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Effect of Ceramic Reinforcements on the Mechanical Behaviour of 7xxx series Aluminium Matrix Composites

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Abstract: The effect of ceramic reinforcements on the mechanical properties of 7xxx series aluminium matrix composites (AMCs) was critically reviewed. Reinforcement of an Al 7xxx alloy with ceramic particulates is expected to improve its tensile strength but in practice the incorporation has produced diverse results. Some researchers have reported significant increases in the tensile strengths of particulate reinforced 7xxx Al matrices while others have reported decreases in this property. The published data including our present experimental work performed on particulate reinforced Al 7xxx alloys was analysed to study the role of ceramic particulates on the tensile and fracture behaviour of this class of composites. It was concluded that high strength of the matrix can negate the benefits of particulate reinforcements though this role is still ambiguous and further work is required to optimise the potential enhancement of Al 7xxx matrix composites reinforced with nano-scale ceramic particles.

Keywords: aluminium-matrix composites, mechanical properties, ceramic-particulates, micro-scale, nano-scale.

1 Introduction

Among aluminium alloys Al 7xxx series alloys enjoy the highest strength to weight ratio and therefore have found wide applications in the automobile and aerospace industries. However, these alloys lose their high strength rapidly when they are exposed to elevated temperatures. This rapid decline in the strength is directly related to the coarsening of very fine precipitates which are then not as effective in obstructing the dislocations. Incorporation of micro-scale and nano-scale particulates in the aluminium systems can greatly enhance their mechanical characteristics. Some material researchers have shown [1-3] that the particulate reinforced aluminium matrix composites (PR AMCs) can be used above 300°C-400°C, which may make them competitive with costly Ti alloys at elevated temperatures. To the best of our knowledge, unlike other PR AMCs (2xxx, 6xxx series) [4-8] including the majority of other AMCs, reinforcement of Al 7xxx series alloys with ceramic particulates has produced inconsistent results. Therefore, the purpose of this paper was to study the mechanical behaviour of these composites and develop a better understanding of the role of ceramic reinforcements in these composites.

2 Tensile properties

The mechanical behaviour of PR AMCs is a function of many micro-structural variables, such as the matrix alloy, the reinforcing material, the volume fraction, the size and shape of the particulates and the heat treatment of the composite material [9-12].The motive behind the development of metal matrix composites (MMCs) has been to enhance the performance of a ductile material with the inclusion of high strength reinforcement material (ceramics). The research to date has not conclusively shown that ceramic particulates are effective in improving the tensile properties of high-strength Al 7xxx series alloys. Doel et al. [13] reported that for a constant volume fraction (15 vol.%) of SiC particulates (p) increasing the particle size from 5µm to 13µm first increased the yield strength (YS) of the Al7075 alloy by 7.7% but then increasing the particle size further to 60µm decreased it by 9.2% below that of the unreinforced alloy. Similarly, 15 vol.% SiC_p/Al7075 composite has demonstrated lower YS at room temperature but slightly higher YS above 250°C as compared to monolithic Al7075 [14]. In SiC(5-16µm) particulate reinforced Al7091 composites a significant increase (32-48%) in the stiffness was achieved at the cost of a decline in the tensile strength [15]. Pandey et al. [16] observed 70% and 13.4% increase in the stiffness and YS respectively of 15 vol.% SiC_p(10µm)/Al7093 composites. Kang [7] reported a reduction in the strength of 10 vol.% SiC_p(13µm)/Al7775 composites but a 9% enhancement in the strength by incorporating 1 vol. % nano-scale SiC_p(50nm). These results suggest a benefit in using nano-scale as opposed to micro-scale particles for the reinforcement. Our tensile test results for 1-5 vol.% SiC_p(50nm)/Al7775 composites [17], shown in Figure 1, are however contrary to those of Kang [7] as we observed a reduction in the strength. Despite only limited enhancement or sometimes a reduction in the tensile strength reported for Al 7xxx series MMCs, the incorporation of ceramic particulate in an Al 7xxx series matrix drastically reduces its ductility and fracture toughness [7,13-17] which hampers the wide spread use of these composites. The strength and ductility decreases with higher volume fractions of particulates [7,11,15]. Increase in particulate size also gives large reduction in ductility [13,15]. Interparticle spacing is considered as the most important factor to determine the fracture toughness of the composites [13].The tensile properties of particulate reinforced Al 7xxx composites reported by a range of researchers are compiled in Table 1.

Table 1 Tensile properties of particulate reinforced Al 7xxx composites

Materials	Particle size (μm)	Volume fraction (%)	Elastic Modulus (GPa)	YS (MPa)	TS (MPa)	Elong-ation (%)	Increase YS (%)	Increase TS (%)	Fracture Toughness (MPa√m)	Temp. (°C)	Ref.
Al7075	-	-	-	552 ^{b}	619	24*	-	-	-	RT	
Al7075/SiC	5	15	-	570 ^{b}	630	10*	3.2	1.7	15.7	RT	
Al7075/SiC	13	15	-	595 ^{b}	645	4.8*	7.7	1.2	13.6	RT	[13]
Al7075/SiC	60	15	-	501 ^{b}	504	1*	-9.2	-18.5	18.5	RT	
Al7075	-	-	-	505	590	15	-	-	-	RT	
Al7075/SiC-T6	14	15	-	478	543	7	-5.3	-7.9		RT	
Al7075	-	-	-	174	185	30	-	-	-	250	
Al7075/SiC-T6	14	15	-	192	202	17	10.3	9.1	-	250	[14]
Al7075	-	-	-	33	37	104	-	-	-	400	
Al7075/SiC-T6	14	15	-	33	37	46	0	0		400	
Al7075	-	-	66.4	577 ^{b}	603	11.8	-	-	-	RT	
Al7075/SiC	50nm	1	62.9	471 ^{b}	505	9.8	-18.3	-16.2	-	RT	
Al7075/SiC	50nm	5	72	485 ^{b}	514.3	6.1	-15.9	-14.7	-	RT	
Al7075	-	-	57.1	260.5 ^{b}	262.2	50.4	-	-	-	215	
Al7075/SiC	50nm	1	55.2	237 ^{b}	239.5	33.6	-9	-8.6	-	215	[17]
Al7075/SiC	50nm	5	58	244 ^{b}	245	19.5	-6.3	-6.5	-	215	
Al7075	-	-	39.2	43.5 ^{b}	44.4	86.8	-	-	-	350	
Al7075/SiC	50nm	1	43.2	44.5 ^{b}	47	74	2.5	5.8	-	350	
Al7075/SiC	50nm	5	33.2	43.6 ^{b}	44.3	38	0.2	-0.2	-	350	
Al7091-T6	-	-	68.5	520	590	10.2	-	-	33	RT	
Al7091/SiC-T6	5	15	90.7	480	530	3.1	-7.7	-10.1	-	RT	
Al7091/SiC-T6	16	15	99.1	490	535	1.1	-5.7	-9.3	-	RT	[15]
Al7091/SiC-T6	5	20	94.1	400	470	1.9	-23	-20.3	14	RT	
Al7091/SiC-T6	16	20	101.4	500	560	1.8	-3.8	-5	16	RT	
Al7093-T6	-	-	67.5	566	622	10	-	-	-	RT	[16]
Al7093/SiC-T6	10	15	95.6	642	694	1.8	13.4	11.5	15.7	RT	
Al7775-T6	-	-	-	534 ^{b}	592	13	-	-	-	RT	
Al7775/SiC-T6	13	10	-	507 ^{b}	566	7	-5	-4.4	-	RT	[7]
Al7775/SiC-T6	50nm	1	-	583 ^{b}	635	7	9.1	7.2	-	RT	
Al7775/SiC-T6	50nm	5	-	552 ^{b}	594	3	3.3	0.3	-	RT	
Al7775/Al_2O_3-T6	50nm	1	-	551 ^{b}	602	5	3.2	1.7	-	RT	

* % reduction in area, ^{b} 0.2 % yield stress

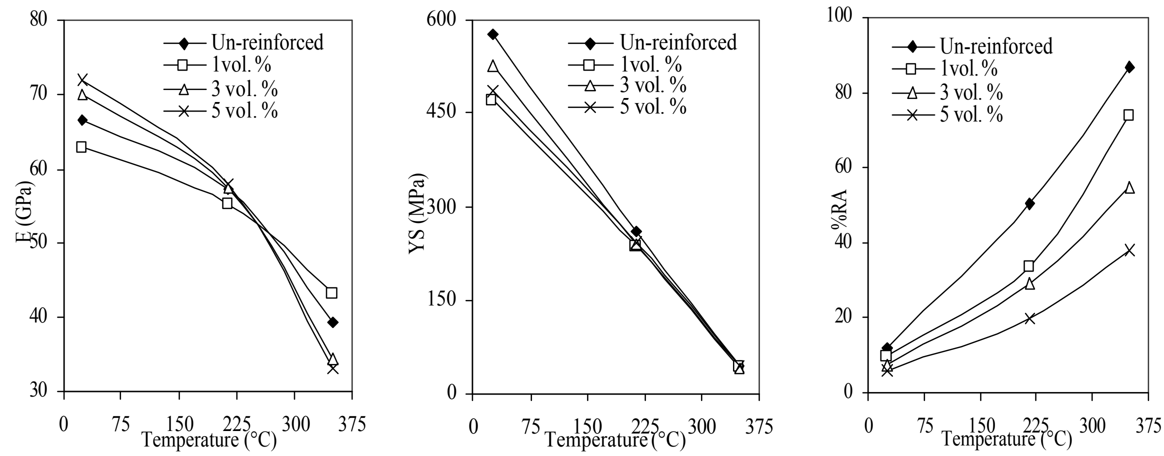

Figure 1- Modulus, YS and ductility of SiC_p/Al7775 composites [17].

3 Strengthening mechanism

Strengthening in PR MMCs has been explained via continuum [18] and/or micromechanics [19] approaches. The continuum approach ignores the influence of particles on the micromechanics of deformation and strengthening mechanisms, such as location of particulates, grain size and dislocation density [20]. Plastic deformation of a metallic material is the measure of dislocation motion at the micro-level. In PR MMCs, there are a variety of obstructers to dislocation motion which contribute in improving strength and are described as follow [21]:

3.1 Thermal mismatch strengthening

Due to large differences in the thermal expansion of Al($23.5*10^{-6}$ $^oC^{-1}$) and SiC($4.5*10^{-6}$ $^oC^{-1}$) residual stresses are built-up during post fabrication treatment (quenching for solution heat treatment) which results in high dislocation densities near ceramic particulates or at the particulate/Al interface [22,23]. For equiaxed particles, the residual stresses are essentially isotropic. The dislocation density generated on cooling is a function of particulate size and volume fraction and the product of temperature change and difference in thermal expansion [21]. This strength contribution is known as “Quench Strengthening”.

3.2 Particulate strengthening

The reinforcement particulates act as obstacles to dislocation motion and increase the composite’s strength. Bypassing of the particulate by dislocation produces a shear loop (Orowan loop) which resists the plastic flow by generating a “back stress”. The Orowan bowing mechanism [24] is significant for highly dispersed nano-scale (~100nm) reinforced MMCs [7,25]. However, while the reinforcement is often observed to lie on the grain boundaries of the matrix, it is still not apparent whether this mechanism can operate at all under these circumstances [12].

3.3 Grain and sub-grain strengthening

Thermomechanical processing results in very fine grain sizes of PR MMCs which have a strengthening effect on the composites. Grain size is usually of the order of a few microns in PR MMCs but can be as fine as 1µm [7]. For particulates of sizes greater than 1µm in diameter, recrystallization also occurs by particulate stimulated nucleation. The particulates pin the grain boundaries and therefore prevent the grain growth and impart strength to the grain structure. It is also found that as the reinforcement volume fraction increases and the particulate size decreases, above a critical ratio of volume fraction to particle size, the composite will retain a fine worked structure after solution treatment. In this case sub-grain structure will contribute to the PR MMC’s strength [21].

3.4 Work hardening

Work hardening is related to the pile-up of dislocations during plastic deformation. Therefore, in PR MMCs work hardening is also influenced by the high dislocation density generated during quenching. The other important factor is the load transferred from the matrix to the reinforcement via the Orowan loops in the early deformation phase. As deformation proceeds the induced stresses at the particulate/matrix interface lead to the relaxation of the Orowan loops at low strains (10^{-4}) [26] which contribute to work hardening by generating dislocations and thus strengthen the composite.

4 Fracture behaviour

In micrometric-PR AMCs, it is considered that the fracture is initiated by the particulate fracture, or near particle fracture and/or debonding between the matrix and reinforcement [13-14]. In addition, obviously, one can have failure of the matrix in both unreinforced alloys and composites. However, particle fracture or a weak interface is unlikely in nano-scale-PR AMCs [7] because small particles are less likely to contain a flaw of critical size and therefore high stresses are needed for the internal damage to occur. Thus the damage accumulates relatively slowly which may lead to greater YS of the composite [7,13]. Failure of a small particulate will produce less damage than the failure of one large particulate which lead to greater ductility in the finer particulate reinforced matrices [13]. Micro-void nucleation occurs first at the largest particulates in the matrix and progresses to smaller and smaller particulates as loading increases. As the particulate size decreases the plastic strain necessary to break it increases. Thus small particulates have better damage tolerance [13,27]. Particle clustering could also severely degrade the strength and ductility of the reinforced alloy by initiating localised damage. The large particles with lower expect ratios and particle-clusters are more prone to crack initiation than the fine, equiaxed particles due to their intrinsic brittleness and their higher loading [7,14,16-17,28-29]. Micro-voids emerge at or in the vicinity of these clusters which nucleate, grow and coalesce and then finally the rupture occurs through the matrix between the clusters [30]. Clustering is more apt to occur in composites reinforced with fine particles [13] and thus extra attention must be paid to ensure the uniform mixing of nano-scale reinforcement particles in the matrix to achieve optimised performance. The micro-voids on the fracture surfaces of PR AMCs have been found to contain large amounts of ceramic particles, signifying that they provides sites for the rupture of the composites [7,14,17]. This could be due to the non-ideal agglomeration of the reinforcement particles, which has proven to be a significant barrier to the successful manufacture of PR AMCs. At high temperatures PR AMCs exhibit significant improvements in ductility and fracture toughness over the values at room temperature because of the matrix's softening therefore less or no particle fracture occurs, and particle-matrix interface debonding thus acted as a preferential mechanism of fracture nucleation [14,16,17].

5 Discussion

It can't be concluded from the compiled data that particulate reinforced Al 7xxx composites are weaker than monolithic counterparts. There are several factors as discussed above which could affect the strength and ductility of the reinforced composites. During ageing treatment, formation of precipitate free zones (PFZ) at the particle-matrix interface [7,16,31] could also be attributable to the low strength of reinforced Al 7xxx matrix. It is possible that interface between the introduced ceramic particles and the matrix may lead to the formation of PFZs which would make the interface region weaker and concentrate plasticity in that zone [16]. For a given ageing treatment, a higher volume fraction of ceramic particulates tends to reduce the precipitation hardening effect and can lead to a drop in the composite's strength [7,32]. Higher amount of work (forging, rolling, extrusion etc) helps to break up intermetallic particles and oxides, which can reduce the elongation of composite produced via powder metallurgy [16]. Since ceramics particulates have high-stiffness compare to the Al matrix, they can only deform elastically. Therefore, higher local matrix strain is required to accommodate any plastic deformation in the composite then in the un-reinforced alloy, resulting in increased matrix stresses [14]. The local YS of the matrix may also be greater than that of the un-reinforced alloy because of increased dislocation density and reduced grain-size [13]. However, it appears that hard reinforcing particles are less incorporable in a much stronger matrix which thus reduces their reinforcing ability because they have a greater tendency to fracture in a stronger matrix then in a comparatively weaker one. In high-strength-matrix based composites where YS is observed to drop, the stress for significant internal damage of the composite is below the YS of the matrix (Figure 2). In this case the applied stress reaches the damage stress, σ_d, before it reaches the YS of the matrix. Hence particle damage and/or near particle damage begins and the actual stress reaches the yield stress of the matrix when macroscopic yielding occurs, which may be at an applied stress below the YS of the monolithic material [13].

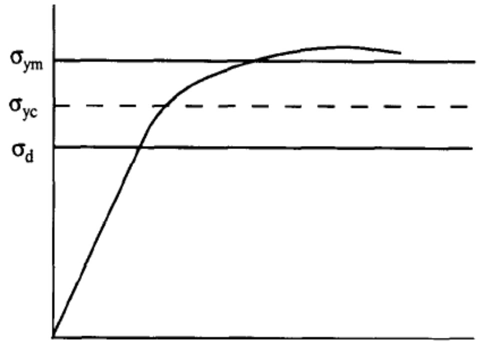

Figure 2- Schematic stress-strain showing how the difference between the YS of the matrix, σ_{ym}, and the stress at which significant internal damage (particle fracture and/or near particle fracture) begins, σ_d, can affect the YS of the composite, σ_{yc}, for high-strength matrix alloys [13].

6 Conclusions and recommendations

The role of ceramic reinforcement on the mechanical behaviour of Al 7xxx series matrix is still ambiguous as the data compiled in this study do not confirm the significant strength benefit of these composites over the monolithic alloys. Hard particulates are also found to markedly reduce the ductility and fracture toughness of the composites which encumber the use of such composites in the aerospace and automobile industry. Manufacturing variables have to be controlled to avoid any contamination and aggregation of reinforcement particulates in the matrix which are believed to be one of the possible causes of premature-failure of the composite. Further work is required to build Al 7xxx matrix composites reinforced with nano-scale particulates as they have the potential to greatly enhance the strength. This work is also desired to improve the ductility and fracture toughness of the reinforced alloy without sacrificing its improved stiffness and strength.

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