ISSN 0511-5728
The West Indian Journal of Engineering
Vol.35, No.2, January 2013, pp.31-35

Mechanical Behaviour of Cold Deformed and Solution Heat-treated Alumina Reinforced AA 6063 Metal Matrix Composites

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(Received 27 April 2012; Revised 29 August 2012; Accepted 25 September 2012)

Abstract: *The mechanical behaviour of cold deformed and solution heat-treated aluminium alloy (6063)- alumina particulate composites was investigated. AA 6063-Al_2O_3 particulate composites having 6, 9, and 12 volume percent of Al_2O_3 were produced using two-step stir casting process. The composites were cold rolled to 20 and 35% deformation before solution heat-treating at 550^oC for 1hour cooling rapidly in water. Density measurements were used as a basis of evaluating the percent porosity of the composites; while tensile properties and fracture toughness were utilised to study the mechanical behaviour. It was discovered that the cold rolling and solution heat-treating processes resulted in remarkable reduction in porosity levels in the AA 6063/Al_2O_{3p} composites (≤ 2.8 % porosity). A good uniform distribution of the alumina particulates in the matrix of the AA 6063 was also produced. The tensile strength and yield strength increased with increase in alumina volume percent and degree of cold rolling. The strain to fracture and fracture toughness decreased with increasing volume percent alumina but improved with increase in the degree of cold deformation.*

Keywords: *stir casting; AA 6063- Al_2O_3; cold rolling; mechanical behaviour; porosity; solution heat-treatment*

1. Introduction

Metal Matrix Composites (MMCs) have become an important class of engineering materials because of the unique properties and higher performance efficiencies they offer over traditional metals and alloys utilised for the same applications (Matthews and Rawlings, 1994; Miracle, 2005). Some of the remarkable property combinations of MMCs are high specific strength and stiffness, better high temperature strength and stability in comparison to its base alloy, low thermal coefficient of expansion, and satisfactory levels of corrosion resistance (Ray, 1993; Zhou and Xu, 1997; Hashim et al., 1999).

Among MMCs, Aluminium based metal matrix composites have been the most developed and utilised for a wide range of engineering applications (Surappa, 2003). Some of its areas of applications are in the design of components/accessories for use in aerospace technology, defence, electronic heat sinks, solar panel substrates and antenna reflectors, automotive drive shaft fins, explosion engine components, sports among others (Chawla et al., 2009; Veeresh Kumar et al., 2010).

There have been sustained efforts by materials researchers to develop AMCs using simple, cost-effective, and technically efficient processing techniques. A two-step stir casting has been explored to develop AMCs with very encouraging results with regards lowered porosity levels (less than 4 %) achieved. However, in the as-cast or solution heat-treated conditions some of the AMCs do not possess sufficient toughness and mechanical strength even when porosity levels are satisfactory (Alaneme and Bodunrin, 2011).

Recently, there has been interest to develop AMCs based on the use of Aluminium alloy 6063 (Khalifa and Mahmoud, 2009; Alaneme and Bodunrin, 2011; Alaneme and Aluko, 2012a). AA 6063 are conventionally applied for the design of medium strength window and door profiles and other architectural design works (Polmear, 2006). The choice of AA 6063 is informed by its local availability and lower cost of processing.

The present research work presented here is aimed at improving the mechanical properties of AA 6063 – alumina composites by adopting cold rolling and solution heat-treatment in combination as a secondary processing stage in the production of the AMCs.

2. Materials

100 percent chemically pure alumina (Al_2O_3) particles having particle size of 28μm and Aluminium alloy 6063 (AA 6063) which served as the matrix; were utilised for the production of the composite. The composition of the AA 6063 is shown in Table 1.

Table 1: Chemical Composition of the Aluminium Alloy 6063

Si	Fe	Cu	Mn	Mg
0.45	0.22	0.02	0.03	0.50

Zn	Cr	Ti	Al
0.02	0.03	0.02	Bal.

3. Methods

3.1 Production of Composites by Stir Casting

Charge calculations were utilised to determine the quantities of Aluminium (6063) alloy and alumina (Al_2O_3) particles required to produce composites having 6, 9, and 12 volume percent alumina. The alumina particles were initially preheated at a temperature of 250°C for 5-10 minutes to help improve wet-ability with the AA 6063 alloy. The AA 6063 ingots were charged into a gas-fired crucible furnace and heated to a temperature of 750°C ± 30°C (above the liquidus temperature of the alloy) and the liquid alloy was then allowed to cool in the furnace to a semi solid state at a temperature of about 600°C.

The preheated alumina was added at this temperature and stirring of the slurry was performed manually for 5-10 minutes. The composite slurry was then superheated to 720°C and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 300rpm for 10 minutes to help improve the distribution of the alumina particles in the molten AA 6063. The molten composite was then cast into prepared sand moulds. Unreinforced AA 6063 was also prepared by casting for control experimentation.

3.2 Cold Rolling and Solution Heat-treatment Processing

The cast composites of 6, 9, and 12 volume percent alumina along with the unreinforced alloy; was subjected to cold deformation using a miniature cold rolling machine. The composites were rolled to 20 and 35 % degrees of deformation using the round orifice of the cold rolling machine before solution heat-treating the samples at 550°C for 1 hour, then cooling rapidly in water. The sample designations for the different temper conditions (as-cast, 20% and 35% cold rolled and solution heat-treated conditions) are presented in Table 2.

Table 2: Sample Designation for the Different Temper Conditions

Vol.% alumina	Temper Condition		
	as-cast	20% cold-rolled + solution heat-treated	35% cold-rolled + solution heat-treated
0	A1	A2	A3
6	B1	B2	B3
9	C1	C2	C3
12	D1	D2	D3

3.3 Density Measurement

The density measurements were carried out to determine the porosity levels of the composites produced. This was achieved by comparing the experimental and theoretical densities of each volume percent Al_2O_3 reinforced composite (both for the as-cast and the cold deformed – solution heat-treated conditions). The experimental density of the samples was evaluated by weighing the test samples using a high precision electronic weighing balance with a tolerance of 0.1mg. The measured weights in each case were divided by the volume of the respective samples. The theoretical density was evaluated by using the rule of mixtures given by:

$$\rho_{AA6063/Al2O3p} = Vol._{AA\ 6063} \times \rho_{AA6063} + Vol._{Al2O3} \times \rho_{Al2O3} \quad \text{............................ (2.1)}$$

Where, $\rho_{AA6063/Al2O3p}$ = Density of Composite, $Vol._{AA\ 6063}$ = Volume fraction of AA 6063, ρ_{AA6063} = Density of AA 6063, $Vol._{Al2O3}$ = Volume fraction Al_2O_3, and ρ_{Al2O3} = Density of Al_2O_3.

The percent porosity of the composites was evaluated using the relations:

$$\% \; Porosity = \{(\rho_T - \rho_{EX}) \div \rho_T\} \times 100\% \quad \text{.......................... (2.2)}$$

Where, ρ_T = Theoretical Density (g/cm^3), ρ_{EX} = Experimental Density (g/cm^3)

3.4 Tensile Properties Determination

Room temperature uniaxial tension tests were performed on round tensile samples machined from the unreinforced alloy and the 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 1mm/s; and the procedure adopted was in conformity with ASTM E8M - 91 standards (ASTM, 1991). Three repeat tests were performed for each test condition to guarantee reliability of the data generated. The tensile properties evaluated from the stress-strain curves developed from the tension test are - the ultimate tensile strength (σ_u), the 0.2% offset yield strength (σ_y), and the strain to fracture (ε_f).

3.5 Fracture Toughness, K_{1C}

Circumferential notch tensile (CNT) specimens were prepared for the evaluation of fracture toughness in accordance with Alaneme (2011). The CNT specimens were machined with gauge length of 30mm, specimen diameter of 6mm (D), notch diameter of 4.5mm (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 the empirical relations by Dieter (1988):

$$K_{1C} = P_f / (D)^{3/2} \, [1.72(D/d) - 1.27] \quad \text{…………….(2.3)}$$

Where, D and d are respectively the specimen diameter and the diameter of the notched section. The validity of the fracture toughness values was evaluated using the relations in accordance with Nath and Das (2006):

$$D \geq (K_{1C} / \sigma_y)^2 \quad \text{…………………. (2.4)}$$

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 is not more than 2%.

3.6 Microstructure

The microstructural investigation was performed using a Zeiss Metallurgical Microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500-1,500µm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10-0.5µm with ethanol solvent. The specimens were etched using $1HNO_3$: 1HCl solution by swabbing before microstructural examination was performed.

4. Results and Discussion

4.1 Microstructure

Figure 1 shows optical photomicrographs for the 9 and 12 volume percent Al_2O_3 reinforced AA 6063 composites in the as-cast and 35% cold rolled and solution heat-treated conditions (which are selected as representative microstructures for all the temper conditions for the composites produced). It is observed that the Al_2O_3 particulates are well dispersed in the cold rolled and solution heat-treated condition in comparison to the as-cast condition. This is a clear indicator that the cold rolling and solution heat-treatment processes helped in achieving a homogeneous distribution of the particulates and reduced particle clusters in the composites produced.

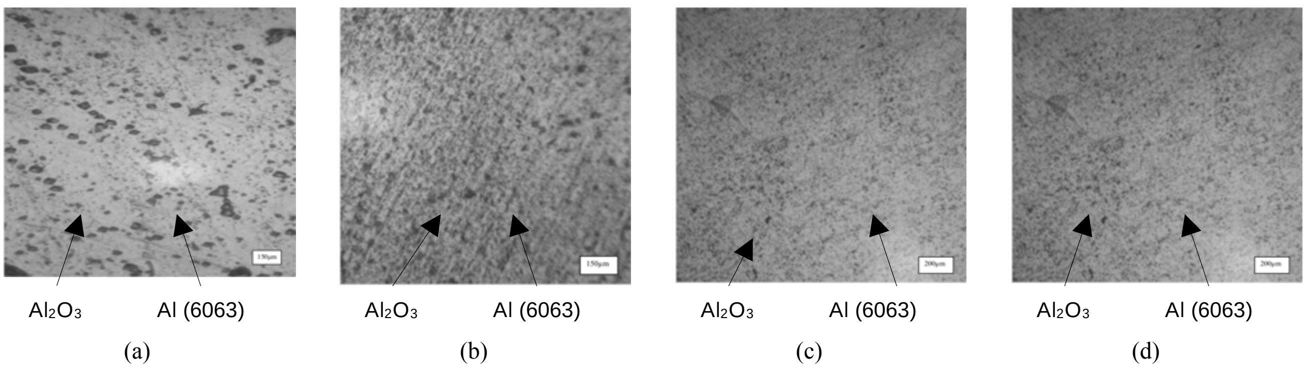

Figure 1: Representative Micrographs for (a) as-cast AA 6063 - 9 vol.% Al_2O_3, (b) as-cast AA 6063 – 12 vol.% Al_2O_3, (c) 35% cold-rolled and solution heat-treated AA 6063 - 9 vol.% Al_2O_3, and (d) 35% cold-rolled and solution heat-treated AA 6063 - 12 vol.% Al_2O_3.

3.2 Percent Porosity

The results of the percent porosity of the as-cast, 20% and 35% cold rolled and solution heat-treated AA 6063/Al_2O_{3p} composites are presented in Figure 2. It is observed that the as-cast AA 6063/Al_2O_{3p} composites had the highest porosity levels (1.85-3.78%) in comparison with the 20% cold rolled and solution heat-treated composites (1.05-2.8 %) and the 35% cold rolled and solution heat-treated composites (0.74-2.0 %). For all temper conditions, it is observed that the percent porosities are less than 4 % which is reported as the maximum permissible porosity level in cast metal matrix composites (Kok, 2005; Prabu et al., 2006; Alaneme and Aluko, 2012a). The percent porosity can be observed to increase with increase in volume percent alumina and decreases with the degree of cold deformation. This is an indication that the cold rolling and solution heat-treating process helps in improving the quality of the cast composites by reducing the percent porosity.

The reduced porosity of the cold deformed and solution heat-treated composites is attributed to the cold rolling process which compresses the composites thereby aiding the collapse of voids, micro-cracks and vacancies in the composite making it more compact and denser (Huda, 2009).

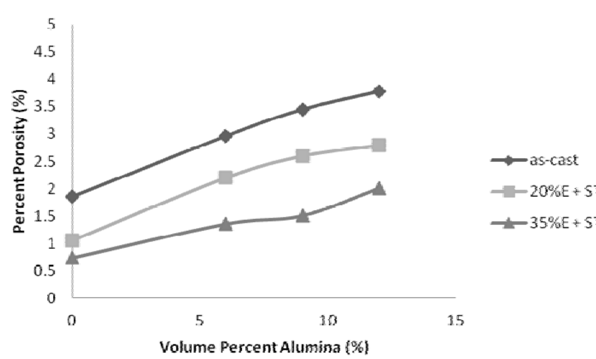

Figure 2: Percent Porosity for the AA 6063 – Al_2O_3 Composites Produced

4.3 Mechanical Properties

The variation of ultimate tensile and yield strengths and strain to fracture are presented. Figure 3 shows clearly that the ultimate tensile and the yield strengths of the composites increases with increase in volume percent alumina and extent of cold deformation. The cold rolling and solution heat-treatment helps in achieving a refined and homogeneous structure by removing voids and micro-voids and also helps in redistributing the particulates and second phase particles resulting in considerable elimination of particle clusters and segregation (Shahani and Clyne, 2003; Huda, 2009). The elimination of a considerable amount of defects in the composite by the cold rolling and solution heat-treatment process helps in enhancing the strain hardening capacity of the composites (Shahani and Clyne, 2003).

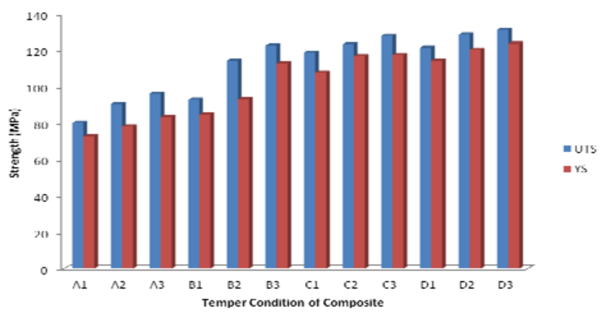

Figure 3: Variation of Ultimate Tensile Strength and Yield Strength for the AA 6063 – Al_2O_3 Composites Produced

The strains to fracture for the composites (see Figure 4) are observed to decrease with increase in volume percent alumina but improve slightly with prior cold deformation. The strain to fractures is observed to be within the range of 0.1(10 %) and .215 (21.5 %). The increased matrix/particulate interfaces with increase in volume percent alumina lead to an increase in the potential sites for void nucleation or micro-crack formation. The uneven plastic strain at the interface facilitates the nucleation of voids or micro-cracks (Alaneme 2012; Chawla and Shen, 2001). The reduced porosity of the cold rolled and solution heat-treated composites is largely responsible for the improved strain to fracture of the composites.

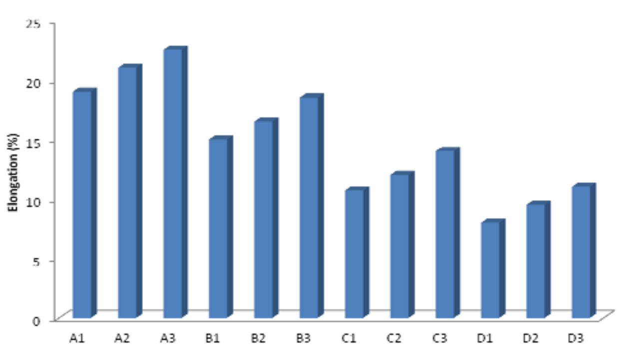

Figure 4: Variation of Percent Elongation for the AA 6063 – Al_2O_3 Composites Produced

The variation of fracture toughness of the composites with increase in Al_2O_3 volume percent is presented in Figure 5.

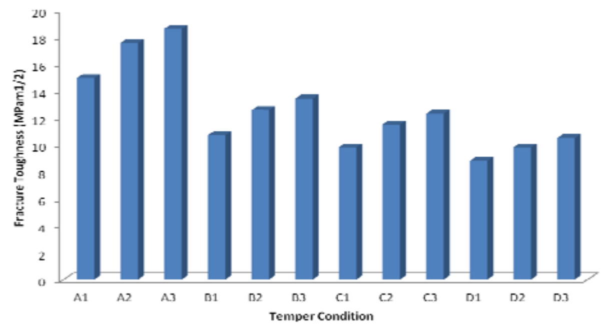

Figure 5: Variation of Fracture Toughness for the AA 6063 – Al_2O_3 Composites Produced

The results were taken to be reliable because the requirement for nominal plain strain condition was met with the specimen diameter of 6mm when the relation D $\geq (K_{1C}/\sigma_y)^2$ (Nath and Das, 2006) was utilised to test for the validity of the K_{1C} values evaluated from the CNT testing. The fracture toughness was observed to decrease with increase in volume percent of Al_2O_3 but improves with degree of cold deformation before solution heat-treatment. The fracture micro-mechanism in particulate reinforced MMCs has been reported to be due to particulate cracking, interfacial cracking or particle debonding (Alaneme and Aluko, 2012b; Ranjbaran, 2010). The reduced porosity and considerable elimination of particle clusters in the composites is responsible for the slight improvement in the fracture toughness of the composites. Generally, the fracture toughness values obtained for the composites were found to be comparable to that of Al matrix composites processed under similar conditions (Milan and Bowen, 2004).

5. Conclusion

It was discovered that the cold deformation and solution heat-treating processes resulted in remarkably reduced porosity levels in the AA 6063/Al_2O_{3p} composites ($\leq$ 2.8 %porosity). A good uniform distribution of the alumina particulates in the matrix of the AA 6063 was also produced. The tensile strength and yield strength increased with increase in alumina volume percent and degree of cold deformation. The strain to fracture and fracture toughness decreased with increasing volume percent alumina but improved with increase in the degree of cold deformation.

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