# Analyses on fracture characteristics of $SiC_p$-6061Al/6061Al composites extruded by different ratios

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Two 6061 Al alloy matrix composites reinforced with rods that are themselves composites of the same Al alloy reinforced with a high volume fraction of SiC particles were studied. After vacuum pressure infiltration, one was hot extruded at a ratio of 10 : 1 and the other at a ratio of 60 : 1. The fracture characteristics of the two $SiC_p$-6061Al/6061Al composites were examined in detail. It was found that increasing the hot extrusion ratio of this kind of composite can improve the bonding between the $SiC_p$-6061Al bars and the 6061Al matrix. The strengths of the $SiC_p$-6061Al bars and the 6061Al matrix were considered to increase with increasing extrusion ratio. Thus, the $SiC_p$-6061Al/6061Al composite extruded at a ratio of 60 : 1 shows fracture characteristics which are different from the composite extruded at a ratio of 10 : 1. The former has a higher fracture toughness, and its crack opening displacement versus load curve indicates a higher elastic modulus and maximum load. After application of the maximum external load, there is a slow decrease with increasing crack opening displacement in the case of the 60 : 1 extruded composite, but the load can be maintained for wide crack opening displacement in the case of the 10 : 1 extruded composite. 

## 1. Introduction

It is well known that many conventional particle reinforced metal matrix composites (PMMCs) have disadvantages, not only in terms of low ductility and fracture toughness but also low fracture energy [1–3]. So, many PMMCs often fracture with little warning on application of a low external load and this limits their engineering applications. Many studies have shown that the presence of a high matrix triaxial stress condition [4, 5] and the localization of plastic deformation in the matrix [6–10] contribute to this. When a crack nucleates in a PMMC, the matrix under such a condition can not blunt it so the crack will propagate rapidly [6, 11]. Therefore, most conventional PMMCs are flaw-sensitive. In the past decade, some studies on ceramic matrix composites (CMCs) have shown that the flaw-sensitiving can be changed to flaw-tolerant behavior by lamination [12–16]. In the same way, many laminated and microstructurally toughened PMMCs have been studied recently [17–24]. The results have shown that such a structural design is an efficient way of improving fracture toughness and fracture energy of PMMCs. In our previous work [25–27], a type of structure-toughened $SiC_p$-6061Al/6061Al composite which has an architecture similar to continuous fiber reinforced composite was fabricated by vacuum pressure infiltration followed by hot extrusion. In the present paper, the fracture characteristics of two variants of this composite extruded at different ratios are discussed in detail.

## 2. Experimental materials and procedures

The fabrication method and microstructures of this type of $SiC_p$-6061Al/6061Al composite have been described previously [25, 27]. Two composites were hot extruded as rods with 12 mm diameter at ratios of 10 : 1 and 60 : 1. After hot extrusion, they have a structure which is similar to a continuous fiber reinforced composite. The 6061Al alloy matrix is reinforced by bars which are themselves composites of the same Al alloy reinforced with a high volume fraction of SiC particles and the $SiC_p$-6061Al bars are arrayed randomly in the

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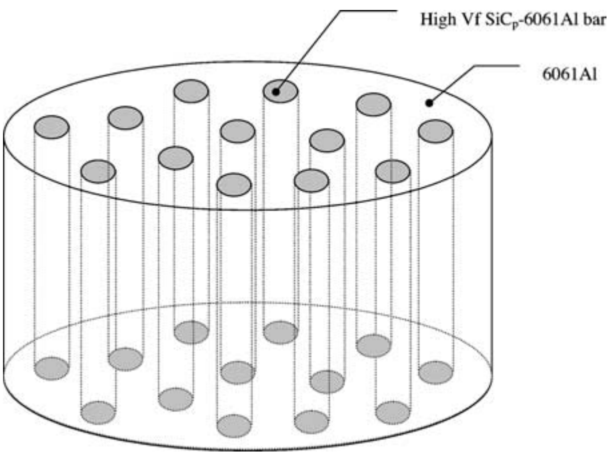


*Figure 1* Schemed structure of the $SiC_p$-6061Al/6061Al composite.

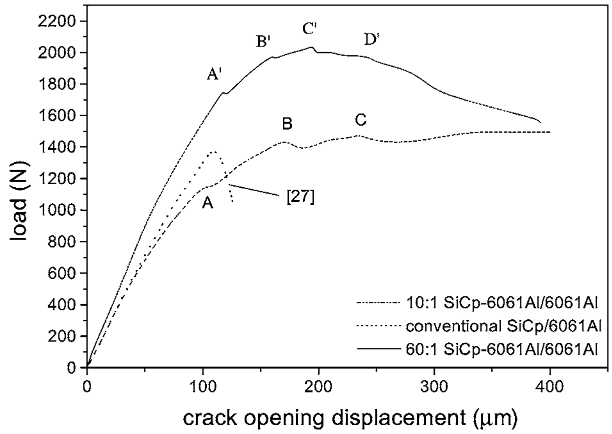


*Figure 2* The COD versus load curves of the two $SiC_p$-6061Al/6061Al composites.

matrix (Fig. 1). The volume fraction of SiC particles in $SiC_p$-6061Al bars and the total SiC volume fraction are 48% and 18% respectively in the composite extruded at a ratio of 10 : 1 (denoted as composite I), and are 45% and 15% respectively in the composite extruded at a ratio of 60 : 1 (denoted as composite II). The nominal size of the SiC particles in both the composites is 14 $\mu$m.

The fracture toughness and crack growth behavior of the two composites were evaluated by means of three point bending specimens with a single edge notch. 60 mm length, 10 mm thickness and 5 mm width rectangular specimens were cut along the extruded rods and notched with a root radius of 80 $\mu$m. All specimens were solution treated at 520°C for 1 hour, then quenched in water at 20°C followed by 8 hours of artificial aging at 160°C (T6 treatment). The bending test was performed on a MTS 810 machine. The cross head moved by a rate of 0.1 mm/min. Crack opening displacement (COD) versus load curves were recorded. Three specimens were tested for each composite. The fracture surfaces were observed using a PHILIP-S515 Scanning Electron Microscope (SEM).

## 3. Experimental results and discussions

The fracture toughness values of the two composites are listed in Table I. For comparison, the fracture toughness values for a conventional 6061Al matrix composite uniformly reinforced with 15 vol.% $SiC_p$ [27] and 6000 series aluminum alloys [28] are shown. The conventional $SiC_p$/6061Al composite was extruded at a ratio of 10 : 1 after stir-casting and has the same SiC particle size and heat treatment condition as the two composites studied in the present work.

It can be seen that the fracture toughness values of the two structure-toughened $SiC_p$-6061Al/6061Al composites are higher than that of the conventional $SiC_p$/6061Al composite. It is especially remarkable that the fracture toughness of the $SiC_p$-6061Al/6061Al composite extruded at 60 : 1 is close to the level of that of 6000 series aluminum alloys. Although the total $SiC_p$ volume fraction of the 10 : 1 extrusion ratio composite is slightly higher than the composite extruded at a ratio of 60 : 1, this is not likely to have a significant effect on fracture toughness [28–30]. Thus, increasing the extrusion ratio results in an improvement in the fracture toughness of the $SiC_p$-6061Al/6061Al composite.

Fig. 2 shows COD versus load curves of the two $SiC_p$-6061Al/6061Al composites and the conventional $SiC_p$/6061Al composite. Both $SiC_p$-6061Al/6061Al composites have a large fracture energy which is much higher than the conventional $SiC_p$/6061Al composite. Failures of the two structure-toughened composites are very different from that of the conventional composite. They show a similar stepped fracture process. Composite I fractures step by step from A-A to C-C (Fig. 3a) corresponding to points A, B and C in Fig. 2. Similarly, composite II fractures step by step from A′-A′ to D′-D′ (Fig. 3b) corresponding to points A′, B′, C′ and D′ in Fig. 2. There are, however, some differences between the two curves as follows.

From the initial linear regions of the curves, composite II shows a higher elastic modulus than composite I. The composite modulus ($E_c$) depends on the modulus of the matrix ($E_m$) and the reinforcement (the high $V_f$% $SiC_p$-6061Al bars) ($E_r$) and the volume fraction of the $SiC_p$-6061Al bars ($V_r$) according to the rule of mixture (ROM) in the case of perfect interfacial bonding [31],

$$E_c = E_r V_r + E_m(1 - V_r)$$

and $E_r$ is determined by,

$$E_r = E_p V_f + E_m(1 - V_f)$$

TABLE I The fracture toughness values of the two $SiC_p$-6061Al/6061Al composites, a conventional $SiC_p$/6061Al composite and 6000 series aluminum alloys

| Materials | Composite I | Composite II | Conventional $SiC_p$/6061Al [27] | 6000 series Al alloys [28] |
|---|---|---|---|---|
| Fracture toughness (MPa $\sqrt{}$m) | 23.3, 23.7, 23.4 mean data: 23.5 | 28.3, 28.9, 27.8 mean data: 28.5 | 21.6 | 27–35 |

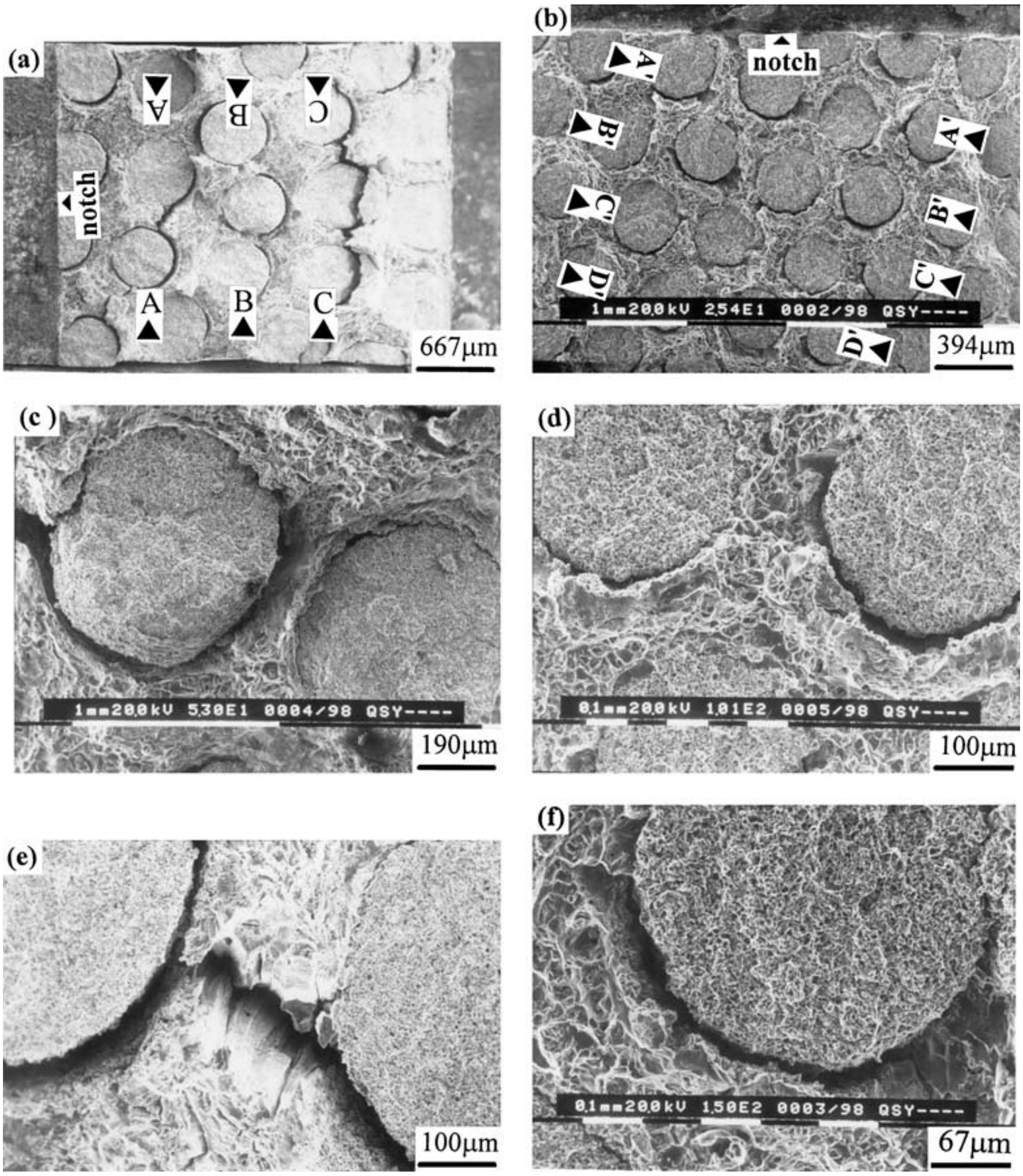


*Figure 3* Bending fractographies of the two structure-toughened composites (a) composite I fractures by stages, (b) composite II fractures by stages, (c) and (e) ($SiC_p$-6061Al)/(6061Al) interfacial debonding in composite I and (d) and (f) ($SiC_p$-6061Al)/(6061Al) interfacial debonding in composite II.

while $E_p$ and $V_f$ are the modulus and volume fraction of SiC particles in the $SiC_p$-6061Al bar, respectively.

In the present two composites, the moduli should be almost identical as the volume fractions of bars and SiC particle within them are similar. However, the interfacial bonding of composite II is better than that of composite I (Fig. 3) because the extrusion ratio of composite I (10 : 1) is much lower than that of composite II (60 : 1).

Further, the maximum load in the curve of composite II is higher than that of composite I. The processes after casting or infiltration, such as hot extrusion and hot rolling, can improve the mechanical properties of PMMCs and the extent of the improvement increases with increasing ratio of extrusion or rolling [32–34]. Since the extrusion ratio of composite II is much larger than that of composite I, not only is the ($SiC_p$-6061Al)/(6061Al) interfacial bonding improved but also the strength of the $SiC_p$-6061Al bars in composite II is higher than that in composite I. In addition, the matrix in composite II is more work hardened than that in composite I. That means that the yield strength and tensile strength of the 6061Al matrix in composite II are higher than those in composite I.

The gradual decrease in the load after the maximum in the curve of composite II, compared with the maintenance of the maximum for large displacements in the curve of composite I, can be accounted for by the decreased deformation capability of the more work hardened matrix in composite II.

The toughening mechanisms of this kind of structure-toughened composite are the debonding of the ($SiC_p$-6061Al)/(6061Al) interface and the deformation of the matrix [25, 27]. In composite I, the stress in the matrix between the $SiC_p$-6061Al bars does not reach the fracture strength of the 6061Al alloy at the maximum load (point C in Fig. 2). So, the 6061Al matrix can still deform and support some load after all the $SiC_p$-6061Al bars have fractured. At the same time, there is interfacial debonding. The fracture process of composite I is shown schematically in Fig. 4.

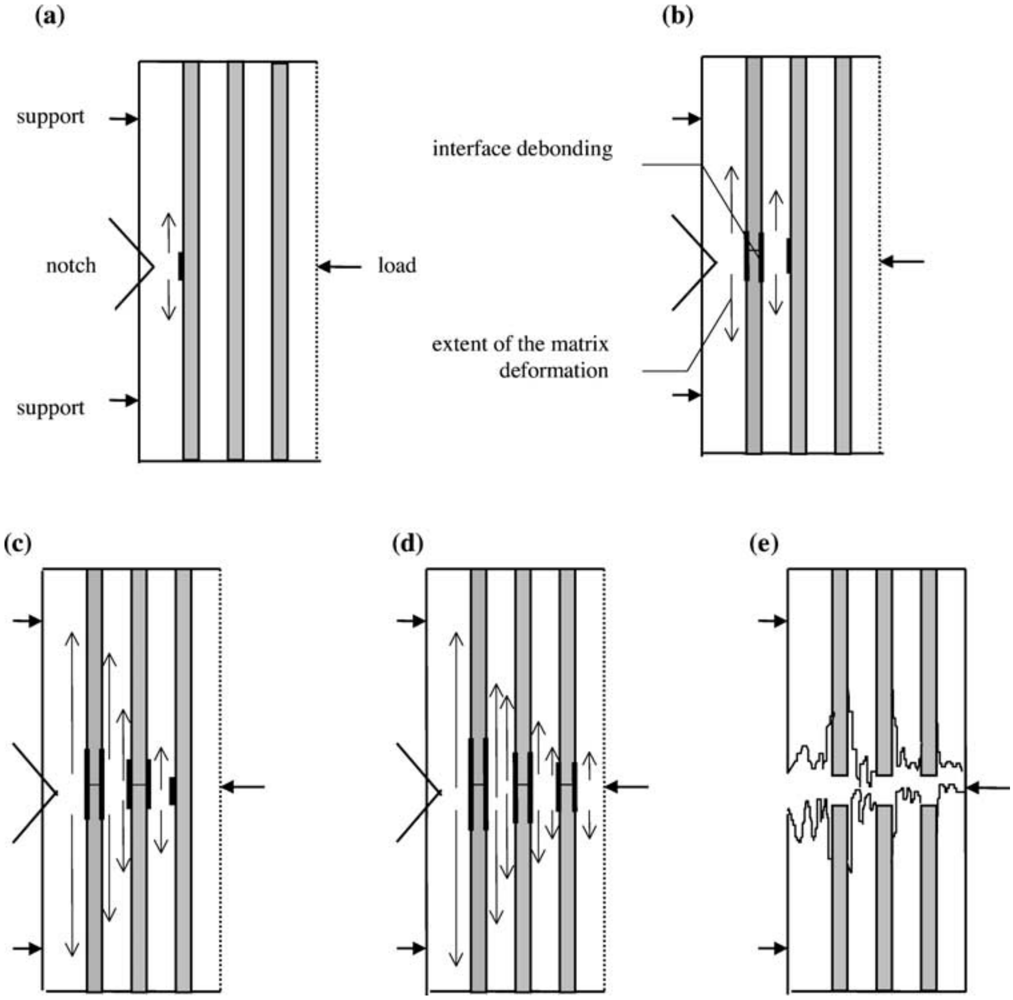


*Figure 4* Schematic illustration of the fracture process in composite I COD increases from (a) to (e).

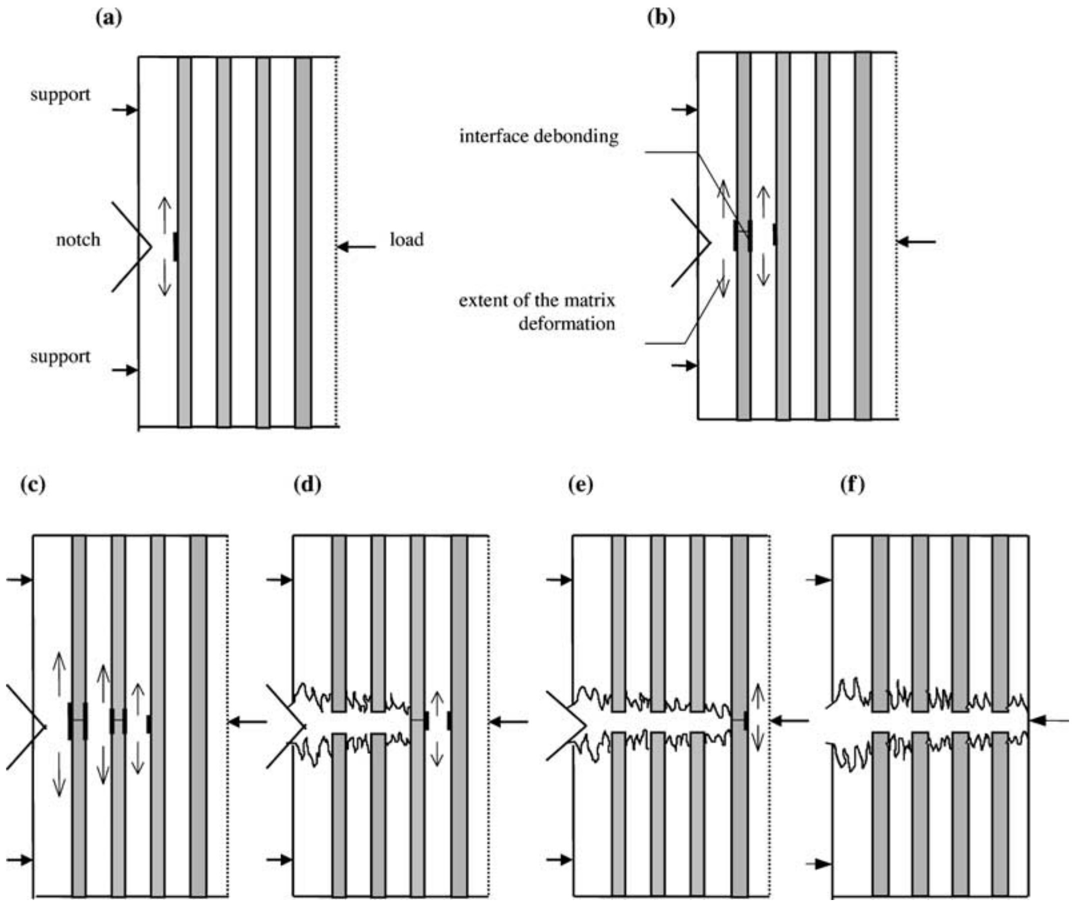


*Figure 5* Schematic illustration of the fracture process in composite II COD increases from (a) to (f).

However, in composite II, the stress in the matrix is close to the fracture strength of 6061Al alloy when the external load reaches a maximum (point C′ in Fig. 2). So, when the $SiC_p$-6061Al bars on the C′-C′ section in Fig. 3b fracture, the matrix between the notch and the C′-C′ section will fail. The loading area of the composite is decreased and its load bearing capability decreases slowly. But the stepped fracture model of composite II does not change and will remain until the composite fails completely. The fracture process of composite II is shown schematically in Fig. 5. In this type of structure-toughened $SiC_p$-6061Al/6061Al composite, increasing the extrusion ratio can improve the modulus, strength and fracture toughness of the composite but decrease the deformation capability of the unreinforced matrix.

## 4. Conclusions

From the above analyses of the fracture processes of the two $SiC_p$-6061Al/6061Al composites, it can be concluded that increasing the hot extrusion ratio of the composite can increase the fracture toughness of this kind of composite. In the COD versus load curves, both the composites show similarly stepped fracture processes. However, increasing the extrusion ratio increases the ($SiC_p$-6061Al)/(6061Al) interfacial bonding and the strengths of the $SiC_p$-6061Al bars and the 6061Al matrix, so the composite extruded at a ratio of 60 : 1 has a higher elastic modulus and higher maximum load. The load bearing capability decreases slowly once the maximum has been reached in the COD versus load curve of the composite extruded at a ratio of 60 : 1 but is maintained for large displacements in the case of the composite extruded at a ratio 10 : 1. This is because the fracture strength of the matrix of the 60 : 1 extruded composite is reached whereas the 10 : 1 extruded composite can continue to deform until the composite fails completely.


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