PRECIPITATION HARDENING BEHAVIOUR OF TWO STAGE STIR CAST AL6061-SIO2 COMPOSITE

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Abstract- In the present work Al6061-SiO_2 composites are produced by two stage stir casting method and subsequently studied various properties. Microstructure, hardness, tensile and wear properties of Al6061 based composite reinforced with silicon oxide particles of various weight percentage (2, 4 and 6% wt.) is analyzed and presented. The aging behavior and tensile properties of the cast material were studied. Experimental results show fairly uniform distribution of the SiO_2 particulates in the matrix of the Al 6061 leading to higher hardness, and tensile strength. Presence of SiO_2 particles in Al6061 alloy accelerating the aging process and thus attains higher strength. These particles provide more sites for the nucleation of fine precipitates. These fine precipitates hinder the movement of dislocation and thus increases hardness as well strength of materials. After aging at 100^{O}C for Al6061/6% wt. SiO_2 composite , highest strength is observed at longer duration of aging. Comparison of the characteristics study before and after heat treatment was done and it is observed that there is an improvement in hardness, tensile strength and wear resistance of both Al6061 alloy and its composites after precipitation hardening treatment.

Index Terms- Al6061 Alloy, Metal Matrix Composites, Stir Casting, Precipitation Hardening

I. INTRODUCTION

In recent times Metal Matrix Composites possessing significantly improved properties like high specific strength, specific modulus, damping capacity, high temperature resistance and good wear resistance compared to unreinforced alloys have evoked a keen interest for potential application in aerospace and automobile industries. Metal matrix composites (MMCs) are engineering materials in which a hard ceramic component is dispersed in a ductile metal matrix in order to obtain characteristics that are superior to those of the conventional monolithic metallic alloys [1]. Aluminium silicon carbide composite material with less weight and more strength is a potential candidate for practical aerospace applications [2]. The composites can be fabricated by various techniques of which Stir casting is a particularly promising route, currently practiced commercially [3]. Stir casting of metal matrix composites was initiated in 1968, when S. Ray introduced alumina particles into aluminum melt by stirring molten aluminum alloys containing the ceramic powders [3]. Stir Casting is one of the most economical methods of processing Metal Matrix Composite for the manufacturing of aluminum alloy based casting composite [4]. The addition of filler content increased the hardness and tensile properties of the composites [2] [5] [6].

Al6061 is a precipitation hardening aluminium alloy, having Mg and Si major elements. This alloy exhibits superior weld ability and mechanical characteristics. It is most commonly used alloy for general applications [7]. With the introduction of Mg the Al-Si alloys can be age hardened by the precipitation of Mg_2Si particles. The age hardening or precipitation hardening is induced by sequential phase transformation that would lead to homogeneous distribution of nano scale, coherent precipitates in a softer, more ductile matrix [8].

Ehsani and rahaine [9] found that in comparison to the 6061 aluminium alloy, the precipitation kinetic was accelerated by adding the reinforcement and this improvement of the kinetics of GP zone formation was related to the higher dislocation density of the metal matrix, due to the thermal mismatch. At higher aging temperatures, the presence of solute clusters and small coherent precipitates in the matrix were easily sheared by mobile dislocations lowering the hardness and abrasive wear resistance of the composites compared to lower aging temperature. The precipitation of small intermetallic compounds increases the hardness and abrasion resistance of the composites and at higher aging time the composites were over aged and this resulted in reduction of hardness and wear resistance due to the coarsening of intermetallic precipitates [9].

In the present work, an attempt is made to investigate possible improvement in the mechanical properties such as hardness tensile strength and wear resistance under both untreated and heat treated condition. The effect of reinforcements on Al 6061 matrix alloy during artificial aging kinetics and behavior of Al 6061-SiO_2 composite produced by stir casting technique are also studied.

II. EXPERIMENTAL DETAILS

A. Base Material

The base matrix chosen in the present study is the aluminium 6061 because it is one of the most extensively used 6000 series aluminium alloys. They have high strength to weight ratio, good formability, age hardenability and other appropriate properties. Among different aluminium alloys, Al 6061 has high machinability, high hardness property and also light weight [10]. Table 1 gives the chemical composition

of Al6061. Silicon Oxide (SiO_2) with a average particle size of 30-33µm was used as reinforcement.

Table 1: Composition of AA 6061 matrix material.

Material	Si	Fe	Cu	Zn	Mg	Cr	Al
Wt%	0.52	0.55	0.24	0.20	0.98	0.23	Rest

B. Double stir casting technique

The Al6061 billets were melted in a graphite crucible by electric resistance furnace of 5 kW rating and melting was allowed to progress until a uniform temperature of 750^{O} C (which is above the liquidus temperature) was attained. Small amount of scum powder is introduced in it to remove the slag or flux. The entire melt is then degassed by adding dry hexa chloro ethane tablet weighing 10 grams (C_2Cl_6) [11]. The SiO_2 particles are preheated for 200^{O}C for 2 h in order to remove the volatile substances, Which results in improving the wettability of the particle [12-14]. The melt was then allowed to cool for 600^{O} C (slightly below the liquidus temperature) to a semi-solid state. At this stage, preheated silicon oxide mixture in varying % wt. (2, 4 and 6%) were poured in the vortex resulting due to stirring. A mild steel stirrer with axis in vertical position was utilised. The speed of stirring was kept in the range 150-200 rpm and mixing is done for 10 min. to permit for better dispersion of the silicon oxide in the molten alloy. While stirring, pieces of Mg (1% wt.) are added to the melt to enhance the wettability of silicon carbide particles with the alloy melt [15]. An external temperature probe was utilized in all cases to monitor the temperature readings of the furnace. After mixing the reinforcements in semisolid state, the composite slurry was reheated and maintained at a temperature of 750^{O} C $\pm$10^{O} C (above the liquidus temperature) and once again stirring operation was performed for 10 minutes at an average stirring rate of 400rpm. The melt was poured in the cast iron molds, which are preheated to 500^{o}C. Al 6061-SiO_2 composites were fabricated by altering the amount of silicon oxide particles in the range 2-6 % wt. and the melt is allowed to solidify in air for 2 h. The casted composites are shown in Fig. 1.

C. Age hardening/ Precipitation hardening treatment

The specimen prepared for above test is subjected to age hardening heat treatment. Specimens are soaked at 558^{O}C for duration of 2h, then immediately quenched in water at room temperature. The quenched specimens were artificially aged in the furnace at 100, 150 and 200^{O}C for various durations of time.

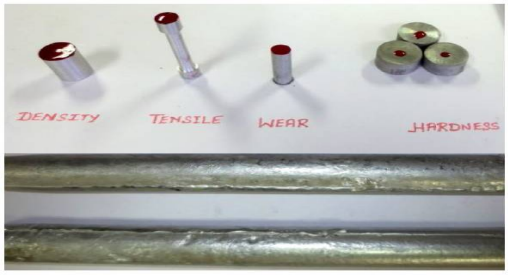


Fig. 1: As cast Al 6061-SiO_2 composites and variuous test specimens

D. Hardness and Tensile testing

Hardness tests were carried out in a Brinell hardness testing machine with steel ball indenter of diameter 5mm and a load of 250 kgf (SAROJ Brinell Hardness Testing Machine, Model:-B/3000/00, Sl# 13/06/08-India). Specimens of diameter 12 mm and length 15 mm are prepared. In order to eliminate possible segregation effect, the average of a minimum of three indentations readings is taken for each specimen at different locations of the test samples.

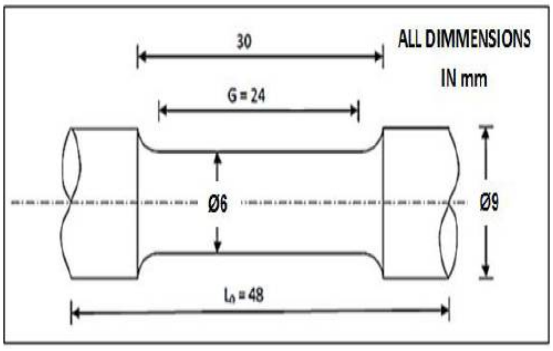


Fig.2 Tensile specimen as per ASTM-E8M standard.

Tensile properties dictate how the material will react to forces being applied in tension. Tensile specimen is prepared according to ASTM-E8M standards [16]. Circular cross section specimen with diameter 6 mm and gauge length of 24 mm is prepared as shown in Fig.2. Tensile test is carried out on tensometer. Diameter of specimen is measured using vernier caliper and cross sectional area is calculated. The load cell value is kept to 20.5 kN and test mode is selected as break. The cross head speed is kept constant at value of 10 mm/ min, with length increment value of 0.01 mm. The specimen is fixed firmly in gripper.

The Wear resistance tests were performed on pin-on-disc tribo-meter under dry sliding conditions (WEAR AND FRICTION MONITOR TR- 201CL). The test were conducted on 8 mm diameter, 25 mm long cylindrical specimens (ASTM G-99) against a rotating EN-32 steel disc (count face) having hardness 63Rc.

III. RESULTS AND DISCUSSION

A. Microstructural features

The optical microscopy illustrates the microstructures of Al6061 composite with 2, 4 and 6% (wt.) SiO_2 as compared to unreinforced alloy. Fig. 3 shows optical microscope images at 20X magnification. The micrographs clearly indicate the evidence of minimal porosity in both the Al6061 alloy and Al6061-SiO_2 composites. The dark spots are the discrete SiO_2 particles embedded in Al6061 matrix. There is no agglomeration of reinforcements in the matrix. Also the microstructure does not reveal the existence of the blow holes or air pockets. This can be attributed to effective stirring action and use of appropriate process parameters.

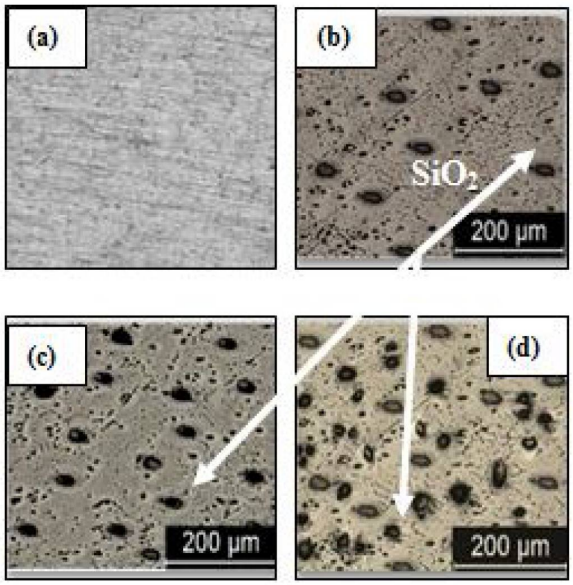


Fig.3: Optical micrographs of a) Al6061 alloy, b) Al6061-2%SiO_2 c) Al6061-4%SiO_2, d) Al6061-6%SiO_2 composites.

B. Hardness

Both as cast and aged samples were tested to determine the Brinnell Hardness Number (BHN). Graphs are plotted showing the hardness values of all the three aging temperatures against the time for Al6061 alloy and Al6061-SiO_2 composites as shown in Figs. 4-7. Fig. 8 shows the peak hardness values obtained in as cast and aging temperatures 100, 150 and 200°C.

In as cast condition it is clear that the hardness values increased with the addition of filler content when compared to the unreinforced alloy. The hardness value found to be increased with increase in weight percentage of SiO_2 reinforcement. The increase in hardness is to be expected since SiO_2 particles being a very hard dispersoid contribute positively to the hardness of the composite [14]. The hardness of as cast Al6061-6%SiO_2 composite is 70 BHN when compared to 50 BHN of Al6061 alloy. Nearly 20% increase in the hardness value is seen for the composite in case of 6% SiO_2 reinforcement in as cast condition over base alloy.

The hardness distribution graphs of age hardened samples in Figures 4-7 show gradual increase in hardness with respect to the increase in aging time where the hardness increases, reaches maximum and later decreases. Presence of reinforcements accelerated aging kinetics as compared to unreinforced matrix alloy. Aging kinetics get accelerated in the composites with increase in wt. % of reinforcements.

Aging is accelerated because of presence of areas with a high concentration of dislocation close to Al6061 matrix and SiO_2 reinforcements interface. These high density locations provide heterogeneous nucleation sites for the precipitation and a high diffusivity path for the diffusion of alloying elements [16].

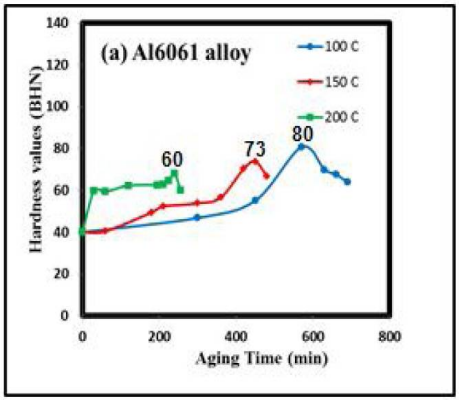


Fig. 4: BHN of Al6061 alloy aged at 100, 150 and 200°C with aging time.

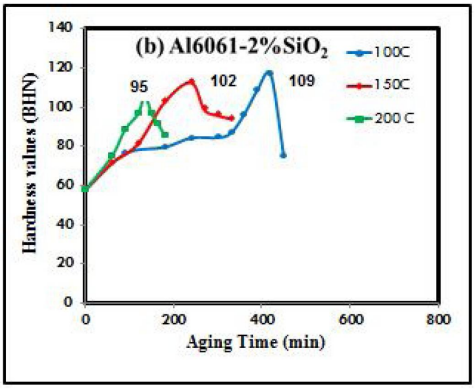


Fig. 5: BHN of Al6061-2% SiO_2 composites aged at 100, 150 and 200°C with aging time

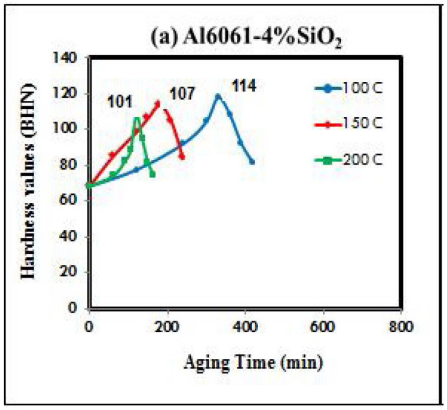


Fig. 6: BHN of Al6061-4% SiO_2 composites aged at 100, 150 and 200°C with aging time.

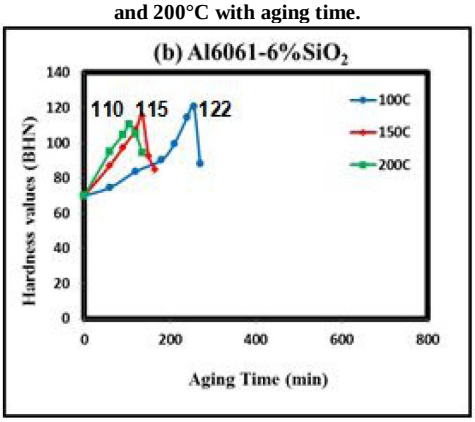
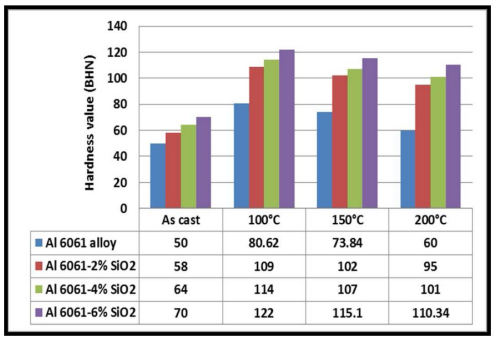


Fig. 7: BHN of Al6061-6% SiO_2 composites aged at 100, 150 and 200°C with aging time.



	As cast	100°C	150°C	200°C
Al 6061 alloy	50	80.62	73.84	60
Al 6061-2% SiO2	58	109	102	95
Al 6061-4% SiO2	64	114	107	101
Al 6061-6% SiO2	70	122	115.1	110.34

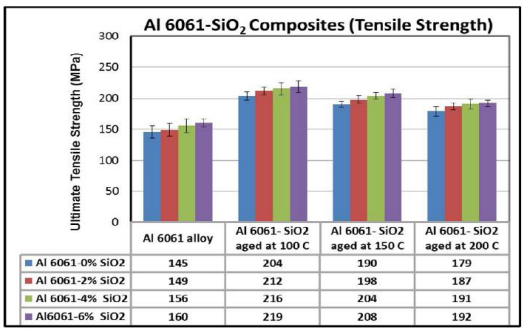
Fig.8: Peak Hardness values of Al6061 alloy and Al 6061-SiO_2 composites under as cast and different aging conditions.

The hardness of the alloy increases with the increase in the wt.% of reinforcements in as-cast condition. Compared to base alloy, composites show drastic increase in the hardness in as cast and treated conditions. Lower aging temperature shows increase in hardness of base alloy as well as composites as compared to higher temperature aging. Lower temperature aging contributes to the increased hardness by increasing the number of intermediate zones during precipitation; increase in the number of finer inter-metallic's and decreased interparticle distances. The hardness value decreases after peak aging condition, due to coarsening of precipitates which form during aging and the condition is termed as over aging.

Over aging induces softness in the alloy due to which hardness value decrease drastically. The rise of temperature causes the ageing rate to increase due the enhanced rate of diffusion of solid atom through the matrix. From the above results it can be concluded that heat treatment has a profound influence on the hardness of matrix alloy as well as composites and higher the aging temperature, lower is the time required to attain peak hardness [17].

C. Tensile test

Tensile test was carried out for as cast and aged specimens. In case of precipitation hardening treatment, tensile test was carried out for peak aged condition. Fig.9 explains the effect of heat treatment condition on UTS for different reinforcement percentages in the composites in as cast and aging conditions.



	Al 6061 alloy	Al 6061- SiO2 aged at 100 C	Al 6061- SiO2 aged at 150 C	Al 6061- SiO2 aged at 200 C
Al 6061 0% SiO2	145	204	190	179
Al 6061-2% SiO2	149	212	198	187
Al 6061-4% SiO2	156	216	204	191
Al6061-6% SiO2	160	219	208	192

Fig. 9 : Ultimate Tensile Strength for Al6061 alloy and its composites

From the Fig.9 it can be observed that the ultimate tensile strength increases by a small margin with the addition of filler content when compared to unreinforced alloy in as cast condition. The reinforcement particles control the mechanical properties of the composites due to the strong interface, which transfers and distributes the load from the matrix to the reinforcement exhibiting increased elastic modulus and strength.

The UTS in composite or base alloy is very sensitive towards age hardening. There is a minimum of 30% additional increase in the UTS by age hardening over untreated specimen. Increase in weight percentage of SiO_2 in the composite linearly increases the UTS at slower rate. The UTS of Al6061-2% SiO_2 is 212 MPa when aged at 100^{O}C and 149 MPa in as cast condition. Whereas, UTS of Al6061-6% SiO_2 is 219 MPa when aged at 100^{O}C and 160 MPa in as cast condition. Hence there is a maximum of 50% additional increase in UTS during lower aging temperature. From the graph, it is clear that higher the weight percentage of reinforcement in the composite and lower the aging temperature better is the ultimate tensile strength. The increase in strength is due to the combined effect of difference in co-efficient of thermal expansion between matrix and SiO_2 particulates and precipitation behavior of solute rich secondary phases.

Therefore this marked improvement in tensile strength of Al6061-SiO_2 composites can be attributed to larger extent due to the formation of intermetallic precipitates (coherent Mg_2Si), which act as the points of obstacles for pinning down the dislocations. This phenomena of multiplication of dislocations curtails the mobility of dislocations, thereby reducing the extent of plastic deformation. This leads to significant improvement in UTS [18].

D. Tribological characteristics

Composite materials used for tribological applications should be able to support a load without undue distortion, deformation or fracture, and should have a low friction coefficient and low wear under sliding contact. The tribological behavior of the composites is known to be affected by the microstructural characteristics of the matrix, and also by the type, shape and volume fraction of the reinforcement. The wear resistance of the alloy is improved significantly due to the incorporation of reinforcements as shown in Fig.10. Under all the testing conditions it is observed that the wear rate of unreinforced Al6061 alloy is maximum irrespective of loads. As the SiO_2 content increases, the degree of effective contact between the asperities of composite surface and counter surface decreases and thus the wear rate of composite reduces.

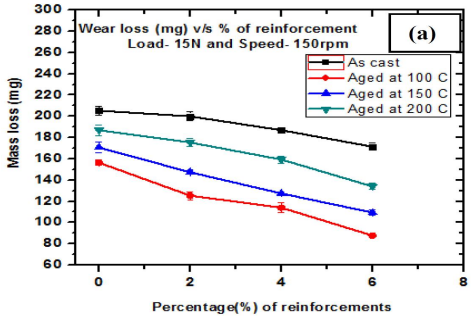
The applied load has a significant influence on the wear rate of tested materials. In general, with the increase of the applied specific load, the wear rate of

both the unreinforced aluminium matrix and composites also increases. The increase in wear rates with increased load of all the materials studied can be attributed to the larger extent of plastic deformation which results in formation of wear debris at higher loads. Greater the extent of plastic deformation, higher will be the probability of subsurface cracking which in turn leads to larger material removal.

The unreinforced aluminium alloy shows continuous increasing trend of wear rate with increasing applied normal load, due to direct metal to metal contact as a result of large scale plastic deformation during dry sliding condition. Whereas, in the case of Aluminium MMC's, the depth of penetration by the harder asperities of hardened steel disk is primarily governed by the protruded hard ceramic reinforcement. Thus, the major portion of the applied load is carried by SiO_2 particles.

The Al6061 alloy and Al6061- SiO_2 composites showed a decreasing trend in wear rate when subjected to precipitation hardening. In all the cases the specimens aged at 100°C showed better wear resistance. Also, it is observed that, as the aging temperature increases the wear resistance of the alloy or the composites decreases. Peak aged samples show improved wear resistance and it is associated with load bearing capacity of the reinforcement in the matrix and the precipitation of intermetallics at the SiO_2 interface. These precipitates are believed to improve the interfacial bonding between reinforcements and the matrix, serve as refractory material and increases hot hardness, which in turn results improvement in high temperature wear resistance.

At 15N load conditions, where the load on the pin is very small the wear rate is small under all the aging conditions. At lower loads the intensity of strain hardening is small, accordingly the wear rate is not so sensitive with sliding distance and aging conditions. But appreciable changes are observed at higher loads. At the given sliding velocity for all the speeds, the wear rate increases as the normal load is raised. This trend is due to the fact that at higher load, force of friction increases which in turn causes an enhanced de-bonding and fracture. During beginning, the initial rubbing breaks the layers of surface, which cleans and smoothens the surface and enhances the strength and contact between the surfaces.



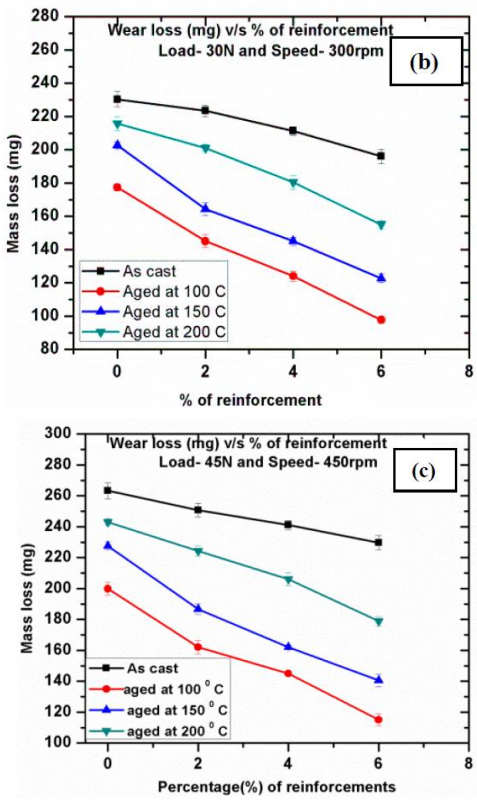


Fig.10: Wear loss with increase in percentage of reinforcement of untreated and heat treated Al6061-SiO_2 composites under different loads and speeds.

The force of friction because of tillage effect between the surfaces leads to rise in the temperature between the mating surfaces. This effect results in adhesion and raises the intensity of deformation at the surface layers, resulting in further loss of the material. For sliding speed of 150 rpm wear rate is minimal, but increase in load and sliding speed has increased wear rate drastically. At high speed there will be more heat generation which induces softness in material. Lower aging temperature (100^{O}C) with higher reinforcement contents (Al6061-6% SiO_2) on the disc is favorable condition for the improvement in wear resistance. On an average there is nearly 30 to 50% improvement in wear resistance in Al6061- SiO_2 composites as compared to Al6061 alloy.

CONCLUSION

In the present work the effect of precipitation hardening treatment on Al6061-SiO_2 composites is studied. Al6061- SiO_2 composites with the reinforcements varying from 2% to 6% in weight are successfully fabricated by two step stir casting technique. The microstructural analysis shows minimal porosity in Al 6061 alloy and Al6061-SiO_2 of the base matrix. The hardness value increases with the addition of filler content when compared to the unreinforced alloy. The precipitation kinetics is slower at lower aging temperatures but peak hardness is higher compared to higher aging temperature for both

base alloy as well as the composites. Al6061-6% SiO_2 composites have higher hardness property in both as cast and peak aged condition when compared to the unreinforced alloy and other composites in study. The increase in ultimate tensile strength of Al6061 alloy and Al6061- SiO_2 composites was marginal in as cast condition. The aging kinetics are accelerated as the weight percentage of SiO_2 increases in the composites making it very sensitive to age hardening irrespective of lower or higher aging temperatures. It is observed that amongst the investigated alloys in as-cast condition Al6061-6%SiO_2 metal matrix composites exhibited highest tensile strength. Also it is found that in aging condition the same Al6061-6% SiO_2 metal matrix composites showed maximum strength. Wear resistance of the alloy is significantly improved with the addition of reinforcements. Peak aged samples show improved wear resistance and it is associated with type and size of the precipitation of intermetallics at the SiO_2 interface. Peak aged composites Al6061-6wt.% SiO_2 reinforcement displays excellent wear resistance. Overall, it can be concluded that Al6061-6% SiO_2 exhibits superior mechanical properties compared with Al6061 alloy, Al6061-2%SiO_2 and Al6061-4% SiO_2 composites.

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