Effect of different reinforcements on composite-strengthening in aluminium

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Abstract. In the development of metal-matrix composites, reinforcements of aluminium and its alloys with ceramic materials has been pursued with keen interest for quite sometime now. However, a systematic comparison of the effect of different reinforcements in powder-processed aluminium and its alloys is not freely available in the published literature. This study examines the influence of SiC, TiC, TiB_2 and B_4C on the modulus and strength of pure aluminium. B_4C appears slightly superior as a reinforcement when comparing the effect of SiC, TiC, B_4C and TiB_2 on specific modulus and specific strength values of composites. However, TiC appears to be a more effective reinforcement, yielding the best modulus and strength values among those considered in this study. The differences in thermal expansion characteristics between aluminium and the reinforcements do not seem to explain this observation. The other advantage of TiC is that it is economically a more viable candidate as compared to B_4C and TiB_2 for reinforcing aluminium alloys. It is suggested that the superior effect of TiC as a reinforcement is probably related to the high integrity of the bond at the Al–TiC interface.

1. Introduction

Discontinuously reinforced aluminium and aluminium alloy composites are increasingly being developed and used in a variety of applications. By and large, ceramic materials in the form of particulates, whiskers or fibres are used for the fabrication of these composites. A great deal of attention has been focussed on the development of aluminium alloys containing SiC in the form of particulates or whiskers (Divecha *et al* 1981; Nair *et al* 1985; Dolowy 1986). The incorporation of SiC reinforcements results in an improvement in the physical and mechanical properties as compared to those of the unreinforced matrix alloy. These improved properties include high strength and specific modulus, high creep strength, high fatigue resistance, low thermal expansion and good thermal stability.

The major approaches for producing these composites are powder metallurgy (extrusion), squeeze infiltration of ceramic preforms and compocasting techniques. Of these various routes, the powder metallurgy technique is very popular, particularly for the fabrication of particulate-reinforced composites, because it results in composites with superior properties as compared to cast composites.

SiC is most widely used for composite strengthening of aluminium alloys. The high modulus and strength of SiC and its compatibility with aluminium makes it a very attractive choice for reinforcement. B_4C also finds application in composite-strengthening of aluminium alloys because of its low density (as compared to many other reinforcements) and reasonably high modulus of elasticity

(Girot *et al* 1987). The possibility of producing fine dispersions of materials like TiB_2 via reactive sintering in an aluminium alloy matrix (Christodonlon *et al* 1986) makes this an attractive choice for reinforcement as well. Table 1 lists the variety of processes used in reinforcing aluminium with different reinforcements. However, there has been no report of any systematic study where different reinforcements have been evaluated using a single processing technique.

In the light of these observations, this study was undertaken to compare the effect of four potential ceramic reinforcements, namely, SiC, B_4C, TiC and TiB_2 in commercially pure aluminium. These composites were fabricated by powder processing. Such a study would help in making cost-effective choice of reinforcements for aluminium alloy matrices.

2. Experimental procedure

The composites were fabricated using powder metallurgy techniques. The particulate reinforcements were SiC, B_4C, TiB_2 and TiC, the sizes of which are given in table 2. A consistent volume fraction of 20% was used for all these reinforcements. Air-atomized aluminium powder having an average particle size of 50 μm was used as the matrix material. The powder was supplied by the Metal Powder Co., Madurai, India.

The processing steps are schematically shown in figure 1. Initial processing involved deagglomeration of the reinforcement particulates in a polar solvent medium using an agate pot mill. This was followed by wet mixing of aluminium

Table 1. Variety of reinforcements and manufacturing routes for aluminium matrix composites.

Material	Process	Reference
Al + 20% SiC_p	PM	Arsenault and Shi (1988)
Al + 20% B_4C	Conform extrusion	Slater and Coon (1988)
Al + Mg–Be + 18% TiB_2	Compocasting	Mccoy *et al* (1988)
7075 Al + 15% TiB_2	XD™	Christodoulou *et al* (1986)
Al–Zn–Mg–Cu–Co + 15% TiC	PM	Macdonald and Ransley (1954)

*PM–powder metallurgy; XD™–Martin Marietta's proprietary process.

Table 2. Characteristics of various ceramic reinforcements.

Rein-force-ment	Particle size (μm)	Density[a] (g/cc)	E (GPa)	CTE ($\times 10^{-6}$/°C)	Manufac-turer	Grade	Relative cost factor
B_4C	1·2	2·52	480[b]	4·5[c]	Hermann C-Starck	HP	6·15
TiC	1·4	4·92	320[b]	7·4[c]	Hermann C-Starck	Standard	1·98
SiC	1·5	3·21	480[b]	4·7[c]	Superior Graphite	056	1·0
TiB_2	4	4·52	430[a]	8·28[a]	Elektroschmelz-werk Kempten GmbH	—	2·9

[a]Lynch *et al* (1966); [b]Girot *et al* (1987); [c]Kingery *et al* (1976).

Reinforcement

Aluminium powder

Deagglomeration

Wet blending

Drying

Cold isostatic pressing

Degassing, 450°C

Sintering, 600°C
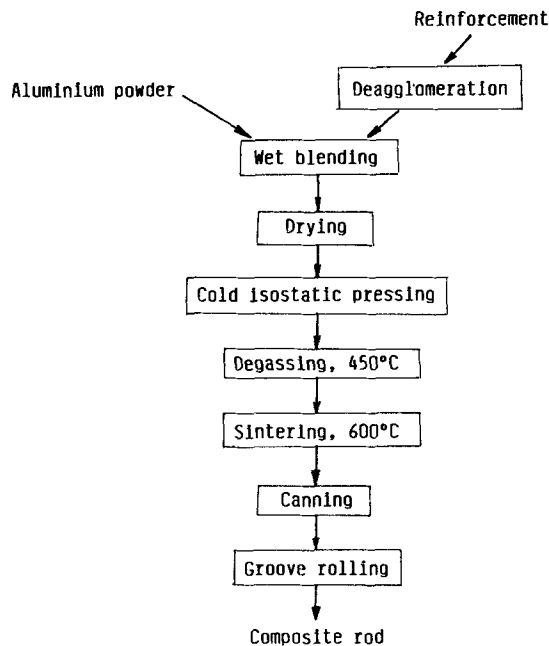
Canning

Groove rolling

Composite rod

Figure 1. Process route for the fabrication of composites.

powder with the deagglomerated particulate slurry by horizontal tumbling in a roller mill. The mixture thus obtained was dried, cold isostatically pressed, degassed at 450°C in vacuum and sintered at 600°C.

The sintered compacts were rolled at 500°C using a canning process which yielded composite rods of 6–8 mm diameter. The effective reduction in area of the composite on rolling was 95% which rendered this consolidation step effective.

Microstructural evaluation involved metallographic polishing and preparation of the composite samples and examination under the scanning electron microscope. The elastic moduli of the composites were measured on machined samples using a resonance technique (by analysing the vibrational behaviour of the sample following an impulse excitation) (Chakraborty *et al* 1989).

The densities of these composites were measured by water displacement. Tensile test samples having a gauge diameter of 4 mm and a gauge length of 25 mm were machined from the rods and tested at a strain rate of 6.6×10^{-4}/s.

3. Results and discussion

The resultant composite microstructures of the four composites are shown in figure 2. These are SEM micrographs of metallographically polished samples. The reinforcement particulates, in all the four cases, appear well-distributed in the matrix and the microstructure does not reveal any porosity. This implies that the processing sequence, including sintering and rolling, has been extremely effective in producing integral composites. The particle sizes and distribution of TiC, B_4C and SiC are comparable whereas those of TiB_2 are slightly larger. The average particle sizes of the reinforcements are shown in table 2.
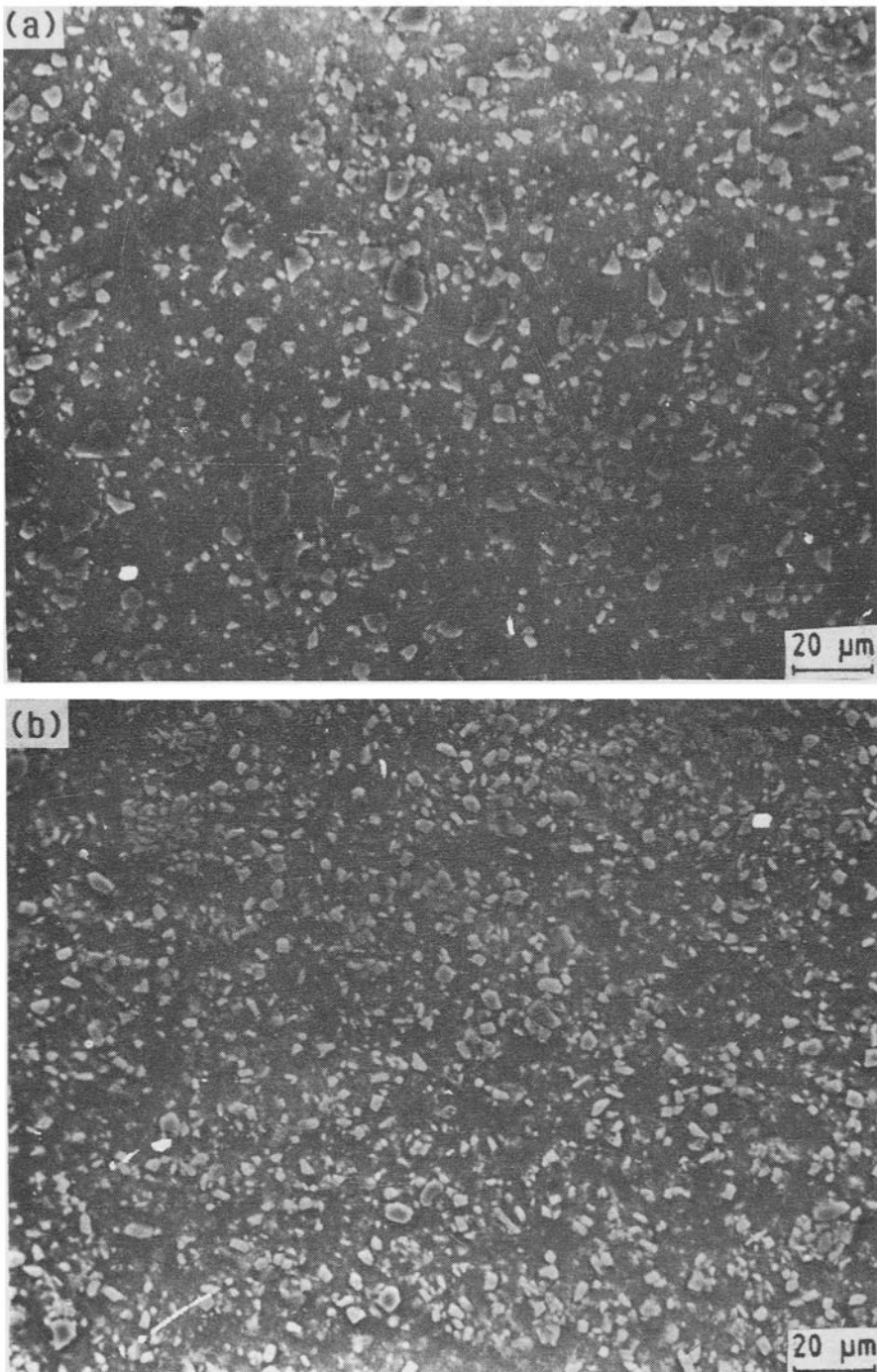
Figure 2. SEM micrographs of composites, (a) Al/SiC, (b) Al/TiC.

The densities of the composites are shown in table 3. These values lie very close to the theoretical values, thus confirming the efficiency of the various processing steps and the "sinter + rolling" technique for consolidation of these composites.
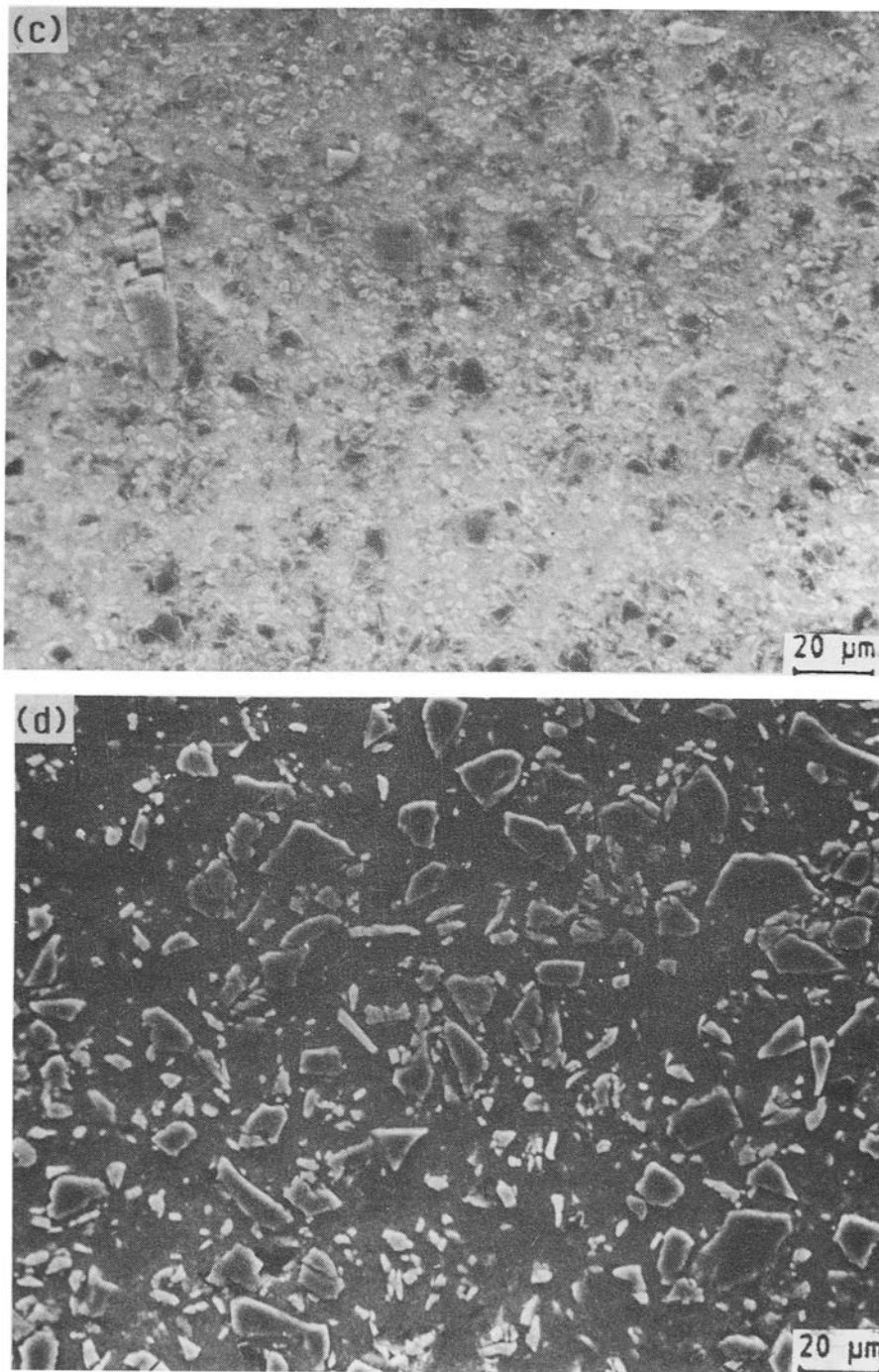
Figure 2. SEM micrographs of composites, (c) Al/B_4C, (d) Al/TiB_2.

The elastic moduli and specific elastic moduli of the composites are shown in table 3 along with that of pure aluminium for comparison. All the reinforcements considered here improve the elastic moduli of aluminium significantly. The Al/TiC

Table 3. Mechanical properties of aluminium matrix composites.

Composite	Density (g/cc)	E (GPa)	ROM-E (GPa)	Specific modulus (GPa/ g/cc)	YS (MPa)	UTS (MPa)	Specific UTS (MPa/ g/cc)	Elongation (%)
Pure Al	2·72	70	—	26·9	64	90	33	21
Al/SiC	2·77	102	152	36·8	117	200	70·3	10
Al/TiC	3·14	116	120	36·9	148	233	74·1	9
Al/B$_4$C	2·75	105	152	38	143	208	75·4	9·2
Al/TiB$_2$	3·05	96	143	31·5	121	166	54·5	16

composite has a value of 116 GPa for the elastic modulus as compared to 96, 102 and 105 GPa, respectively, for Al/TiB$_2$, Al/SiC and Al/B$_4$C composites. Compared to the elastic modulus of aluminium, which is 70 GPa, the Al/TiB$_2$ composite displays a 37% higher elastic modulus. Prior work has shown the modulus values of powder-processed Al/20% B$_4$C to be 96 GPa (Nieh and Chellman 1984) whereas it was shown to be 122 GPa when the processing was by conform extrusion (Slater and Coon 1988). Of the four reinforcements considered here, the contribution of B$_4$C appears superior when comparing specific moduli. However, considering that the density of B$_4$C is about 50% that of TiC and that the specific moduli of Al/B$_4$C and Al/TiC are not vastly different, it can be inferred that TiC is a more potent reinforcement in aluminium. Though the specific moduli of Al/TiC and Al/SiC are nearly the same, it should be noted that the density of SiC is only about 65% that of TiC. The greater effectiveness of TiC in improving the modulus of aluminium as compared to the other reinforcement, is thus further established.

The elastic moduli predicted by calculations based on the rule of mixtures (using the modulus values for the reinforcements given in table 2) are also shown alongside the observed values in table 3 under the heading ROM-E. The most interesting observation is that the observed value (116 GPa) is closest to the predicted value (120 GPa) in the Al/TiC composite. In the Al/B$_4$C, Al/SiC and Al/TiB$_2$ composites, the observed values are considerably lower than the predicted values. Since the rule of mixtures essentially assumes that there is an effective transfer of the load from the matrix to the reinforcement through the interface, the present observation suggests that the interface in the Al/TiC composite is superior in some way when compared to the other composites. This is also possible indication of the integrity of the composite and the efficiency of the reinforcement in composite strengthening. This comparison also makes it clear that TiC is a more potent reinforcement in aluminium when compared to B$_4$C, SiC and TiB$_2$.

The tensile test results are also recorded in table 3. The strength and ductility (% elongation) of identically-processed aluminium is also shown for comparison. The Al/TiC composite displays a UTS of 233 MPa as compared to 200, 208 and 166 MPa, respectively, for Al/SiC, Al/B$_4$C and Al/TiB$_2$ composites. Ductilities, expressed as % elongation, are of the order of about 9–10% for Al/SiC, Al/TiC and Al/B$_4$C as compared to 16% for Al/TiB$_2$. Slater and Coon (1988) have reported a UTS of 190 MPa for the Al/20% B$_4$C composite produced by conform extrusion which is lower than the 208 MPa observed in this study. This is indicative of the efficiency of the sinter + rolling sequence used in the consolidation of these composites. Using spray-deposition and hot-rolling (500°C), Singer and Ozbek

(1985) have produced Al/22–28% SiC_p which showed UTS values of 153 MPa as compared to 200 MPa observed here. In addition the spray-deposited and hot-rolled product displayed only 1% elongation before failure. Arsenault and Wu (1988), however, have reported values of 250 MPa for UTS in Al/20% SiC_p produced by powder metallurgy. The average particle size of SiC_p used in that study was 0·5 μm whereas, in the present, it was 1·5 μm, which could account for the difference in the strength values. Chellman and Slaughter (1983) have reported a UTS value of 199 MPa for Al/19% SiC_p which is comparable to the strength obtained in this study. Among the four reinforcements considered, TiC appears to have the maximum effect in composite strengthening.

Arsenault and Shi (1986) have proposed that the major component of the increase in strength, when reinforcing a matrix, results from the differences in the coefficient of thermal expansion between the matrix and the reinforcement which help to generate interfacial dislocations during heating/cooling while processing. In essence, for a given volume fraction of reinforcement,

$$\Delta\sigma\alpha \; \frac{\Delta CTE}{particle\ size},$$

where $\Delta\sigma$ is the major component of composite strengthening which is proportional to ΔCTE which is the difference in the coefficient of thermal expansion. Considering the coefficients of thermal expansion of these reinforcements (as shown in table 2), the increase in strength resulting from this component would be maximum for Al/SiC and Al/B_4C, (CTE for Al is $22.4 \times 10^{-6}/°C$) followed by Al/TiC (the particle sizes are similar – table 2). Since the increase in strength due to other reasons like reduction in subgrain size etc. remain relatively small in all the cases (Arsenault and Shi 1986), the effect that is predicted by this argument is contrary to the observation in this study where maximum strengthening is observed in the Al/TiC composite. This would suggest that the effectiveness of TiC may be related to the interface of Al and TiC more than anything else. Though a comparison of hardness values of the reinforcements may be applicable more in the case of continuous reinforcements, it is still worthwhile to note that TiC is harder (KHN of 3170 kg/mm^2) than B_4C and SiC (2800 and 2740–2960 respectively). These three reinforcements have comparable particle sizes in this study.

A comparison of the specific strength shows that the improvement in strength obtained by adding a low density reinforcement like B_4C as compared to that obtained by adding TiC (which is 2 times denser than B_4C) is only marginal. The Al/TiC composite appears to be superior even to the Al/SiC composite. These observations, thus reinforce the inference that TiC is a very potent reinforcement in aluminium. It has also been observed in cast aluminium containing refractory Ti compounds that TiC is more effective in increasing the hardness of the composite than either TiB_2 or TiN (Baturinskaya *et al* 1983).

It is essential to normalize these results with respect to particle sizes in order to have a fair comparison. The particle sizes of TiC, B_4C and SiC are similar. Comparing TiC and B_4C, the Al/TiC composite appears superior in spite of the fact that TiC is slightly larger than B_4C. Among reinforcements of comparable size, TiC appears to be more effective.

Fractographs of the fractured tensile samples are shown in figure 3. They display dimples on the fracture surfaces with dimple sizes being more or less the same in all
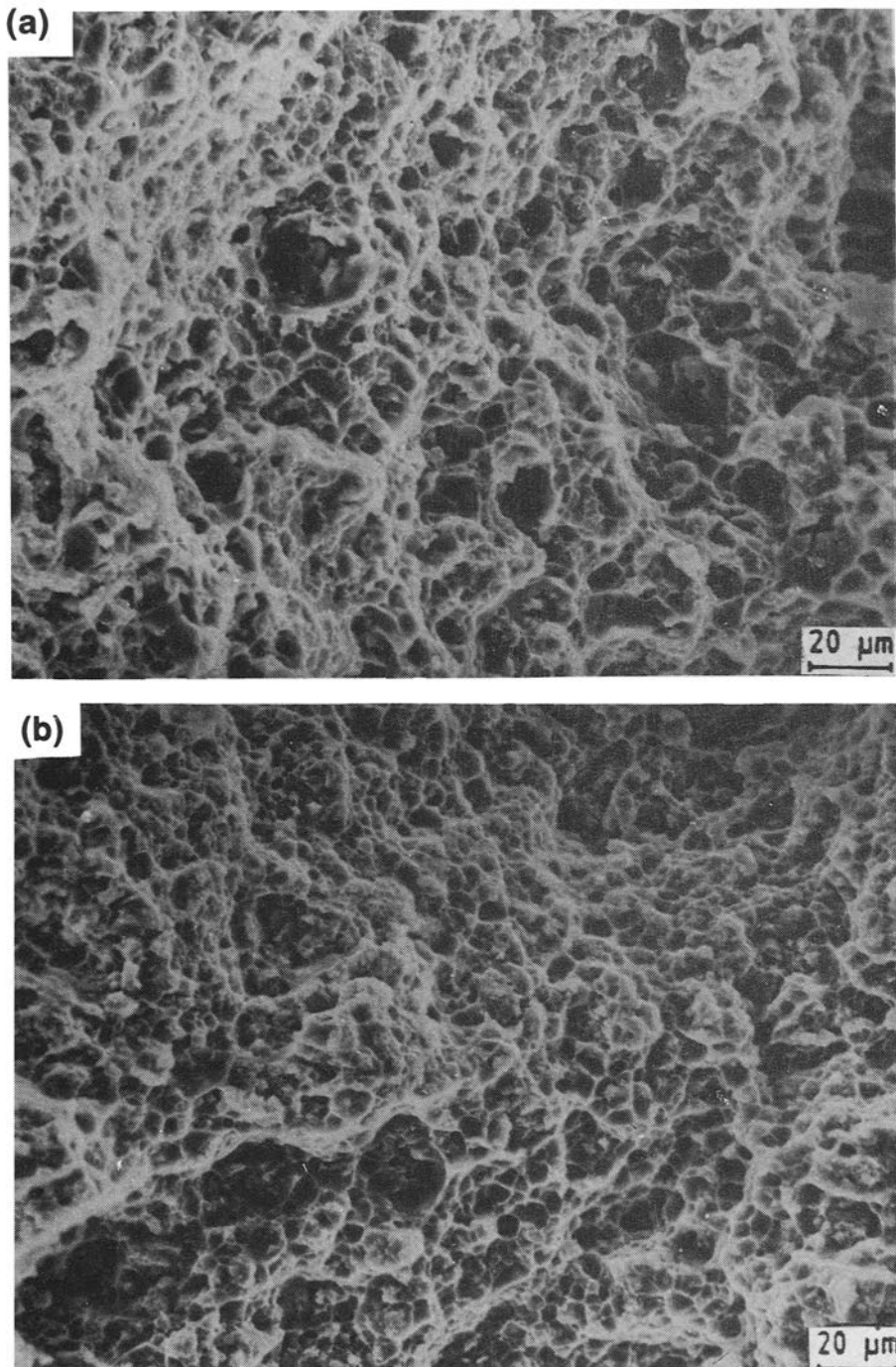
Figure 3. Fractographs of composite samples tested in tension, (a) Al/SiC, (b) Al/TiC.

the composites except that containing TiB_2, in which the dimple sizes are slightly larger. This increase in the dimple size corresponds to the larger interparticle
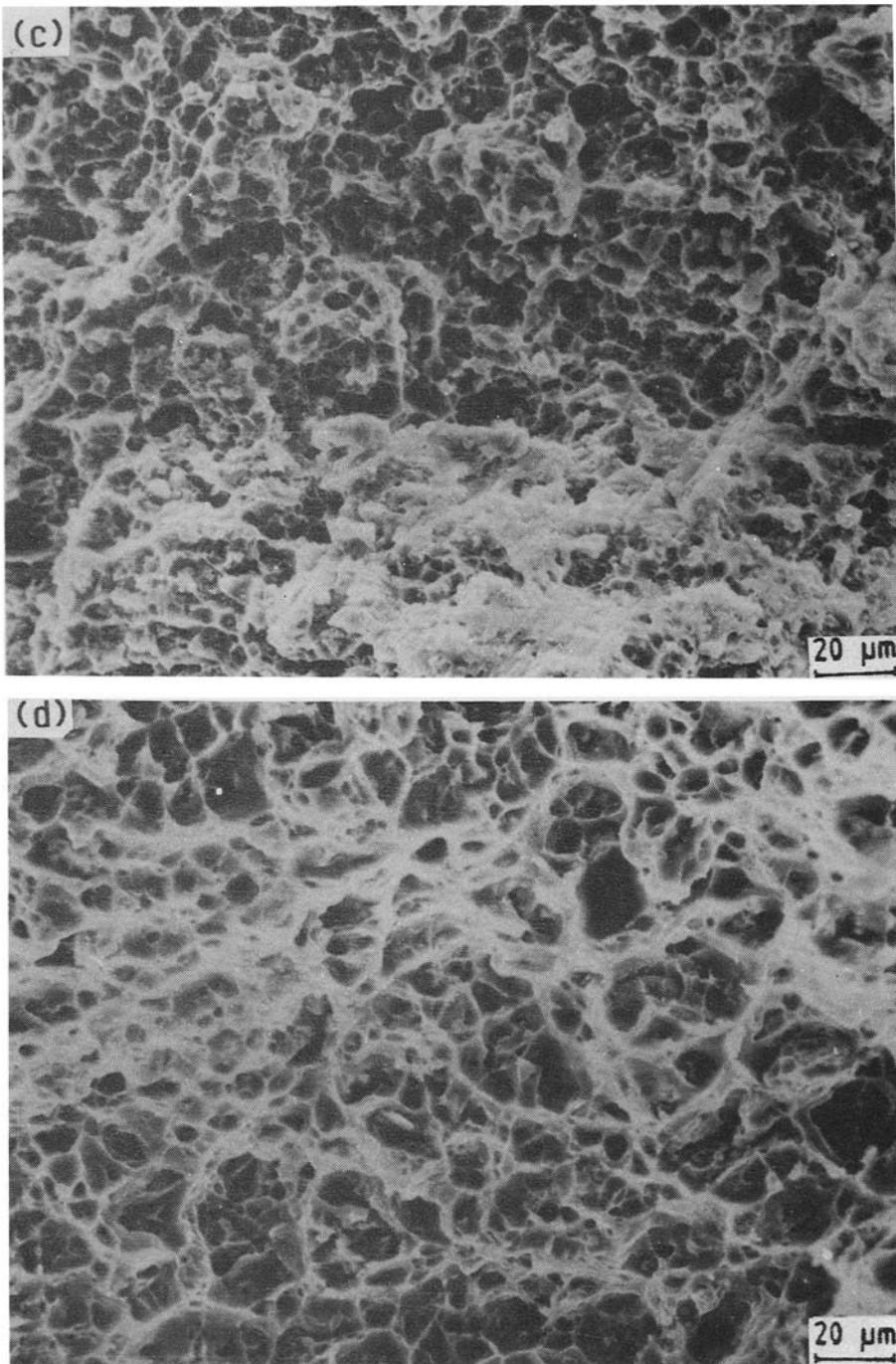
Figure 3. Fractographs of composite samples tested in tension, (c) Al/B$_4$C, (d) Al/TiB$_2$.

spacing as a result of the larger particle size of TiB$_2$. It is interesting to note that the highest ductility was observed in the Al/TiB$_2$ composite which also corresponds

to the coarsest particle sizes of the reinforcements considered. The fracture surfaces do not display major differences to show any variation in the effect of the reinforcement on the matrix.

In order to examine the interface of the reinforcement and the matrix, a sample from the Al/TiC composite was examined in a transmission electron microscope. The Al/TiC was chosen because of its superior properties as compared to the other composites. The electron micrograph is shown in figure 4. It is clear from these micrographs that there is no interfacial reaction of any kind and the interface remains clearly delineated.

Any choice of reinforcement would also include a cost factor when choosing composites for most applications. A column showing the relative cost (relative to the cost of SiC taken as 1) per kilogram of the reinforcement is included in table 2. It is clear from this table, that SiC would be the natural choice from the point of view of cost and the reasonably good properties that Al/SiC composites display. It is interesting to note that though TiC is more expensive than SiC (by almost a factor of 2), it is still considerably cheaper than B_4C (by a factor of 3). Considering that there is an effort to use B_4C for composite strengthening in aluminium, TiC would be a more efficient choice in terms of both cost and strengthening of the matrix.

3. Conclusion

Four different reinforcements, namely SiC, TiC, B_4C and TiB_2 have been added to the aluminium matrix in order to evaluate their effectiveness in composite strengthening. Of the three reinforcements which have comparable particle sizes (i.e.
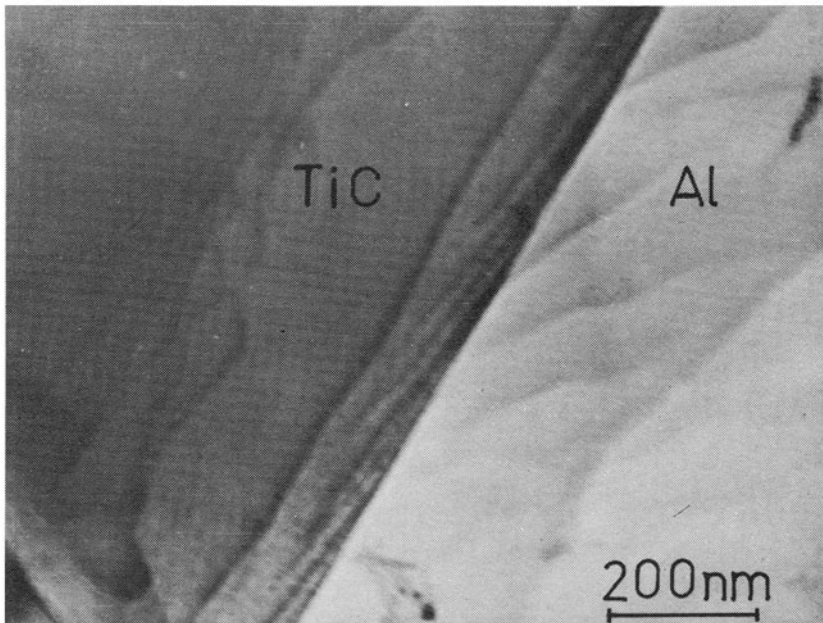

Figure 4. TEM micrograph showing the clean Al/TiC interface.

SiC, TiC and B_4C), TiC appears to be the most potent in aluminium. A comparison of thermal expansion characteristics show that differences in the coefficients of thermal expansion between the matrix and the reinforcement does not explain the trend in strengthening observed here. In fact, the trend appears to be more consistent with the hardness values of the reinforcements. The effectiveness of TiC in composite strengthening is, therefore, most likely due to the nature of the interface in the Al–TiC system which permits an efficient transfer of load from the matrix to the reinforcement.

Acknowledgements

References

Arsenault R J and Shi N 1986 *Mater. Sci. Eng.* **81** 175

Arsenault R J and Wu S B 1988 *Scr. Metall.* **22** 769

Baturinskaya N L, Kol'chuk N A, Servetskaya M G and Chernyi V G 1983 *Izv. Akad. Nauk. SSSR Met.* **3** 166 (*Chem. Abst.* **99** 57356)

Chakraborty A, Bhaduri S B, Reddy J J, Mohan Rao R and Mahajan Y R 1989 *Proc. ICF-7* **4** *Advances in fracture research* (eds) K Salama, K Ravichander, D M R Taplin and P Rama Rao (Oxford: Pergamon Press) p. 2905

Chellman D J and Slaughter H C 1983 *Investigation of 1100 Al alloy systems reinforced with discontinuous silicon carbides*, Presented at 112th AIME Annual Meeting, Atlanta, Georgia, March 6–10, 1983

Christodoulou L, Nagle D C and Brupbacher 1986 *Aluminum-ceramic composites*, Int. Pat. No. WO86/06366

Divecha A D, Fishman S G and Karmarkar S D 1981 *J. Met.* **33** 12

Dolowy J F 1986 *Light Met. Age* **44(6)** 9

Girot F A, Quenisset J M and Naslain R 1987 *Compos. Sci. Technol.* **30** 155

Kingery W D, Bowen H K and Uhlmann D R 1976 *Introduction to ceramics* (New York: John Wiley & Sons) p. 595

Lynch J F, Ruderer C G and Duckworth W H 1966 *Engineering properties of selected ceramic materials* (Columbus, Ohio: Am. Ceram. Soc.)

Macdonald N F and Ransley C E 1954 Proc. of Symp. on Powder Metallurgy *Metal Powder for Engineering purposes* (London: The Iron and Steel Institute and Institute of Metals)

Mccoy J W, Jones C and Wawner F E 1988 *SAMPE Q.* **19(2)** 37

Nair S V, Tien J K and Bates R C 1985 *Int. Metall. Rev.* **30** 275

Nieh T G and Chellman D J 1984 *Scr. Metall.* **18** 925

Singer A R E and Ozbek S 1985 *Powder Metall.* **28(2)** 72

Slater H K and Coon P M 1988 Proc. Fourth Int. Al extrusion Tech. Seminar, **2**, Chicago (Washington D.C.: The Aluminum Association) p. 525