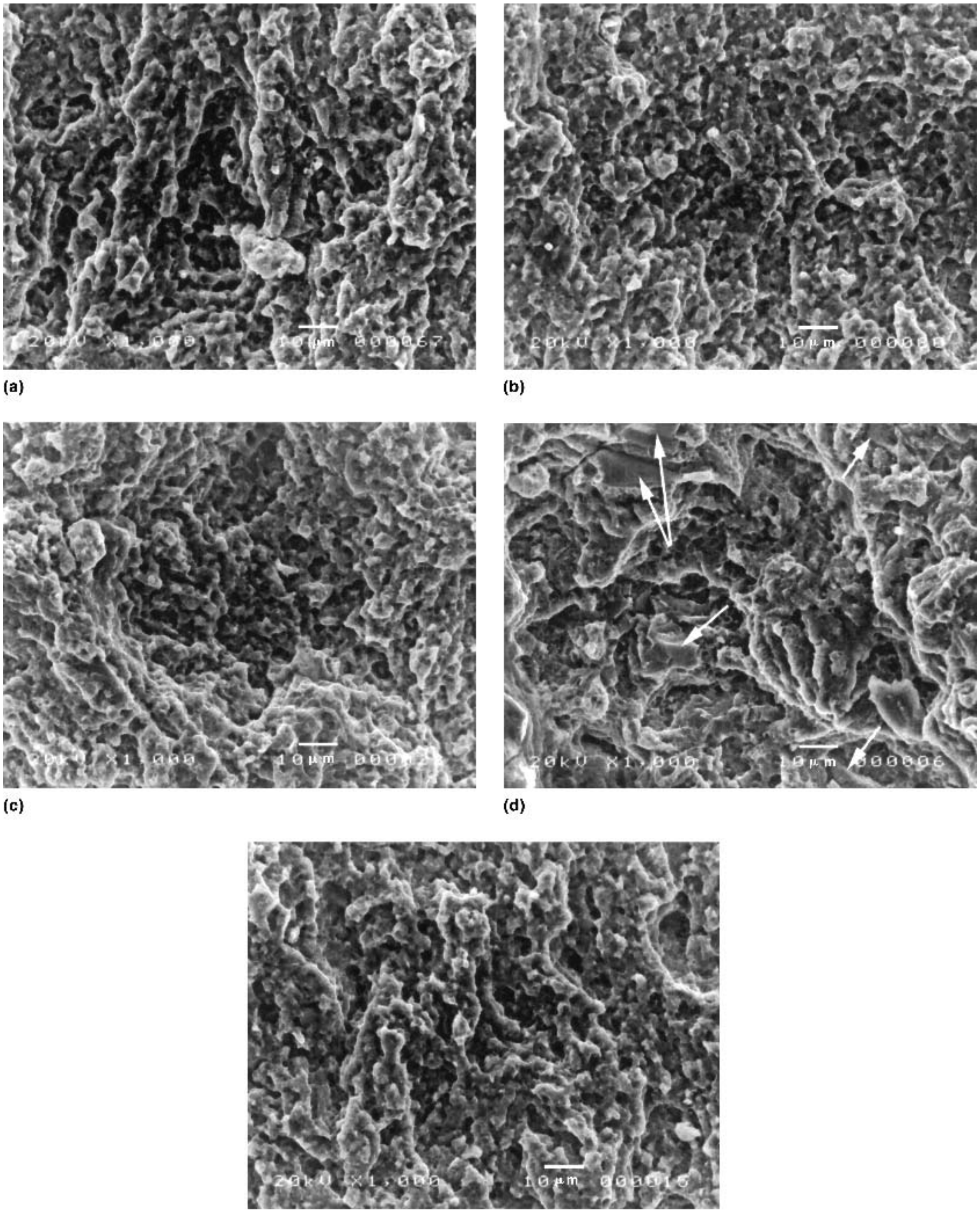

Fig. 5 SEM micrographs of fatigue fracture surfaces, observed at $\Delta K = 7.0\ \text{MPa}\sqrt{\text{m}}^{1/2}$. **(a)** Al2124 + 17% SiC (3 μm); **(b)** Al2124 + 25% SiC (3 μm); **(c)** Al2124 + 17% SiC (3 μm); **(d)** Al2124 + 25% SiC (20 μm), with some of the fractured particles indicated by arrows; and **(e)** Al6061 + 25% SiC (3 μm)

25% SiC (3 μm) shows higher fatigue crack growth rates than the Al2124 + 25% SiC (20 μm), which suggests a higher K_{max} dependence (lower toughness) for the composite with smaller particles.

4.2.3 Effects of Matrix Strength. Figure 4 shows the effects of matrix composition on the fatigue crack growth resistance of the composites with the same particle volume fraction and particle size. Because both roughness levels and E are expected to be approximately the same, the only significant variable is the matrix strength, and its effect on fatigue crack growth resistance can be assessed. The results show that strength apparently has no effect on the fatigue crack growth rates of the composites at near threshold and in the Paris regions.

It was seen earlier that the Al2124-based composite exhibited higher strength/lower ductility than the Al6061-based composite of the same volume fraction and particle size (Table 1). Higher matrix strength reduces CTOD levels, as seen in Table 2, enhancing closure effects and reducing plastic strain ahead of the crack tip. Therefore, fatigue crack growth resistance was expected to be higher. On the other hand, a stronger/less-ductile material would increase the K_{max} dependence of the fatigue crack growth rate. Therefore, it is possible that when the strength of the matrix increases, there is a balance between the opposing effects that is caused by lower CTOD/plastic strain and higher K_{max} dependence.

Near final failure, CTOD values are higher, and the contribution of static modes of failure is likely to be more important than closure. Indeed, the Al2124 + 25% SiC (3 μm) composite exhibited higher fatigue crack growth rates than the Al6061 + 25% SiC (3 μm) composite (Fig. 4), suggesting a higher K_{max} dependence (lower fracture toughness) for the high-strength/low-ductility Al2124 + 25% SiC (3 μm) composite.

4.3 Fractography

Figure 5 shows scanning electron microscope (SEM) micrographs of the fatigue fracture surfaces observed at a $\Delta K = 7.0\ \text{MPa}\sqrt{\text{m}}^{1/2}$ ($K_{max} = 10.0\ \text{MPa}\sqrt{\text{m}}^{1/2}$). It was observed that the fracture was transgranular and relatively featureless, with very few decohered particles seen on the fracture surfaces of the 3 μm particle size composites. Therefore, at the intermediate K value observed, it seems that the crack tends to avoid the SiC particles and grow around them. No significant difference in fracture surface morphology was seen when particle volume fraction or matrix strength was varied. However, in the Al2124 + 25% SiC (20 μm) composite (Fig. 5d), where the particle size is larger and inherently weaker, a few fractured particles can be detected on the fracture surface.

5. Conclusions

- The addition of SiC particles to the Al alloy matrix increases the fatigue crack growth resistance at near threshold and Paris regimens, and reduces it near to the final failure stage.
- An increase in particle volume fraction and particle size increases the fatigue crack growth resistance at near threshold and in the Paris regimens, with matrix strength having the smaller effect. This is mainly attributed to the increase in surface roughness, which increases closure levels and leads to crack deflection mechanisms.
- Near final failure, the fatigue crack growth resistance is affected by the contribution of static modes of failure as K_{max} approaches K_{IC}, especially in the stronger and less ductile composites.

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