Direct RESEARCH JOURNALS

Direct Research Journal of Engineering and Information Technology
Vol. 6(4), pp. 24-29 November 2019
ISSN 2354-4155
DOI: https://doi.org/10.5281/zenodo.3533619
Article Number: DRJEIT15272995
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Full Length Research Paper

Effects of quenching media on mechanical properties of an aluminium–tin reinforced silica metal matrix composite

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Received 4 October 2019; Accepted 5 November, 2019

Metal matrix composites have attracted considerable attention in engineering applications as a result of their relatively low cost and considerable isotropic properties. In an effort to achieve optimality in structure and properties, various fabrication and heat treatment techniques have been used. In this paper, aluminium metal matrix composites were fabricated through stir casting technique using 3.0wt% of SiO_2 as reinforcement. The metal matrix composites were heat-treated by soaking at 450°C for 4 h in a muffle furnace so that the elements formed a solid solution. One set of the metal matrix composite was quenched in still air at room temperature, another set was quenched in water at room temperature (20°C – 35°C) while another set in boiling water. Samples of the metal matrix composites were further aged at 150°C for 4 h. The metal matrix composites were then subjected to hardness and tensile strength tests. Results of hardness and tensile strength tests showed that heat treatment had a significant effect on the hardness and tensile strength of the metal matrix composites compared to the as-cast sample. Samples quenched in water at room temperature had the highest improvement in hardness of 42.5HRB and ultimate tensile strength(UTS) of 120 N/mm^2 at a peak load of 14724.7N showing an improvement of 10% in hardness and 7.5% in ultimate tensile strength over the as-cast samples. The improvements maybe attributed to the combined effects of bonding between the SiO_2 particles and the aluminium matrix due to lower temperature and the formation and stabilization of Mg_2Si intermetallic phase with the matrix. This shows that during solutionizing heat treatment, the cooling rate needs to be fast enough to prevent solid-state diffusion and precipitation of the phase. Rapid quenching creates a saturated solution and allows for increased mechanical properties of the metal matrix composite.

Keywords: Metal matrix composites, heat treatment, quenching media, hardness, tensile strength

INTRODUCTION

Following the United Nation's vision and goal on sustainable development and directive on reduction of CO_2 emission many applied technologies may become unprofitable. Due to this, there is urgent need to create or modify existing technology especially in the field of materials engineering. One of the options to reduce CO_2 emission is the replacement of parts and materials made of steel with light metals such as aluminium, magnesium titanium, copper etc, mainly, in branches such as automotive and air craft industry (Kaczmarek et al., 2009). Light metals are not strong enough to attain the desired material properties in such industries, thus they are reinforced with ceramics, industrial waste and most recently, agro waste derivatives to attain properties comparable to steel (Bodurin et al., 2015). Similarly, current engineering applications required materials that are stronger, lighter and less expensive. A good example is in the current interest in the development of materials that have good strength to weight ratio suitable for automobile applications where fuel economy with improved

engine performance is becoming more and more critical (Kumar et al., 2016). Metal matrix composites have been developed and are still been developed to meet the aforementioned engineering challenges. Metal matrix composites are a combination of two or more chemically non-reactive materials to form a new material system with enhance material properties in which alloys of light metals such as titanium, aluminum, and magnesium have been popularly used as matrix metals and some non-metallic materials commonly, ceramics such as: silicon carbide, aluminum oxide, graphite, silicon dioxide; industrial waste such as fly ash, red mud, and agro waste derivatives such as rice husk ash, coconut shell ash and bamboo leaf ash maybe used as reinforcing materials (Das et al., 2014; Bodunrin et al., 2015). Metal matrix composites are thus fast replacing conventional alloys in many applications as their use have been extended from predominantly aerospace and automobile industries to defense, marine, sports, construction and recreation industries (Kok, 2015). The matrix material is usually selected on the basis of oxidation and corrosion resistance, low weight and density, processing flexibility and mechanical properties while the reinforcement is selected on the basis of its chemical compatibility with the matrix metal, type, size, shape, modulus of elasticity, hardness, distribution in the matrix among others (Bobic et al., 2010; Bodunrin et al., 2015). Nowadays researchers all over the world are focusing mainly on aluminum as the matrix material. This is because of its unique combination of good corrosion resistance, low density and excellent mechanical properties. The unique thermal properties of aluminum composites such as metallic conductivity with coefficient of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics. In addition, literature also reveals that most of the published work have considered aluminum matrix because of the wide alloy range, heat treatment capability and processing flexibility (Aigbodion et al., 2010). A variety of fabrication ways have been established for the development of aluminium metal matrix composites. Stir casting is one of the most universally used approaches to manufacture particle reinforced composites due to its simplicity flexibility and commercial viability. Stir casting is suitable for manufacturing metal matrix composites with up to 30% volume fraction of reinforcement (Saravanan et al., 2015).

In stir casting, a dispersed phase (reinforcement) is mixed with molten metal matrix by means of manual or mechanical stirrer. Stir casting of metal matrix composites was initiated in 1968 when S Ray introduced alumina particles into an aluminum melt using a mechanical stirrer (Rajeshkumar and Pavshuram, 2013). A major concern associated with the stir casting of metal matrix composites is the segregation of reinforcing particles which is caused by the surfacing or settling of the reinforcement particles during the casting process.

The final distribution of the reinforcement in the metal matrix depends on the reinforcement properties or process parameters such as wetting conditions of the reinforcement with the matrix melt strength of mixing, relative densities and rate of solidification (Rajeshkumar and Pavshuram, 2013). Thus, homogeneous mixing or good wetting can be achieved by selecting appropriate processing parameters such as stirring speed, and time, temperature of molten metal, preheating of reinforcement, preheating of mould and also uniform feed rate of the reinforcing particle. Wettability between the matrix and reinforcing materials can also be improved by addition of wetting agents such as borax and magnesium or sometimes the cast composite are further extruded to reduce porosity, refine the microstructure and homogenize the distribution of the reinforcement (Saravanan et al., 2013). The mechanical properties of the developed metal matrix composite can further be improved upon by heat treatment (Das et al., 2014). Heat treatment of metals is an important operation in the final fabrication process of many engineering components. The object of heat treatment process is to make the metal better suited, structurally and physically for some specific application. This process consists of heating a metal or alloy to a specific predetermined temperature, holding at this temperature for required time and finally cooling from this temperature (Rajan et al., 1988). In aluminium alloys, the basic aim of heat treatment is to increase strength and hardness. Depending on the rate of heating, soaking time at a given temperature and cooling rate, the properties can be varied according to requirement. Heat treatment to increase strength in aluminium alloys is a three step process.

(a) Solution heat treatment (Solutionizing): Dissolution of soluble phases.
(b) Quenching (Rapid cooling): Development of super saturated solution.
(c) Aging (Age hardening): Precipitation of solute atoms either at room temperature (natural ageing) or elevated temperature (artificial ageing) (Ramani et al., 2016)

Solution heat treatment of aluminium alloys allows the maximum concentration of hardening solute to dissolve into solid solution. This process is carefully carried out by heat treatment of an alloy to a temperature at which only one single solid solution phase exists. By this heat treatment, the solute atoms that were originally part of a two phase solid solution dissolve into a solution and originate as one single phase solid solution. Overheating and under heating are to be avoided. Overheating may cause formation of surface blisters, excessive grain growth and eutectic melting in some alloys. On the other hand, under heating may lead to in complete solutionizing prior to precipitation (Rajan et al., 1988).

Rajan et al. (1988) further noted that, soaking temperature is different for various aluminium alloys.

It depends on the various phases which are present in alloys. Each phase will dissolve in solid solution at different rates. The rate of dissolution increases with rise of temperature. Soaking time also depends on the conditions under which the alloys are cast. For example, sand cast part, have coarser structures than permanent mould casting, therefore, a sand casting takes longer time for dissolution of strengthening phases, and the holding time for sand cast alloy is longer (about 12 h) than permanent mould casting (about 8 h). Quenching is the process of rapid cooling of materials systems to room temperature to preserve the solute in solution. The cooling rate needs to be fast enough to prevent solid state diffusion and precipitation of the phase. The rapid quenching creates a saturated solution and allows for increase hardness and mechanical properties of the system (Ramani et al., 2016). After quenching, precipitation of second – phase particles occurs. Precipitation with time at room temperature is called natural ageing whereas precipitation at higher temperatures is referred to as artificial ageing. The hardness after solution treatment is usually comparatively low. The maximum hardness and strength develops when alloys is aged at a suitable temperature which normally ranges between 120°C and 200°C. In some cases, the ageing temperature maybe as high as 300°C while ageing time may vary from 4 to 24 h (Rajan et al., 1988). Beside mechanical properties, physico-chemical properties are also affected by ageing. This happens due to the metastable structures of the alloy which are formed during ageing of supersaturated solid solution obtained by solution treatment. Following steps are associated with the process of precipitation hardening in most aluminum alloys as noted by Rajan et al., (1988) and Ramani et al. (2016).

(i) The first stage preceding the formation of particles of the precipitating phase consists of rearrangement of atoms within the crystal lattice. This constitutes formation of clusters of Guiner -Preston zones. During this process, mechanical properties are improved due to development of micro strains in the lattice.
(ii) Formation of transition structures in the form of modified Guinier - Preston zones (e.g. GP – II zones) and intermediate phases. This may give rise to maximum strengthening in the alloy.
(iii) Formation of stable phase from transition phases whose particles have common boundaries with grains of the matrix.
(iv) Growth of certain larger particles at the expenses of neighboring smaller particles.

Due to this, stress relief takes place in the lattices usually at higher ageing temperature which causes considerable decrease in strength and increase in ductility of the alloy. This work was aimed at developing an aluminium–tin reinforced silica powder metal matrix composite and investigating the effects of quenching media during heat treatment on the mechanical properties of the metal matrix composite.

MATERIALS AND METHODS

The materials used for the development of the metal matrix composite are aluminium – tin bearing alloy which served as matrix material and ultrafine silica (SiO_2) powder as the reinforcement. The aluminum - tin bearing alloy was procured from the open market based on the requirement of aluminium - tin bearing alloy A750 grade while the silica powder (quartzite) was sourced from Jos, Plateau State Nigeria. The choice of silica powder as the reinforcement was based on its availability, relative high melting point 1740°C, low coefficient of thermal expansion 5.4 x 10^{-7}/°C and ability to withstand thermal shock. The chemical composition of the aluminum – tin alloy and silica powder were determined using Optical Emission Spectrometer technique. Water was chosen as the quenching medium because of its low – cost, availability and ease of handling. No pollution problem is associated with the use of water and it can easily be disposed of and it has the maximum cooling rates amongst all common quenchants except aqueous solutions. Most of the non -ferrous alloys, especially precipitation hardenable types are solution annealed, followed by water quenching. The layer of scale formed on the surface during heating is also broken by water quenching, thus eliminating an additional process of surface cleaning (Rajan et al., 1988). Required masses of the aluminum alloy were obtained while the locally source quartzite was washed with clean water, sun dried and ball milled to 20 - 30 micron particle size for the work. Required masses for the production of 3wt% of the silica powder were obtained. Stir casting technique was adopted for the development of the metal matrix composite. The stir casting was carried out at the National Metallurgical Development Centre, Jos. Graphite fired crucible furnace was used for the fabrication of the metal matrix composite. The alloy ingot was first preheated to a temperature of 250°C to dry off any possible coating and volatile matter that could lead to contamination. The crucible pot was also preheated to red hot to ensure it was free from moisture and contamination. Similarly the weighed silica powder was preheated to improve the wetting properties. Required quantity of the aluminum-tin alloys was charged into the crucible pot inside the furnace and heated to a temperature of 730°C which is the casting temperature of aluminum and its alloys. At this temperature, the slag was scooped and removed from the surface of the molten alloy melt. 1 wt% of magnesium was added to enhance wetting of the reinforcement. This produced a spark of glow which subsided immediately. Weighed quantity of the Silica powder was preheated to 250°C and then

introduced into the molten alloy melt while stirring. The composition was stirred vigorously using a stainless steel stirrer for about five minutes. It was removed from the furnace using pairing tong and stirred vigorously until it became mushy and 'then reheated for another five minutes and stirred vigorously until a vortex was formed. The formation of the vortex enhanced the absorption of the silica powder. The composition was then casted into already prepared metal moulds. The cast metal matrix composite was then allowed to cool and solidify in the moulds, afterwards the moulds were opened and the developed metal matrix composite removed. The developed metal matrix composite were then subjected to heat treatment by soaking at 450°C for 4 h in a muffle furnace so that the elements formed a solid solution. Samples of the developed metal matrix composite were then quenched in three different media: still air at room temperature, water at room temperature and boiling water. The samples were further aged at 150°C and held at this temperature for 4 h. Samples were prepared for hardness and tensile strength tests. They tests were carried out according to ASTM E18 standards. Hardness test was carried using a Rockwell hardness tester while tensile strength test was carried using a Tinus – Olsen universal testing machine.

RESULTS AND DISCUSSION

Chemical composition

The results of the chemical analysis of the Al- Sn alloy used as the matrix material and the silica powder used as the reinforcement are shown in (Tables 1 and 2) respectively.

Hardness test

The results of the effects of different quenching media on the hardness are presented in (Figure 1). It was observed that the solutionized and quenched in water at room temperature Al-Sn reinforced 3 wt% SiO_2 metal matrix composites exhibited higher hardness as compared to as cast, still air at room temperature and boiling water quenched samples. The still air quenched specimen showed increase of 2.5% compared to the as - cast samples. Water at room temperature quenched samples displayed an improvement in hardness of 10%. Quenching in boiling water showed a drop in hardness of 7.36% compared to as- cast specimens. The water at room temperature showed higher hardness value compared to other quenching media which may be due to the combined effect of enhanced bonding between the SiO_2 particles and the matrix due to lower temperature and formation and stabilization of Mg_2Si intermetallic phase with the matrix (Sarada et al., 2016).

When quenching at a high temperature, the cooling power of water is lowered and thus a slow quenching rate is observed. As a result of slower cooling rates a significant loss in hardness is observed because the cooling rate of the boiling water is not sufficient to freeze the solute atoms during the quench. Rajan et al., (1988) observed that cooling rates should be fast but in order to avoid high thermal stresses during quenching it is better to use hot quenching media such as boiling water, hot oil or fused baths can be used.

Tensile strength test

The variation of ultimate tensile strength (UTS) and peak load under different quenching media is as shown in (Figures 2 and 3). The water at room temperature quenched specimen showed an increase of 7.5% of ultimate tensile strength and peak load respectively over the as - cast samples. Still air quenched sample showed a decrease of 1.7% while the boiling water quenched sample showed a decrease of 25% respectively compared to as – cast samples. The water at room temperature samples achieved a higher level of residual stresses. When the temperature of water is raised to boiling point, the effectiveness of water quenching is drastically reduced as the quenching speed is lowered. As a result of slower cooling rates increasing, the water temperature may have resulted in a significant loss in hardness and tensile properties as noted by Sarada et al., (2016). In general, significant loss in tensile properties may result when water temperature is raised because the cooling rate is not sufficient to freeze the solute atoms during the quench. Quenching in boiling water can both be beneficial and troublesome. It is beneficial in that lowered residual stresses are achieved when compared to cold water or air quenching. The disadvantage in that, there is a significant reduction in the strength level achieved due to reduction in cooling rate. Rajan et al. (1988) suggested that boiling water quenching should be employed when the dimensional stability of the material is much more important than the strength level desired, so, the strength is sacrificed for dimensional stability. However, for boiling water quenching, quenching explosion that occurs when the samples hit the boiling water must be put into consideration. The improvement in tensile strength of the Al- Sn reinforced 3 wt% SiO_2 metal matrix composite on heat treatment can be attributed to a large extent on formation of intermetallic precipitates which act as obstacles for pinning down the dislocation. This curtails the mobility of dislocations, thereby reducing the extent of plastic deformation which leads to significant improvement in ultimate tensile strength. Sample quenched in water at room temperature showed higher ultimate tensile stress due to formation and stabilization of intermetallic phase of Mg_2Si and enhanced bonding between SiO_2 particles and matrix due to lower tempera-

Table 1. Chemical composition of Al-Sn alloy in percentages.

Element	Al	P	Cr	Mn	Fe	Ni	Cu	As	Sn	Zn	Pb	Si	Bi	Mg	K	Ca
	91.5	0.08	0.01	0.06	0.88	0.14	1.03	0.06	4.34	0.18	0.20	0.06	0.01	0.89	0.01	0.34

Table 2. Chemical composition of silica (S_iO_2) powder in percentage.

Compound	SiO_2	FeO	F_2O_3	Al_2O_3	MgO	CaO
	96.01	1.05	1.52	1.20	0.50	*

*Trace quantity.

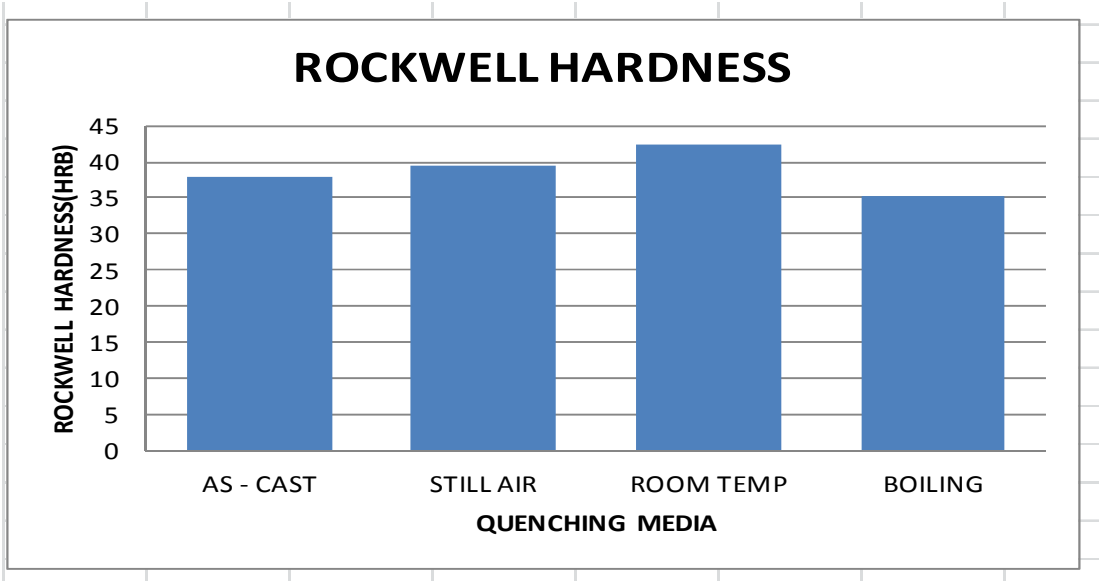

Figure 1. Variation of hardness under different quenching media.

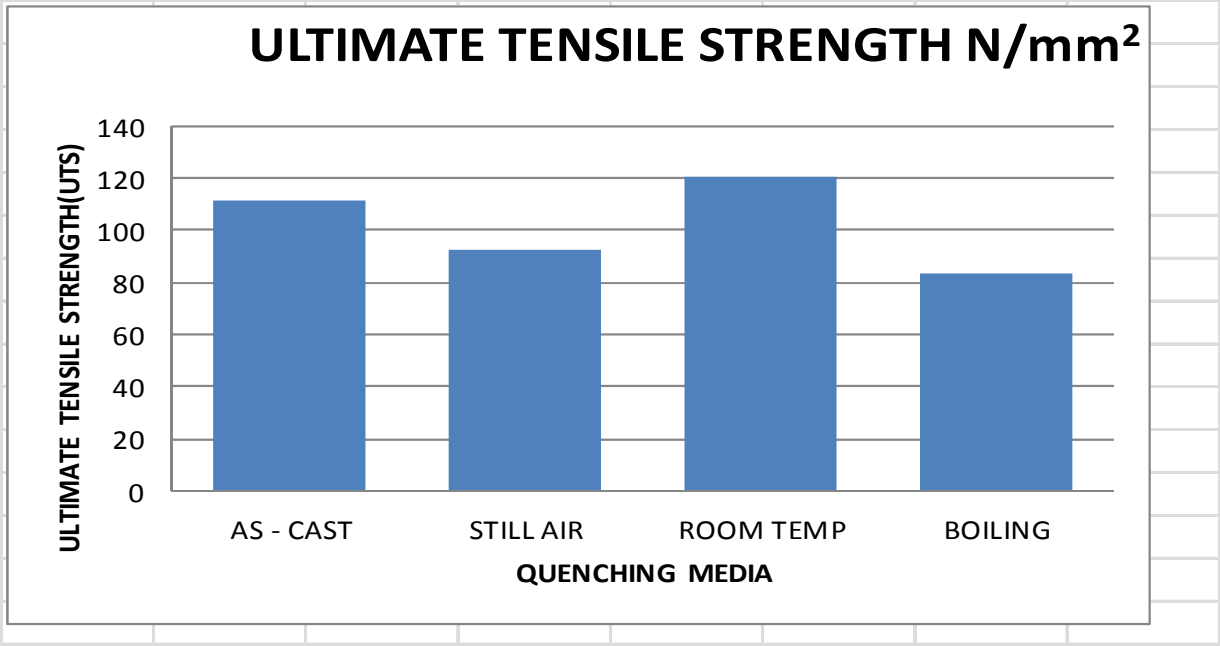

Figure 2. Variation of tensile strength under different quenching media.

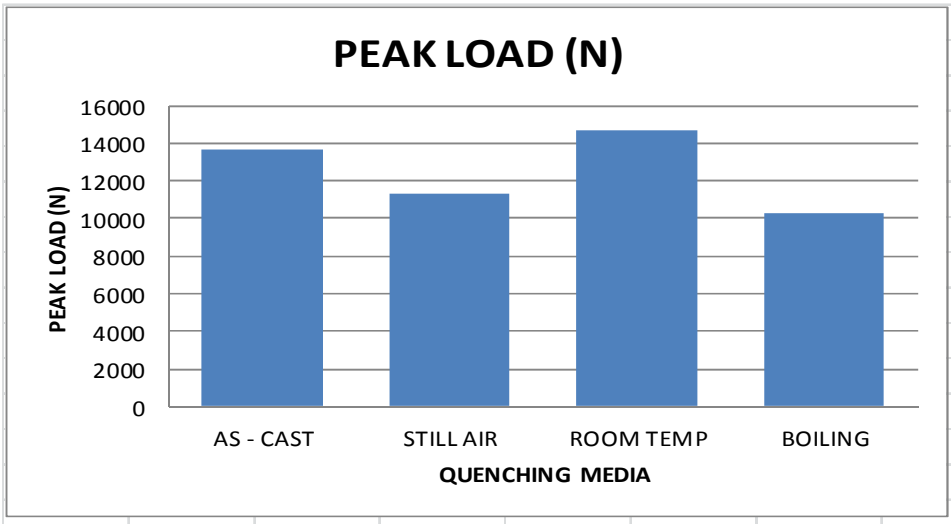

Figure 3. Variation of peak load under different quenching media.

ture. Air hardening could have relieved the internal stresses leading to lower value of tensile strength as noted by Sarada et al., (2016).

Conclusion

The following conclusions were drawn from the above research work.

(i) An aluminum-tin reinforced silicon dioxide metal matrix composite was successfully cast.
(ii) Solutionizing and quenching in different media were successfully carried out on samples.
(iii) Heat treated samples showed variations in hardness and ultimate tensile stress when compared to as – cast sample.
(iv) Samples quenched in water at room temperature had higher hardness and tensile strength values when compared to other quenching media.
(v) Quenching in boiling water should be employed when hardness and tensile strength are not a priority but dimensional stability.

Authors' declaration

We declared that this study is an original research by our research team and we agree to publish it in the journal.

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