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Tensile and Fracture Toughness Properties of SiC_p Reinforced Al Alloys: Effects of Particle Size, Particle Volume Fraction, and Matrix Strength

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The goal of this work was to evaluate the effects of particle size, particle volume fraction, and matrix strength on the monotonic fracture properties of two different Al alloys, namely T1-Al2124 and T1-Al6061, reinforced with silicon carbide particles (SiC_p). From the tensile tests, an increase in particle volume fraction and/or matrix strength increased strength and decreased ductility. On the other hand, an increase in particle size reduced strength and increased the composite ductility. In fracture toughness tests, an increase in particle volume fraction reduced the toughness of the composites. An increase in matrix strength reduced both K_{crit} and δ_{crit} values. However, in terms of K_Q (5%) values, the Al6061 composite showed a value similar to the corresponding Al2124 composite. This was mainly attributed to premature yielding caused by the high ductility/low strength of the Al6061 matrix and the testpiece dimensions. The effect of particle size on the fracture toughness depends on the type of matrix and toughness parameter used. In general, an increase in particle size decreased the K_Q (5%) value, but simultaneously increased the amount of plastic strain that the matrix is capable of accommodating, increasing both δ_{crit} and K_{crit} values.

Keywords composite, fracture toughness, matrix strength, particle size, tensile properties, volume fraction

1. Introduction

Particle-reinforced aluminum alloys have the potential to be used in a wide range of engineering applications due to their higher stiffness and strength when compared with conventional aluminum alloys. Although this form of reinforcement is less efficient than fibers, these materials exhibit the additional advantages of isotropic properties, low material and fabrication costs, and the ability to be shaped by conventional means such as rolling, extrusion, and forging. For these materials, silicon carbide (SiC) has become the main type of reinforcement used. SiC exhibits good thermal conductivity and chemical compatibility with aluminum, creating a strong bond between particle and matrix (Ref 1). However, the increase in strength and stiffness occurs at the expense of toughness. The goal of this work was to evaluate the effects of particle size, particle volume fraction, and matrix strength on the monotonic fracture properties of two different aluminum alloys reinforced with SiC_p. For clarity, the discussion focuses on the effect that these parameters had on stiffness, strength, ductility, and fracture toughness of the composites.

2. Monotonic Fracture Properties of Metal Matrix Composites

2.1 Young's Modulus

Young's modulus increases with the addition of reinforcement. Dynamic measuring methods tend to give higher values than those determined from the initial slope of a quasi-static stress-strain curve (Ref 2). Also, static values depend on whether the measurements are made in tension or compression and are due to the presence of any residual stresses (Ref 3).

An increase in the particle volume fraction increases the stiffness of the composites (Ref 4-6). Particle size apparently has no significant effect on the Young's modulus (Ref 4, 7). However, some researchers have reported a small increase in modulus when the particle size decreases, which was attributed to a higher dislocation density and more efficient load transfer as a result of the increased interfacial area in the "small particle" composite (Ref 6, 8).

Matrix composition appears to have no significant effect on Young's modulus (Ref 2). However, it is important to mention that in aluminum-lithium-based composites with the same particle size and particle volume fraction, the stiffness of the composite is much higher than other Al alloy composites due to the

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Nomenclature	
E	Young's modulus
K_{crit}	applied stress intensity factor at catastrophic failure
K_{max}	applied stress intensity factor at plastic collapse
K_Q (5%)	provisional fracture toughness obtained by the 5% tangent offset method
K_{IC}	mode I plane strain fracture toughness
ε_t	total elongation at failure
δ_{crit}	crack tip opening displacement at catastrophic failure
δ_{max}	crack tip opening displacement at plastic collapse
σ_f	fracture stress
σ_{ys}	0.2% offset yield stress
RA	reduction of area
UTS	ultimate tensile strength

unusual phenomenon that for every 1 wt.% Li addition, there is an increase of 6% in Young's modulus.

2.2 Strength

McDanels carried out one of the first studies of strength in discontinuously reinforced composites, reporting increases of up to 60% in tensile strength, depending on the particle volume fraction, matrix composition, and heat treatment (Ref 4). Several mechanisms have been proposed to explain the strengthening in particulate composites. These mechanisms act either independently or concurrently, and they are generally divided in two groups: those by which the reinforcement directly contributes to the increase in strength and those whereby an indirect strengthening of the matrix is achieved (Ref 9). They are briefly discussed below.

Cho and Gurland considered that overall strengthening results from the strengths of the individual components as per the rule of mixture theory and by the load transfer from the ductile matrix to the hard and brittle ceramic reinforcement, as predicted by the Shear Lag theory (Ref 10). This theory was developed for fiber-reinforced composites and underestimates the strength in particulate composites. Better agreement was found when end-loading effects were taken into account (Ref 11). The problem with this approach is that it ignores the influence of particles on the micromechanics of deformation, such as the very high work hardening and modifications in the microstructure, such as grain size and dislocation density (Ref 12). If an Orowan type model is applied, it is seen that the particles are too large to contribute to the strengthening mechanisms. However, the reduced grain size observed in powder-processed composites can be an additional means of strengthening (Ref 9, 12). The mismatches in thermal expansion coefficients and Young's moduli between the matrix and reinforcement result in the generation of thermal tensile residual stresses in the matrix when the composite is cooled from the processing temperature. These residual stresses can be partially relaxed by the generation of a large number of dislocations in the matrix, which can cover most of the matrix domain (Ref 13, 14). Higher particle volume fraction, smaller particle size (smaller interparticle spacing), and aging heat treatment result in a higher dislocation density (Ref 2, 15-17). The increase in dislocation density also increases the composite strength by facilitating the nucleation of S′ precipitates in the matrix during heat treatment (Ref 18). Additionally, when load is applied, strengthening arises from constrained plastic flow in the ductile matrix due to the presence of the hard particles as a result of dislocation pileup around the particles, increasing back stress, and the work hardening of the composites (Ref 19). It is important to note that the strengthening effects caused by the back stress and matrix constraint can be reduced by plastic relaxation due to the formation of prismatic dislocation loops around the particles (Ref 20). Moreover, the tensile residual stress state of the matrix can promote premature yielding and/or void nucleation, resulting in a smaller increase in strength (Ref 2, 12).

Several authors have reported that an increase in particle volume fraction increases the strength of composites (Ref 5, 18, 21, 22). An increase in particle volume fraction increases both the dislocation density and dislocation-particle interactions resulting in larger back stresses and work hardening (Ref 22). Numerical modeling of compressive plastic deformation of particle-reinforced metal-matrix composites shows that both the flow stress and the strain-hardening rate increase with increasing particle volume fraction (Ref 23). However, some authors have reported an upper limit of the particle volume fraction above which no gain in strength is obtained (Ref 12, 24, 25). These results were justified due to difficulties in obtaining uniform particle distribution, resulting in clustering of particles. The presence of clusters results in a high state of stress triaxiality in the matrix, which increases the possibility of crack nucleation (Ref 2, 26).

Particle size also affects the strength of composites. For a constant particle volume fraction, several authors found a decrease in strength with increasing particle size (Ref 2, 5, 7, 27). According to Lloyd (Ref 12), these results can be rationalized by the fact that the larger the particle, the more it will be loaded by fiber and end-loading mechanisms, and, additionally, coarser ceramic particles will have a greater probability of containing a critical size defect. Therefore, particle fracture is more likely to occur in large particle composites. If a particle fractures, it loses the ability to bear a tensile load, and the stress in the matrix increases, reducing the strength of the composite. Moreover, in "large particle" reinforced composites, the interparticle distance is greater and the dislocation density is smaller, and, consequently, the strengthening mechanisms are less effective (Ref 28). On the other hand, the greater interparticle distance and lower levels of particle clustering will also result in a less severe triaxial stress state in the matrix, which could be beneficial to the composite. In fact, some authors found that as particle size increases, the yield stress increases up to a critical value before decreasing (Ref 29, 30).

In general, higher matrix strength results in higher composite strength (Ref 4, 31). However, the increment in strength (compared with the matrix) is less significant as the matrix strength increases, and in some cases, there is even a decrease in strength (below the matrix values) (Ref 32). This can be rationalized by the fact that a higher yield stress of the matrix results in a higher tensile thermal residual stress and smaller dislocation density. Additionally, as the composites are loaded, high stresses are applied to the particles causing them to fracture prematurely and, therefore, exhibit void nucleation at lower stresses leading to early failure. This mechanism is supported by the work of Wang et al., who found that a stronger matrix increases particle fracture probability (Ref 33).

2.3 Ductility

One of the major disadvantages of metal-matrix composites is their poor ductility. To understand why ductility in composites is reduced, it is first necessary to understand the failure mechanisms that operate in such materials. Failure in composites is mainly associated with void nucleation and growth. Nucleation occurs due to particle fracture and decohesion and/or microcracking of the matrix within particle clusters (Ref 7, 17, 34, 35).

Increasing amounts of reinforcement reduces the ductility (Ref 5, 24). The small interparticle spacing in high-volume fraction composites and/or particle clusters contributes to the failure process primarily by imposing high levels of constraint to the matrix and raising the tensile residual stress/stress triaxiality to a level significantly greater than that normally associated with matrix failure (Ref 26, 36, 37). The importance of triaxial stresses on ductility was further confirmed by Vasudevan et al., who showed that a significant increase in the ductility of composites occurred when tested under a superimposed hydrostatic pressure (Ref 38).

The literature shows that an increase in particle size generally reduces the ductility and increases the number of fractured particles at the fracture surface (Ref 5, 7, 12, 29, 33). Again, this can be explained by the fact that a large particle is easier to fracture than a small one. Other studies highlighted the importance of matrix alloy and aging conditions on the ductility and failure mechanisms of particulate composites. In general, stronger and less ductile matrix alloys will result in less ductile composites (Ref 4, 31, 39). Additionally, several researchers found an increase in the density of fractured particles with an increase in the matrix strength (Ref 12, 26, 33).

2.4 Fracture Toughness

Fracture toughness is one of the principal factors used in damage-tolerant design of structures. Studies have shown that the plane-strain fracture toughness (K_{IC}) of aluminum alloys reinforced with various ceramic reinforcements typically falls into the range of 8 to 38 MPa $\sqrt{m}$, and generally, this property is not as large as for the unreinforced alloy (Ref 40). According to Lloyd (Ref 36), obtaining a valid plane strain fracture toughness value for aluminum alloy composites can be a problem, and many of the results in the literature are invalid according to standard testing practice. Friend (Ref 41) and Manoharan and Kamat (Ref 42) also pointed out that no single parameter (e.g., linear elastic initiation K_{IC}) seems to be capable of describing the toughness response of metal-matrix composites and that both initiation and propagation resistance must be considered in a proper assessment of fracture toughness of composites.

In general, the fracture surface appearance of a fracture toughness testpiece is similar to that of the tensile testpieces. Features such as particle fracture, particle decohesion, and ductile failure of the matrix are also present on the fracture surface (Ref 29). However, the mechanisms of damage accumulation and crack propagation are different due to the high stresses and plastic zone that develops ahead of the crack tip. The most accepted mechanism suggests that microcracking occurs ahead of the crack tip both by matrix void formation within the particle clusters and by particle fracture and decohesion. The main crack then joins the various microcracks by matrix microvoid coalescence (Ref 7, 26, 27). The presence of either decohered or fractured particles will depend on several factors, such as matrix composition, heat treatment, particle volume fraction, and particle size. Davidson (Ref 43) summarized the main fracture toughness related events for particle-reinforced composites. They are the deformation within the plastic zone, void formation along the fracture surface (voids have not been found away from the fracture path), fracture of SiC particles along the crack path and within the plastic zone, particle-matrix decohesion, increased surface area due to tortuous fracture crack path, and matrix cracking ahead of the crack tip. These events operate simultaneously, and, therefore, the fracture toughness value will be the result of the synergy that exists among them.

In general, considering the effects of particle volume fraction, the fracture toughness mirrors to some extent the ductility; that is, higher volume fractions result in lower toughness (Ref 36, 40, 43, 44). As discussed earlier, higher particle volume fractions result in smaller interparticle spacings and a greater number of clustering sites. Therefore, the matrix tensile residual stress/stress triaxiality is higher, favoring particle damage and ductile failure of the matrix. Additionally, based on an analysis of the stress field ahead of the crack tip performed by McMeeking (Ref 45), Couch developed a model for the micromechanism of fast fracture in Al-Li 8090 composites (Ref 27). The model suggests that both the yield stress of the composite and interparticle distance are important in determining the extent of particle damage ahead of the crack tip. An increase of volume fraction will result in higher maximum stresses ahead of the crack tip, and because the interparticle distance is smaller, a larger number of particles will be under the influence of the maximum stresses, therefore, reducing the toughness.

The effect of the matrix composition on fracture toughness is similar to the effect observed for the ductility in the tensile tests. Assuming that particle volume fraction, particle size, and heat treatment are held constant, composites with less ductile/stronger matrices will normally result in composites with lower toughness (Ref 36, 39, 44). As discussed earlier, a composite based on a stronger matrix alloy will result in higher matrix tensile residual stress/stress triaxiality, leading to a higher probability of particle damage (Ref 2, 33). It is important to note that heat treatment will also affect the strength and stress state of the matrix and, consequently, the fracture toughness values. Some models available in the literature show a dependence of fracture toughness with the strength. A micromechanical model for crack growth resistance in particle-reinforced composites predicts that crack growth resistance is proportional to the ratio E/σ_o, where σ_o is the flow stress (Ref 42). A strong matrix has a high flow stress, and, consequently, the composite will exhibit low toughness. The model proposed by Couch also predicts that a higher matrix yield stress will result in lower toughness because the maximum stresses ahead of the crack tip will be higher (Ref 27).

The effects of particle size on fracture toughness have also been studied (Ref 7, 27, 29, 32, 37, 46-48). The results show that the particle size effect on fracture toughness is less understood, and there is a great variation in toughness trends. Depending on the combination of matrix strength and particle size range, it was found that an increase in particle size can either decrease (Ref 37, 46) or increase toughness (Ref 27, 29, 47, 48). In some cases, no effect of particle size was found (Ref 7, 32).

3. Materials and Experimental Procedures

The materials of this study were prepared by Aerospace Metal Composites-UK (AMC) (Farnborough, UK) using powder metallurgy techniques. The SiC particles were mixed with the aluminum alloy powder by mechanical alloying. Hot isostatic pressing (hipping) was subsequently used to consolidate the bimaterial cylinder at 500 °C for 1 h. After consolidation the material was cooled to room temperature in air (T1 heat treatment) with no subsequent heat treatment. The nominal chemical composition (in wt.%) of the Al2124 is 4% Cu, 1.5% Mg, 0.6% Mn, balance Al, and that of the Al6061 is 0.3% Cu, 1% Mg, 0.6% Si, balance Al.

Besides the Al2124 and Al6061 matrices, several composite systems were available for testing with different matrix compositions, nominal particle volume fractions (%), and average particle sizes as supplied by AMC:

- Al2124 + 17% SiC_p (3 μm)
- Al2124 + 25% SiC_p (3 μm)
- Al2124 + 35% SiC_p (3 μm)
- Al2124 + 25% SiC_p (20 μm)
- Al6061 + 25% SiC_p (3 μm)

Tensile tests were performed in air at room temperature in the as-pressed condition (T1 heat treatment) using a crosshead speed of 0.5 mm/min. Fracture toughness testpieces (Fig. 1) were machined using electrodischarge machining. A fatigue precrack was then introduced using load-shedding techniques. The final maximum applied stress intensity factor during precracking was less than 60% of the estimated K_{IC} for the materials. The fracture toughness tests were performed in accordance with BS 7448:1991 (Ref 49) under four-point bend loading (inner span = 10 mm, outer span = 40 mm) at a nominal crosshead speed of 0.5 mm/min. During the tests, crack opening displacements were measured using a clip gage attached to knife edges on the upper surface of the testpiece. Load-clip gage displacements were plotted on a chart recorder. Provisional fracture toughness values [K_Q (5%)] were obtained using the 5% tangent offset procedure, and the maximum crack tip opening displacement values (δ_{crit} or δ_{max}) were calculated according to BS 7448:1991 (Ref 49). For several testpieces, K_Q (5%) does not conform to requirements for the mode I plane strain fracture toughness K_{IC}. However, since the nature of this work is to make comparisons between the composites, K_Q (5%) is an adequate toughness parameter to discriminate behavior.

4. Results and Discussion

4.1 Stiffness and Strength

4.1.1 Effect of Particle Volume Fraction. Table 1 presents the tensile properties of the aluminum alloys and aluminum composites. In general, the increase of SiC particles in the matrix caused an increase in both the stiffness and strength of all composites, and, therefore, the predominant strengthening factor in particulate reinforced composites is the volume fraction of reinforcement. Some of the composites did not reach a maximum in tensile strength (UTS) so fracture stresses (σ_f) were tabulated. It is suggested that the strengthening effect observed is mainly due to the load transfer from the matrix to the particles, the mismatch in thermal expansion coefficients of the matrix and particle (which generates a large number of dislocations), and the back stress. Consequently, the larger the particle volume fraction, the higher the strength is expected to be. The reduction in strength for high particle volume fractions due to presence of particle clusters is not observed here (Ref 24, 36). It is suggested that this was the result of the good particle distribution in these composites and the low initial strength of the matrix, which minimize the tensile residual stress/triaxial stress within the matrix.

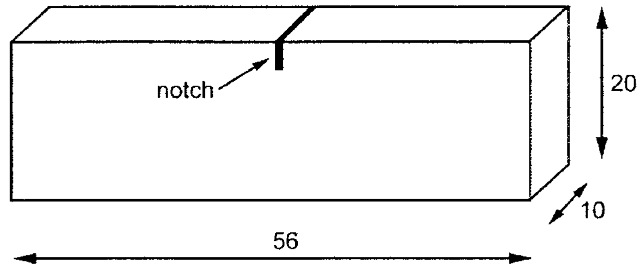

Fig. 1 Fracture toughness testpiece geometry. All dimensions are in millimeters.

Table 1 Tensile properties

Material	*E*, GPa	σ_{ys} (0.2%), MPa	UTS(a), MPa	ε_t %	RA, %
Al2124	69.5	157	275	17.0	30.8
	70.9	161	270	15.2	29.6
Average	**70.2**	**159**	**273**	**16.1**	**30.2**
Al2124 + 17%SiC (3 μm)	102.0	170	340	5.2	6.3
	100.0	192	333	5.6	5.9
Average	**101.0**	**181**	**337**	**5.4**	**6.1**
Al2124 + 25%SiC (3 μm)	116.5	260	427(a)	3.0	3.0
	114.7	284	451(a)	2.3	2.2
Average	**115.8**	**272**	**439(a)**	**2.7**	**2.6**
Al2124 + 35%SiC (3 μm)	138.0	415	478(a)	1.9	1.6
	133.0	375	482(a)	1.5	1.4
Average	**135.5**	**395**	**480(a)**	**1.7**	**1.5**
Al2124 + 25%SiC (20 μm)	116.4	174	295(a)	3.6	3.7
	113.4	166	304(a)	3.0	3.3
Average	**114.9**	**170**	**300(a)**	**3.3**	**3.5**
Al6061	70.0	104	154	24.0	59.8
	67.8	96	156	22.4	54.4
Average	**68.9**	**100**	**155**	**23.2**	**57.1**
Al6061 + 25%SiC (3 μm)	116.0	230	362(a)	5.1	5.4
	113.4	220	354(a)	5.1	5.2
Average	**114.7**	**225**	**358(a)**	**5.1**	**5.3**

See nomenclature, (a) σ_f

4.1.2 Effect of Matrix Strength. Stiffness was not affected by matrix composition. However, the strength of the Al2124 composite was higher than the Al6061 composite of same particle size and same particle volume fraction (Table 1). This was expected since the strength of the Al2124 is higher than the Al6061. However, the increment in strength compared with the matrix is more significant for the Al6061 composite than for the Al2124 composites, and this may be due to the fact that a higher yield stress of the matrix results in both a higher tensile thermal residual stress and a higher stress triaxiality in the matrix, which are superimposed to the applied stresses. Also, it is possible that localized plastic deformation around the particles occurs more easily in the low-strength Al6061 matrix, reducing the probability of particle-related damage mechanisms. The combination of these two factors

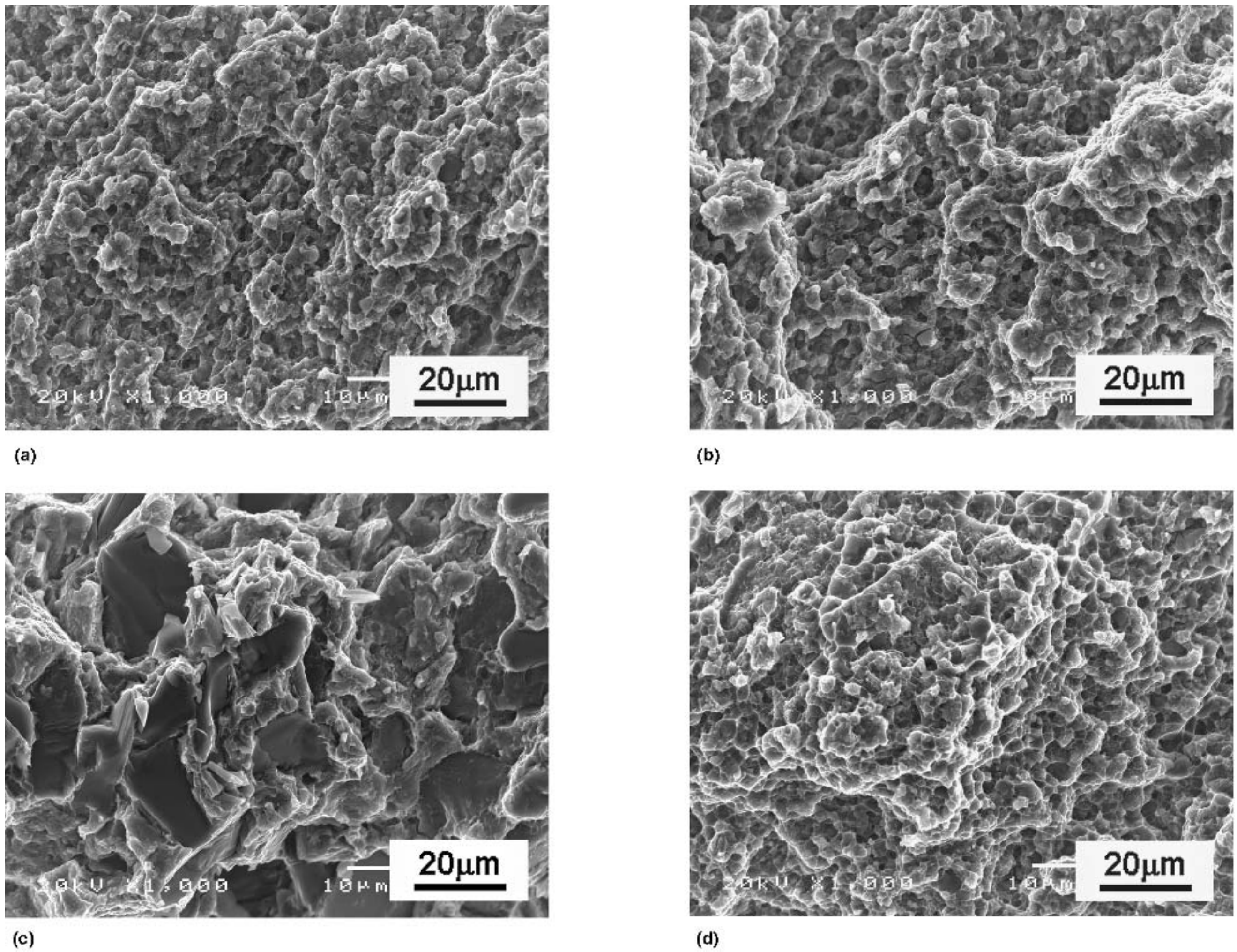

Fig. 2 SEM micrographs of tensile fracture surfaces of some of the composites. (a) Al2124 + 35%SiC_p (3 μm). (b) Al2124 + 25%SiC_p (3 μm). (c) Al2124 + 25%SiC_p (20 μm). (d) Al6061 + 25%SiC_p (3 μm)

results in a smaller increment in strength (compared with the matrix) for the Al2124 composites than for the Al6061 composite.

4.1.3 Effect of Particle Size. Particle size did not affect significantly the Young's modulus of the composites. Nevertheless, Table 1 shows that the composite with particle size of 20 μm possessed lower strength than the composite reinforced with 3 μm particles. This observation has been attributed to the increased probability that a large particle will contain a critical defect, and, therefore, the intrinsic strength of the particle is lower. If the particle breaks or decoheres, its ability to bear load decreases, leading to a higher matrix stress, which means more particles will break. Consequently, the overall strength of the composite is reduced. Additionally, it is possible that the increase in the interparticle distance due to the larger particles reduces the effectiveness of the strengthening mechanisms due to a reduction of the dislocation density (Ref 28). If the dislocation density is lower, the matrix strength is lower and the load transfer from matrix to particles is reduced because plastic straining around the particles occurs more easily. Moreover, the effectiveness of load transfer to the particles is reduced because the large particle composite has a lower total particle/matrix interfacial area.

4.2 Ductility

4.2.1 Effect of Particle Volume Fraction. Table 1 shows that in all composites, the increase of strength occurred at the expense of ductility. Both the total elongation and the reduction of area were reduced as the SiC content increased. This is expected as a result of the higher triaxial stress state caused by the increase in the number of cluster sites and/or reduction of interparticle distance as the particle volume fraction increases.

Macroscopically, the fracture appearance of the composites was brittle, but microscopically the fracture surface exhibits typical void nucleation and growth aspects (Fig. 2). In the 3 μm composites, it was difficult to find particles, which suggests that the void nucleation occurs mainly through the matrix between the SiC particles rather than by particle decohesion and fracture. Additionally, by comparing Fig. 2(a) and (b), no significant difference in the fracture surface appearance was observed when the volume fraction varied while particle size and matrix strength were kept constant.

4.2.2 Effect of Matrix Composition. According to Table 1, the Al6061 composite had higher values of reduction in area and total elongation at failure than the Al2124 composites when composites of same particle volume fraction and particle size were compared. The increased ductility of the Al6061 composites is consistent with the higher ductility and lower strength of the Al6061 matrix. This suggests that the matrix triaxial stress/tensile residual stress in the Al6061 composites is less severe than it is in the Al2124 composites.

No significant difference was observed on the fracture surfaces, when comparing the Al2124 composite and the Al6061 composite reinforced with the 3 μm particle (Fig. 2b and d, respectively), although some researchers have reported an increase in the number of fractured particles on the fracture surface due to the increase in matrix strength (Ref 12, 26, 33). It is possible that due to the T1 heat treatment, the matrix is not strong enough to cause any significant damage to the small particles (i.e., by load transfer), and, therefore, fracture takes place preferentially within the matrix rather than by particle decohesion and fracture.

4.2.3 Effect of Particle Size. The results presented in Table 1 also show that for a volume fraction equal to 25%, the composites with the larger particle size (20 μm) had higher values of total elongation and reduction in area than the small particle composites (3 μm). Large particles are inherently weaker than small ones, and, as a result, several flat facets of broken SiC particles can be seen at the fracture surface of the 20 μm composite (Fig. 2c), indicating that the crack path tends to seek the reinforcement. If particle fracture is likely to be more frequent in the large particle composites, a decrease in ductility would be expected. However, the results showed lower ductility for the small particle composites. This suggests the presence of higher levels of clustering (higher triaxial stress/tensile residual stress) due to the smaller interparticle spacing in the 3 μm composites. Consequently, there may be a reduction in the levels of plastic strain that can be accommodated before failure within the interparticle spacing of the matrix, leading to premature failure of the small particle composites.

4.3 Fracture Toughness

Table 2 shows the provisional K_Q (5%), K_{max} or K_{crit}, and δ_{max} or δ_{crit} values for all materials tested. K_{max} and δ_{max} are the applied stress intensity factor and crack tip opening displacement, respectively, attained by the unreinforced aluminum alloys testpieces at the onset of plastic collapse. K_{crit} and δ_{crit} are the applied stress intensity factor and crack tip opening displacement, respectively, attained by the composite testpieces at catastrophic failure. K_{max} and δ_{max} are difficult to evaluate since they describe the phenomenon of plastic collapse. The values of K_{max} and δ_{max} are determined by the final crack length at collapse (controlled by the yielding of the ligament net section) and the crack growth resistance curve, which controls the ease with which the initial fatigue precrack length extends to the final crack length at plastic collapse.

4.3.1 Effect of Particle Volume Fraction. According to Table 2, all the Al2124 composites exhibited lower K_Q (5%), K_{crit}, and δ_{crit} values than the unreinforced Al2124 alloy. Similar to the fracture surfaces of the tensile testpieces, the composites exhibited the typical failure mechanism of void nucleation and growth (Fig. 3). The void growth in the 3 μm composites is limited by the small interparticle spacing within the SiC particles. Regardless of the particle volume fraction, few particles were seen, suggesting that the main failure mechanism is caused by crack propagation through the matrix between the SiC particles.

Table 2 Fracture toughness properties

Material	K_Q (5%), MPa · m$^{1/2}$	K_{max} or K_{crit}, MPa · m$^{1/2}$	δ_{crit} (b), μm
Al2124	16.0	29.0(a)	111.8(b)
	16.6	27.8(a)	107.4(b)
Average	**16.3**	**28.4(a)**	**109.6(b)**
Al2124 + 17%SiC (3μm)	16.0	21.2	26.0
	15.6	21.3	30.7
	15.8	21.0	26.4
Average	**15.8**	**21.2**	**27.7**
A2l24 + 25%SiC (3 μm)	15.2	18.4	10.8
	15.4	18.2	9.0
Average	**15.3**	**18.3**	**9.9**
Al2124 + 35%SiC (3 μm)	13.4	14.7	3.3
	12.6	13.9	2.7
Average	**13.0**	**14.3**	**3.0**
Al2124 + 25%SiC (20 μm)	12.2	20.8	25.0
	11.9	19.5	22.4
	12.0	20.3	23.4
Average	**12.0**	**20.2**	**23.6**
Al6061 + 25%SiC (3 μm)	14.8	24.9	21.3
	15.3	23.7	18.1
Average	**15.1**	**24.3**	**19.7**

See nomenclature. (a) *K*. (b) δ_{max}

Also, it is observed from Table 2 that increasing the SiC volume fraction reduced the fracture toughness of the composites. This was expected because initial damage is localized to SiC particles and an increase in the particle volume fraction reduces the interparticle spacing and increases the clustering levels, leading to a higher triaxial stress state in the matrix. Moreover, a higher volume fraction of SiC, which results in higher matrix strength due to a higher dislocation density, increases the probability of microcracking because the maximum stresses ahead of the crack tip will be higher.

4.3.2 Effect of Matrix Strength. Table 2 shows that for the same particle size and same particle volume fraction, the Al6061 composite exhibited higher K_{crit} and δ_{crit} values than the Al2124 composite. Such a trend in toughness was also observed near the final failure of fatigue crack propagation tests (Ref 1). The ductility results presented in Table 1 suggest that the lower yield stress of the Al6061 matrix results in lower tensile residual stress/triaxial stress in the matrix between the SiC particles. Additionally, it is important to remember that the maximum stress ahead of the crack tip is expected to be higher for the Al2124 composites because the matrix strength is also higher, which facilitates microcrack nucleation within the matrix. However, if the effects of matrix composition are analyzed in terms of the K_Q (5%) values, then the Al6061 composite exhibits a K_Q (5%) value similar to that of the Al2124 composite. Such a result is likely to have occurred as a consequence of the low strength/high ductility of the Al6061 matrix and testpiece geometry, which results in premature yielding.

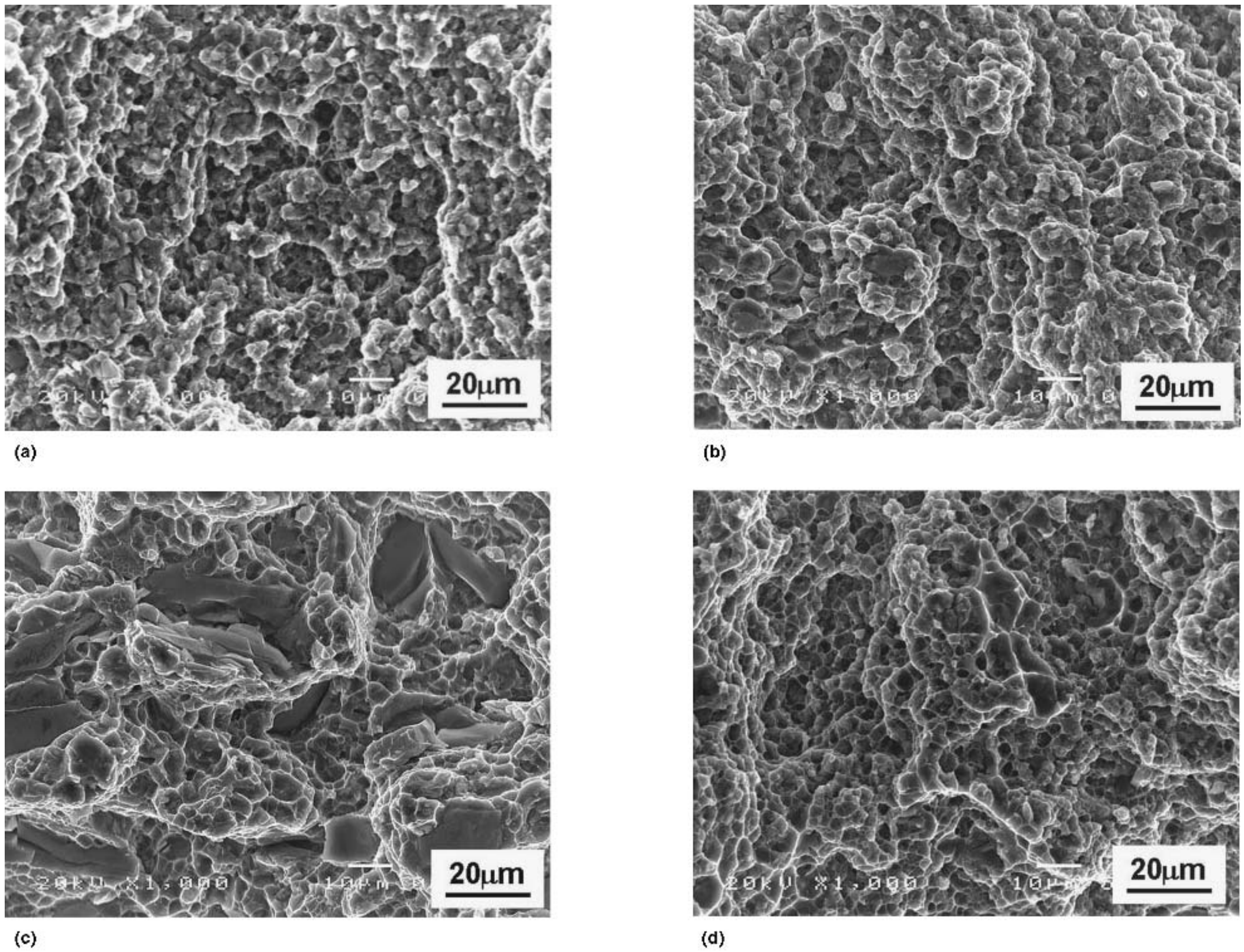

Fig. 3 Fractographic analysis of fracture toughness testpieces of some of the composites. (a) Al2124 + 35%SiC_p (3 μm). (b) Al2124 + 25%SiC_p (3 μm). (c) Al2124 + 25%SiC_p (20 μm). (d) Al6061 + 25%SiC_p (3 μm)

Although the Al2124 matrix is stronger than the Al6061 matrix, no significant difference was observed with respect to the number of particles that appear on the fracture surfaces of the Al2124 + 25%SiC composite (3 μm) (Fig. 3b) and Al6061 + 25%SiC composite (3 μm) (Fig. 3d). As for the tensile fracture surfaces, this can be rationalized by the low strength of both matrices due to the T1 heat-treating condition. Plastic deformation occurs more easily under such a condition, reducing the effectiveness of load transfer from the matrix to the reinforcement, thus reducing the probability of damage, either by decohesion or by fracture.

4.3.3 Effect of Particle Size. For a constant particle volume fraction of 25%, an increase in particle size from 3 to 20 μm reduced the K_Q (5%) value from 15.3 to 12.0 MPa$\sqrt{m}$, as shown in Table 2. This can be explained by the fact that fracture of particles ahead of the crack tip at early stages of loading may reduce the K_Q (5%) value. However, in terms of K_{crit} and δ_{crit} values, the Al2124 + 25%SiC composite (20 μm) exhibited higher fracture toughness than the Al2124 + 25%SiC composite (3 μm). The large particle composites (Fig. 3c) exhibited several flat facets of fractured particles and the voids within the matrix are larger. The failure mechanism seems to be a combination of particle fracture and ductile failure through the matrix with linkage of the fractured particles. Therefore, although the 20 μm particles are more likely to break than the 3 μm particles, it is possible that the Al2124 + 25%SiC composite (20 μm) is capable of accommodating a higher level of plastic strain between the particles (as demonstrated by larger voids) because the interparticle spacing is larger and clustering levels are smaller. This increases both K_{crit} and δ_{crit} values.

Depending on the matrix alloy studied and on the type of toughness parameter [K_Q (5%), K_{crit}, or δ_{crit}] used, a different trend in toughness can be obtained. The above interpretation may help to explain such variation. In addition, there seems to be an optimum particle size for a given particle volume fraction/matrix strength in which the toughness is maximized. It is suggested that a more complex investigation of the effects of particle size should be undertaken, using several composites reinforced with particle size ranging from 1 to 40 μm with different matrix alloys.

4. Conclusions

The following conclusions can be drawn in relation to the T1-Al2124 + SiC_p and T1-Al6061 + SiC_p composite systems:

- Stiffness was affected exclusively by the particle volume fraction.
- An increase in particle volume fraction and/or matrix strength increased strength and decreased ductility of the composites. On the other hand, an increase in particle size reduced strength and increased ductility of the composites.
- An increase in particle volume fraction for a given particle size reduced K_Q (5%), K_{crit}, and δ_{crit} of the composites.
- An increase in matrix strength for a given particle size and particle volume fraction reduced both K_{crit} and δ_{crit} of the composite. However, in terms of K_Q (5%) values, the Al6061 composite showed a value similar to that of the corresponding Al2124 composite. This was mainly attributed to premature yielding caused by the high ductility/low strength of the Al6061 matrix and to the testpiece dimensions.
- The effects of particle size on the fracture toughness depend on the type of matrix and toughness parameter used. In general, an increase in particle size decreased the K_Q (5%) value, but simultaneously increased the amount of plastic strain that the matrix is capable of accommodating, increasing both δ_{crit} and K_{crit} values.

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