Scientia Iranica A (2012) 19 (4), 992–996

SCIENTIA IRANICA

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Scientia Iranica

Transactions A: Civil Engineering

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Fracture toughness (K_{1C}) and tensile properties of as-cast and age-hardened aluminium (6063)–silicon carbide particulate composites

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Received 29 May 2011; revised 3 February 2012; accepted 21 April 2012

KEYWORDS

Fracture toughness;
Al (6063)–SiC composite;
Ageing treatment;
Stir-casting;
Tensile properties.

Abstract The tensile and fracture behavior of as-cast and age-hardened aluminium (6063), silicon carbide particulate composites produced, using borax additive and a two step stir casting method, was investigated. Al (6063), SiC_p composites having 3, 6, 9, and 12 volume percent of SiC were produced, and sample representatives of each composition were subjected to age-hardening treatment at 1800 °C for 3 hours. Tensile and Circumferential Notched Tensile (CNT) specimens were utilized for tension testing to evaluate, respectively, the tensile properties and fracture toughness of the composites. Experimental results show that the ageing treatment resulted in little improvement in the tensile strength of the composites. The tensile strength and yield strength increased to almost the same magnitude with an increase in SiC volume percent for both as-cast and age-hardened conditions. The increase was, however, more significant for the 9 and 12 volume percent SiC reinforcement. The strain to fracture was less sensitive to volume percent SiC reinforcement and ageing treatment, with values less than 12% strain to fracture observed in all cases. The fracture toughness, however, improved significantly with ageing treatment (as-cast $K_{1C} = 6.63 - 6.71$ MPa $m^{1/2}$; ageing treatment $K_{1C} = 7.57 - 8.2$ MPa $m^{1/2}$).

1. Introduction

Aluminium and its alloys have continued to maintain their mark as the matrix material most in demand for the development of Metal Matrix Composites (MMCs). This is primarily due to the broad spectrum of unique properties it offers at relatively low processing cost [1–3]. Some of the attractive property combinations of Al based matrix composites are: high specific stiffness and strength, better high temperature properties (in comparison with its monolithic alloy), thermal conductivity, and low thermal expansion [4,5]. The multifunctional nature of Al matrix composites has seen its application in aerospace technology, electronic heat sinks, solar panel substrates and antenna reflectors, automotive drive shaft fins, and explosion engine components, among others [5,6].

Deriving optimized material properties from Al based matrix composites have been reported to be majorly dependent on:

(1) The base Al alloy composition;
(2) The nature of the reinforcing material;
(3) The processing techniques adopted for production of the composite [7–9].

Thus, most research work reported in literature has strived to address how these factors affect the properties and performance of Al based matrix composites. Most work reported in literature has been devoted to aluminium alloy-based composites, such as A357, A359, 2618, 2214, 6061 and 7075 [10–12]. However, not much has been reported on the use of Al (6063) as a base material for the development of Al matrix composites [13,14]. Al (6063) alloy happens to be the most readily available Aluminium alloy in the metal markets of most developing countries. It is processed in commercial quantities at low cost by most Aluminium processing companies in these countries for applications such as the production of glazing bars and window sections, windscreen and sliding

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Peer review under responsibility of Sharif University of Technology.

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doi:10.1016/j.scient.2012.06.001

Table 1: Chemical composition of the Al 6063 matrix alloy (wt%).

Matrix alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Bal
	0.45	0.22	0.02	0.03	0.50	0.02	0.02	0.02	Al

roof sections for the automobile industry, pipes and tubing, and aluminium furniture [15,16]. The potential for developing high performance SiC reinforced Aluminium based matrix composites using Al (6063) alloy as a matrix has formed the thrust of this research work. The fracture toughness and tensile properties of as-cast and age-hardened Al (6063) matrix composites developed using silicon carbide pre-mixed with borax and a double stir casting process is specifically reported in this paper. The benefit of the borax additive is to improve wettability between the Al (6063) matrix and the SiC particulates contributing to improved dispersion of the particulates in the Al matrix [14].

2. Materials and methods

2.1. Materials

The base material for the investigation is wrought aluminium alloy (6063), as-received in the form of slabs with a chemical composition (determined by the use of a spectrometric analyzer) as presented in Table 1. Silicon carbide (SiC) with a particle size of 30 μm (600 grits) was used as reinforcement, along with Hydrated Sodium tetra borate (borax) $(Na_2B_4)_7 \cdot 10H_2O$, for improvement of the wettability of the molten aluminium (6063) and the silicon carbide particles during melting.

2.2. Method

2.2.1. Stir casting

The double stir casting processing parameters utilized in this work is in accordance with Alaneme and Aluko [14] and Singla et al. [17]. Charge calculations following standard procedures were utilized to estimate the amount of the Al (6063) scrap billets and silicon carbide required to produce 3, 6, 9 and 12 vol% SiC reinforcements in the composite. The borax which serves as a wetting agent was dehydrated by heating at 250 °C for 20 min after which it was mixed with specified amounts of SiC in a ratio of 1:2. The Al (6063) billets were charged into the furnace and melting was allowed to progress until a uniform temperature of 750 °C (which is above the liquidus temperature) was attained. The melt was then allowed to cool to 600 °C (slightly below the liquidus temperature) to a semi-solid state. At this stage, the silicon carbide and dehydrated borax mixture was added into the melt and manual stirring of the slurry was performed for 20 min. An external temperature probe was utilized in all cases to monitor the melt temperature. After manual stirring, the composite slurry was reheated and maintained at a temperature of 750 °C ± 10 °C (above the liquidus temperature) and then mechanical stirring was performed. The stirring operation was performed for 20 min at an average stirring rate of 300 rpm. Casting was then performed on prepared sand moulds at a pouring temperature of 720° C.

2.2.2. Age—hardening treatment

Age-hardening of selected samples from each volume percent of the composites produced was performed. The selected samples were solution-treated in the furnace at 560 °C for 2 h, followed by water quenching. Thereafter, ageing was performed at 180 °C for 3 h, followed by water quenching.

2.2.3. Tensile testing

Room temperature uniaxial tension tests were performed on cylindrical tensile samples machined from the monolithic alloy and composites with dimensions of 6 mm diameter and 30 mm gauge length. The testing was performed using an instron universal testing machine, operated at a constant cross head speed of 1 mm/s, and the procedure adopted was in conformity with ASTM E8M—91 standards [18]. A minimum of two repeat tests were performed for each test condition to ensure the reliability of the data generated. The tensile properties evaluated from the stress–strain curves developed from the tension test are: ultimate tensile strength (σ_u), 0.2% offset yield strength (σ_y), strain to fracture (ε_f), and elastic modulus (E).

2.2.4. Fracture toughness, K_{1C}

Circumferential Notch Tensile (CNT) specimens were prepared for the evaluation of fracture toughness, in accordance with Bayram et al. [19] and Alaneme [20]. The CNT specimens were machined with a gauge length of 30 mm, specimen diameter of 6 mm (D), notch diameter of 4.5 mm (d) and notch angle of 60°. The specimens were then subjected to tensile loading to fracture using an instron universal testing machine. The fracture load (P_f) obtained from the CNT specimens' load-extension plots were used to evaluate the fracture toughness using empirical relations by Dieter [21]:

$$K_{1C} = P_f/(D)^{3/2}[1.72(D/d) - 1.27], \tag{1}$$

where D and d are, respectively, the specimen diameter and the diameter of the notched section. The validity of the CNT testing method for the evaluation of fracture toughness has been well discussed by Ibrahim and Stark [22]. The achievement of the plane strain condition and, by extension, the reliability of the CNT testing method, was evaluated using the relations in accordance with Nath and Das [23]:

$$D \geq (K_{1C}/\sigma_y)^2. \tag{2}$$

Also, the requirement that the length of the specimen be at least 4D [24] was taken into consideration while preparing the CNT specimens. A minimum of two repeat tests were performed for each treatment condition and the results obtained were taken to be highly consistent if the difference between measured values for a given treatment condition was not more than 2%.

2.2.5. Microstructure

The microstructural investigation was performed using a Datteng Software–Driven Metallurgical Microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500 μm to 1500 μm, while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10 μm to 0.5 μm, with ethanol solvent. The specimens were etched with 0.5% HF solution by swabbing for 3–6 min (followed by rinsing in water and drying) before observation in the optical microscope.

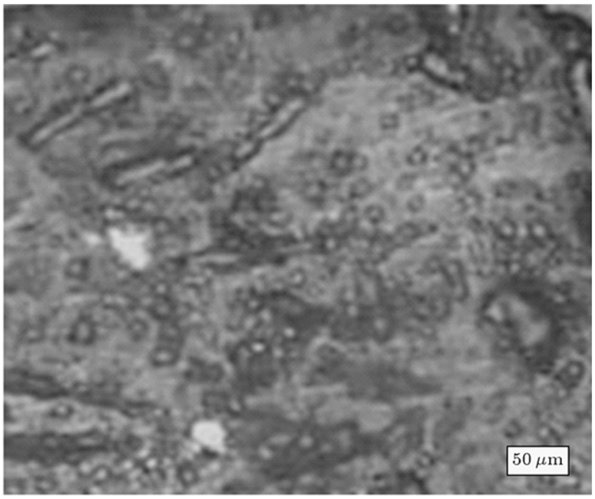

Figure 1a: Representative optical micrograph of the as-cast Al (6063)—9 vol% SiC_p composite showing some localized SiC particles clustering.

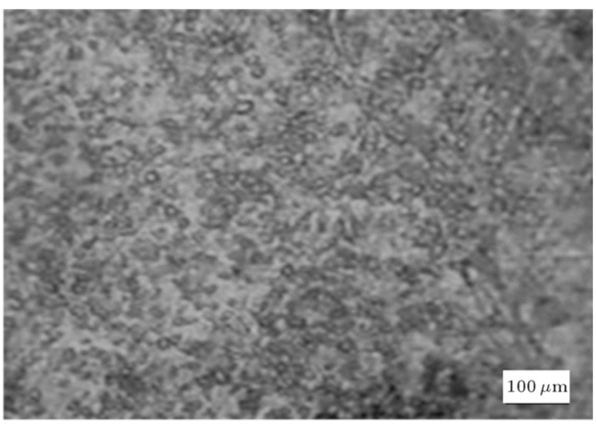

Figure 1b: Representative optical micrograph of the aged Al (6063)—9 vol% SiC_p composite showing a more homogeneous distribution of the SiC particles.

3. Results and discussion

3.1. Microstructure

Fig. 1 shows representative optical micrographs for the 9 vol% SiC reinforced Al (6063) composite under as-cast and solution treated, age-hardened conditions. It is observed that the SiC particulates are evident under as-cast and solution treated aged conditions. The volume percent of silicon carbide did not appear to influence the pattern of distribution of SiC under as-cast and solution treated, age-hardened conditions for the other volume percent SiC reinforced Al (6063) matrix composites. (Because of this similarity, the microstructures of the other volume percents of the composites are not presented.)

3.2. Tensile properties

The average values of the ultimate tensile strength, yield strength, and strain to fracture obtained from the tensile test are summarized in Table 2. Variations of σ_u, σ_y and ε_f with SiC volume percent are plotted in Fig. 2. It is observed that the tensile strength and yield strength increased with an increase in SiC volume percent for both as-cast and age-hardened

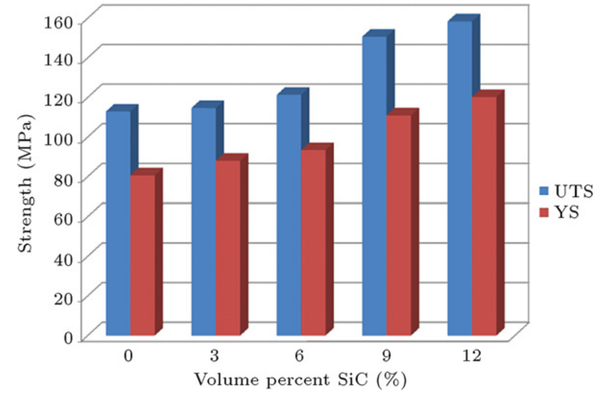

Figure 2a: Variation of ultimate tensile strength and yield strength with increase in vol% SiC in the as-cast composites.

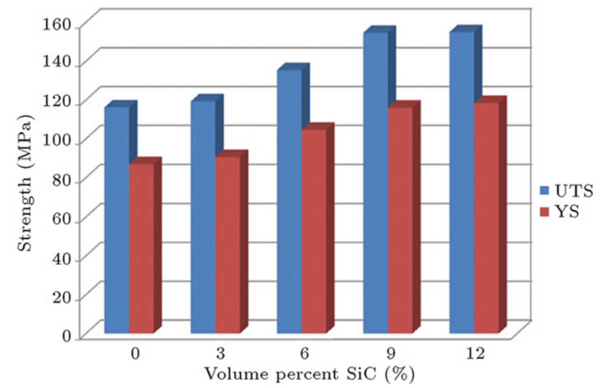

Figure 2b: Variation of ultimate tensile strength and yield strength with increase in vol% SiC in the age-hardened composites.

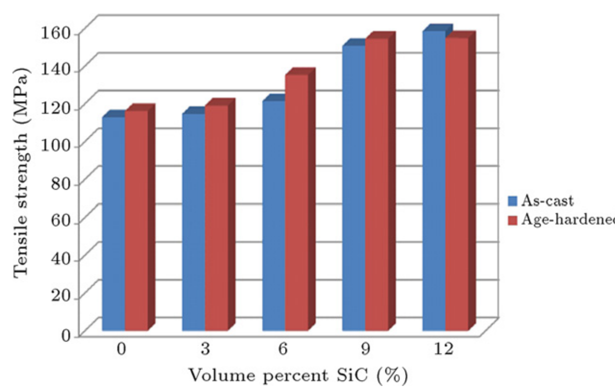

Figure 2c: Comparison of ultimate tensile strength with increase in vol% SiC for the as-cast and age-hardened composites.

conditions (Figures 2a and 2b, respectively). The increase was more significant for the 9 and 12 vol% SiC reinforcements, with 33% and 40% increase in tensile strength obtained for the as-cast, and 33% and 33.33% for the age-hardened condition, relative to the tensile strength of their respective monolithic alloys.

The increase in tensile strength is due to the presence of the hard and higher modulus SiC particles embedded in the Al (6063) matrix, which act as a barrier to resist plastic flow when the composite is subjected to strain from an applied load [25]. Also, the decreased interparticle spacing, due to the increasing volume percent of SiC reinforcement, creates

Table 2: Tensile and fracture properties of the as-cast and age-hardened Al (6063)—SiC_p Composites.

Treatment	Volume percent SiC (%)	UTS, σ_u (MPa)	Yield strength, σ_y (MPa)	Strain to failure, ε_f (%)	K_{1C} (MPa $m^{1/2}$)	σ_{NTS} (MPa)	NSR
As-cast	0	112.93	80.75	8	6.64	146.23	1.12
	3	114.7	88.02	7.6	6.61	148.5	1.3
	6	121.40	93.43	9	6.59	145.0	1.19
	9	150.74	111.0	11	5.63	123.97	0.84
	12	158.5	120.24	8.3	6.71	159.74	1.007
Age-hardened	0	116.17	86.95	8	7.57	146.98	1.29
	3	119.2	90.54	12	7.60	151.25	1.26
	6	135.36	118.4	7	7.65	160.56	1.18
	9	154.54	116	8.5	7.8	168.34	1.09
	12	154.9	118.4	8.2	8.2	180.52	1.16

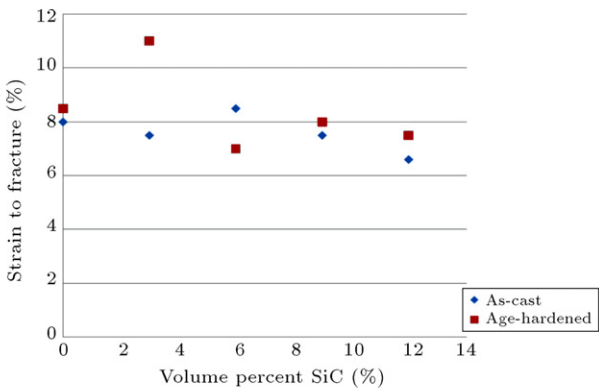

Figure 2d: Variation of strain to fracture with increase in vol% SiC in the as-cast and age-hardened composites.

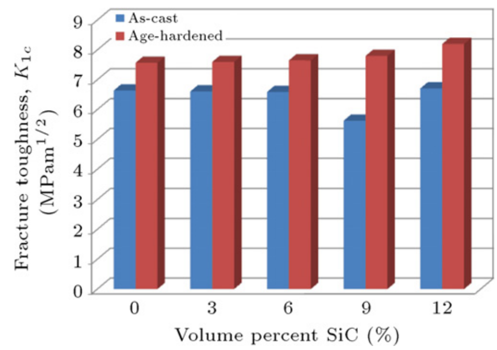

Figure 3: Variation of fracture toughness (K_{1C}) with increase in vol% SiC in the as-cast and age-hardened composites.

increased resistance to dislocation motion, which contributes to the enhanced strength of the composites [26,27]. Ehsani and Seyed Reihani [28] reported that thermal mismatch between the high expansion metallic matrix and the low expansion ceramic results in the generation of dislocations at the reinforcement/matrix interface upon cooling, which contributes to the strengthening of the matrix.

Figure 2c compares the tensile strength of the composite under the as-cast and age-hardened conditions. It is observed that to a large extent, there is only a slight improvement in tensile strength when ageing treatment is performed (2.6% for the monolithic alloy; 3.5% for the 3 vol% SiC reinforcement; 11.6% for the 6 vol% SiC reinforcement; 2% for the 9 vol% SiC reinforcement; and −1.9% for the 12 vol% SiC reinforcement). This could be attributed to the formation of coherent Mg_2Si precipitates in the Al (6063) matrix by virtue of the aging treatment. Alaneme [16] reported that coherent Mg_2Si precipitates (β—phase) are formed during optimum aging of Al (6063) alloys and the precipitates contribute to strengthening by serving as barriers to dislocation movement. However, the strain to fracture (Figure 2d) for the composites did not follow a clear trend with an increase in volume percent SiC under both as-cast and age-hardened conditions. Naturally, the strain to fracture is expected to reduce with an increase in volume percent of SiC [26]. The scatter in the data observed can be attributed to slight degrees of porosity (less than 2.2% for all SiC content) and particle clustering observed in the composites. The strain to fracture of the composites was generally low (less than 12% in all cases) and comparable to values obtained from SiC reinforced Al alloy matrix composites produced using similar processing techniques [6]. The observed low strain to fracture of the composites is attributed to the ease of void nucleation (micro crack formation) at the matrix/particulate interface, as a result of uneven plastic straining the particulates and the Al matrix, which is undergone during tensile deformation [28]. Also, void coalesce occurs with ease at regions with porosity and particle clusters. Thus, it can be stated that the ageing treatment under processing conditions utilized in this research resulted in a slight improvement in the tensile properties of the Al (6063)—SiC particulate composites produced.

3.3. *Fracture toughness*

The variation of fracture toughness for the as-cast and age-hardened Al (6063)—SiC composites are presented in Figure 3. The results were taken to be reliable, because the requirement for a nominal plane strain condition was met with the specimen diameter of 6 mm when relation $D \geq (K_{1C}/\sigma_y)^2$ [23] was utilized to test for the validity of the K_{1C} values evaluated from the CNT testing. The fracture toughness (which is a measure of the composites resistance to crack propagation) was observed to improve significantly with adoption of the ageing treatment (as-cast K_{1C} = 6.63–6.71 MPa $m^{1/2}$; ageing treatment K_{1C} = 7.57–8.2 MPa $m^{1/2}$), with increases as high as 22% achieved for the 12 vol% SiC reinforcement. The improvement might be due to the presence and distribution of fine coherent Mg_2Si precipitates formed in the Al (6063) matrix during ageing. Under the as-cast condition, the fracture toughness was observed to decrease with an increase in volume percent of SiC (with the exception of the 12 vol% SiC reinforcement), which is consistent with the trend in most as-cast Al based, SiC reinforced composites [27,29,30]. Naturally, it is expected that the fracture toughness should decrease with an increase in volume percent of SiC, due to the increased sites (particles, particle/matrix interfaces, and particle clusters) for crack nucleation [30]. Fracture in particulate MMCs has been reported to involve a wide range of damage modes under monotonic loading, depending on the relative ductility of the matrix and reinforcement materials, particle size and the interfacial strength levels [1]. The fracture micro-mechanism may be due to particulate cracking, interfacial cracking or particle debonding [31,32]. Generally, the fracture toughness values obtained for the composites were found to be comparable to that of Al matrix composites processed under similar conditions [26].

4. Conclusion

From the results of this research investigation, the following conclusions are drawn:

Significant improvement in the strength of the Al (6063) matrix composites is achieved when 9 and 12 vol% of SiC is used as reinforcement; and the ductility of the composites is not adversely affected at these compositions in comparison with the monolithic alloy. Also, the ageing treatment was more beneficial in improving fracture toughness than the strength of the composites. Overall, Al (6063) alloy can be considered as a suitable matrix for the development of SiC reinforced Aluminium based composites.

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