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Experimental investigation on thermal behavior of fly ash reinforced aluminium alloy (Al6061) hybrid composite

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ABSTRACT

In the present study, the thermal behavior of pure Al6061 and fly ash reinforced Al6061 with varying particulate sizes were investigated for the first time. Metal matrix syntactic foams of ceramic fly ash (4 – 16 wt. %) embedded in aluminum (Al6061) matrix have been fabricated by using stir casting technique with different fly ash particulate sizes of size below 50µm and 51µm-100µm, respectively. The microstructural characteristics were studied by using scanning electron microscopy (SEM). It has been observed that there is a uniform distribution of lower particulate size fly ash as compared to higher particulate size in the aluminium matrix respectively. For all the cases, the accumulation of fly ash in Al6061 decreases the thermal conductivity and increases the specific heat carrying capacity of a hybrid composite. Increase in weight percentage of fly ash in Al6061 decreases thermal conductivity and thermal diffusivity respectively.

Keywords: Metal matrix composites; Al6061 and fly ash; microstructure; thermal behavior.

INTRODUCTION

Aluminium Metal matrix composites are well-known to possess higher specific strength, high stiffness and low thermal expansion co-efficient when reinforced with suitable particles compared to their base alloy matrices. Low density and low cost reinforcements in composites attracted the researcher to work on different types of reinforced composites. As fly ash is a byproduct of coal fired thermal power stations acting as dispersive reinforcements in various applications due to its huge availability as solid waste. Fly ash can be incorporated into metal as the dispersed phase to make low cost metal matrix composites with a range of useful properties[1-2]. One advantage of metal matrix composites is the ability to modify the thermal properties, such as thermal conductivity and coefficient of thermal expansion through the proper control of reinforcement and matrix. In addition, the manufacturing flexibility of the metal matrix composite by various processes allows the fabrication of complicated shaped parts [3, 4]. Aluminium metal matrix composites are desired engineering material for aerospace, automobile and mineral processing industries for various high performing components that are being used for varieties of applications [5]; owing to their lower weight and excellent thermal conductivity properties [6]. Al6061 and Al7075 are explored significantly due to their enhanced properties such as heat treatable, highly corrosion resistant, moderate strength etc.

Sudarshan et al. [1] characterized the A356 Al - fly ash composites with two different ranges of particle sizes. They concluded that increase in elastic modulus, hardness and proof stress by incorporation of fly ash and they also reported that greater mechanical properties were obtained with small size range fly ash particle as compared to larger fly ash particles. Chittaranjan. V. et al. [7] made an attempts to study the thermal properties of Al6061-fly ash composite by stir casting process with fly ash particles sized between 0.1-100μm in Al6061. By varying the fly ash weight percentage thermal conductivity of composite decreases due to the fact that fly ash has lesser density. They have also concluded that the thermal properties of like cracking, expansion and resistance are enhanced compared to other metals. Anilkumar H.C. et al. [8] prepared the specimens with varying weight percentage of 10, 15 and 20% of fly ash and particle sized 4-25 μm, 40-50 μm and 75-100 μm reinforced Al6061 by stir casting method. The effect on tribological, mechanical properties and their co-relations, due to variation in particle size of fly ash in the composite has been studied. They observed that, wear and hardness properties were enriched due to increase in volume fraction of silicon carbide in aluminium alloy composites. Anilkumar H.C. et al. [9] prepared the graphite and silicon carbide particles reinforced aluminium alloy composites. They found that increase in volume fraction of graphite and silicon carbide particles due to fly ash in composite, enhances the mechanical properties of composite. Mahendra et al. [10] described that the properties of composite made with Al- 4.5% Cu alloy and fly ash as reinforcement increases with increase in the fly ash content. Veeresh kumar G. B. et al. [11] conveyed that the mechanical properties of composite made with Al6061-Al_2O_3 & Al7075-SiC were found to be improved with increase in reinforcement in the composites. It was also reported that dispersion of SiC in Al7075 and Al2O3 in Al6061 enhances the mechanical properties. Lokesh G.N et al. [12] Revealed that the wear resistance of the aluminium matrix with fly ash reinforcement, properties of composite improved with increase in fly ash content, but declines with increase in track velocity and normal load. Mahagundappa M. Benal et al. [13] studied the effect of thermal aging and fly ash reinforcement in Al6061 composite, and reported that increase in fly ash reinforcement decreases the ductility of composite but enhances its mechanical properties. Das T et al. [14] studied the two different composites with variation in the reinforcement pattern such as angular reinforcements and spherical reinforcements. They found that with the addition of both angular and spherical reinforcements there is a significant increase in the elastic modulus, percent proof stress, ultimate tensile stress, but ductility decreases compared with the unreinforced alloy.

This work mainly deals with the examination of thermal properties of fly ash reinforced Al6061. The microstructure of fly ash reinforcement in Al6061 with varying particle and percentage weights were discussed. Further, thermal properties such as co-efficient of thermal expansion, specific heat capacity, thermal conductivity and thermal diffusivity, respectively, were investigated and discussed based on the experimental investigations. The Pure Al6061 and composites of Al6061-flyash were fabricated by using stir casting Method.

EXPERIMENTAL PROCEDURE

Materials

The composition of commercial Al6061 and fly ash were listed in Table 1 and Table 2. The aluminium alloy matrix used in the present study was Al6061. The fly ash, form of syntactic foam has been chosen as filler. The material property of fly ash were specific gravity within 1.8 - 2.5 and a bulk density of about 0.7–1.0 tons per cubic [15]. The specific exterior area of fly ash alters within 2,200 to 7,800 cm^2 per gram. Fly ash comprises of cenospheres - resonating spherical particles having a completely low bulk density of 0.5 - 0.7 tons per cubic meter, which establish up to 6% of the ash weight and are appropriate to be employed for superior industrial applications [16].

Table 1. Chemical Composition of Al6061 by weight %

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
6061	0.41-0.8	0.72	0.15-0.42	0.15	0.8-1.3	0.03-0.35	0.27	0.16	0.04

Table 2. Chemical Composition of fly ash by weight %

Components of fly ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Percentage (%)	67.25	29.15	0.18	1.4	1.8

Fabrication process

A pure Al6061 and Fly ash reinforced Aluminum (Al6061) composite specimens were prepared through the stir-casting technique which involved melting of aluminum alloy, mixing of preheated fly ash particles in the melt through mechanical stirring of 0.25 HP motor. The stirring was maintained between 5 to 7 mins at an impeller speed of 200 rpm. The melt temperature was maintained at 700ºC during the addition of fly ash particles. The dispersion of fly ash was achieved by the vortex method and casting of the fly ash -melt mixture in a preheated dies assemblies under application of slight pressure (1–3 MPa). The two sets of composite castings were prepared for below 50 microns and greater than 50 micron (51-100 microns) fly ash particle size with Al6061. For each set of composite castings with varying weight percentage (wt. %) of fly ash such as 0.04, 0.08, 0.12 and 0.16 were added to Al6061. Pure Al6061 and two sets of composite castings were obtained according to the standard die sizes required for testing.

Testing

In this study Dilatometer apparatus was used to measure the linear coefficient of thermal expansion. Cylindrical specimens of 8 mm diameter, 40 mm length and operating temperature of 400°C were used for testing linear coefficient of thermal expansion. Specific heat capacity, thermal conductivity and thermal diffusivity were measured for pure Al6061 and two sets of composite castings using standard experimental setup.

Micro Structure Characterization setups

The samples were polished using standard metallographic techniques and etched with the Keller's reagent. This etched sample were given gold sputtering, prior to scanning electron microscope (SEM, Helios Nanolab600i) examination. The microstructure of pure Al6061 and fly ash reinforced Al6061 were examined by SEM.

Linear Coefficient of Thermal expansion (CTE)

The coefficient of thermal expansion is measure of change in material per unit length. The CTE values were found out for pure Al6061 and both the sets of composites by varying the temperature range between 150 ^{0}C to 350 ^{0}C. The Experiments were carried out for pure Al6061 and varying weight percentage with different particulate sizes of fly ash, and their corresponding deflection were noted down. The following Equation (1) was used to calculate the coefficient of thermal expansion with varying temperature range and corresponding defection of composites.

$$\alpha = \frac{L_f - L_o}{L_o(T_f - T_o)} = \frac{\Delta L}{L_o(\Delta T)} = \frac{\varepsilon}{(\Delta T)} \tag{1}$$

Where T_0 and T_f are initial and final temperatures (in K), L_0 and L_f are the initial and final dimensions of the material and is the strain. It was found that the CTE of Al6061 and fly ash were 25.3 × 10^{-6} m/°C, 6.1×10^{-6}m /°C respectively [14]. Apparatus used to measure the linear coefficient of thermal expansion is Dilatometer and its specification as shown in Table 3. The standard cylindrical specimens of size of 40 mm length and 6mm diameter as shown in the Figure 1.

Figure 1. Specimen used in experiment.

Table 3. Specification of Dilatometer Machine

Specifications	Minimum	Maximum
Maximum Operating Temperature	1000 ^{0}C	1200 ^{0}C
Furnace Temperature	30 ^{0}C	1200 ^{0}C
Furnace Power	4.5kW	
Minimum resolution	20nm in ΔL and 0.1˚C in ΔL	
Maximum elongation	4000µm	
Watt power supply	220-240V 50Hz	

Specific Heat Capacity of composite solid (Cp)

Heat capacity is the ability of material to absorb heat from surroundings and also it prescribes the amount of energy required to produce a unit degree temperature rise. It was found that specific heat capacity of Al6061 alloy and fly ash were 0.896 J/g-°C, 0.9497 J/g-°C respectively. The Figure 2 shows the setup for specific heat capacity measurement which includes ammeter of 0-2A, voltmeter of 0-200v, thermocouples of 0-250 ^{0}C, temperature indicator maximum of 1250 ^{0}C, Dimmer stat of 4A load, insulated container and heater. The weight of specimen and temperature of 200 ml of water in the container was noted.

Figure 2. Experimental setup used for the measurement of specific heat capacity.

The specimen was heated to a temperature of 100 ^{0}C by mica heater with dimmer stat. The dimmer stat controls the temperature of specimen with constant supply of heat. When specimen reaches to the desired temperature, it was dipped in a water of insulated container and the heat transfer will takes place between heated metal workpiece specimen water. After some time the water and heated specimens attains the same temperature, and the temperatures were noted down and specific heat capacity of metal pieces were calculated by using the Equation (2) (By balancing the below equation).

$$Q = mC_p \Delta t \tag{2}$$

Thermal conductivity of composite solid (k)

Thermal conductivity is the ability of material to conduct heat transfer. Many engineering situations involve the use of composite materials that consists of two or more materials of different thermal conductivity. The specimens are prepared according to the standards of dimensions 100 mm diameter and 6 mm thick.

The setup prepared for the measurement of thermal conductivity of composite material was shown in below Figure 5 and Figure 3. The equipment's used for the setup were voltmeter, ammeter, dimmer stat, thermocouples and thermometer. The measurement of water inlet and outlet temperature, cooling jacket, heater, standard disc (mild steel with k=45W/m-k), specimen, insulated container isolated with ceramic wool etc. were noted down by placing thermocouples. Water flow rate through the cooling jacket was adjusted according to the requirement. During the conduction of experiment, constant heat was supplied to the heater through dimmer stat so heat transfer will takes place in composite slab. Due to the presence of insulating material (asbestos with k=0.1668 W/mk) there will be temperature difference between discs. All the temperatures were noted down and also voltmeter and ammeter readings. Heat supplied was calculated by multiplying current and voltage readings and was repeated for a time interval of 20 minute up to 3 hours so that composite slab will reach the steady state. Heat lost though the slab was calculated by taking water inlet and outlet temperatures. The corresponding thermal conductivity was calculated.

Figure 3. Experimental setup used for measurement of thermal conductivity of composite.

Thermal diffusivity of composite (α)

The measure of thermal diffusivity is the capability of a material to transfer thermal energy relative to its ability to withheld thermal energy. The Equation (3) was used to calculate the thermal diffusivity.

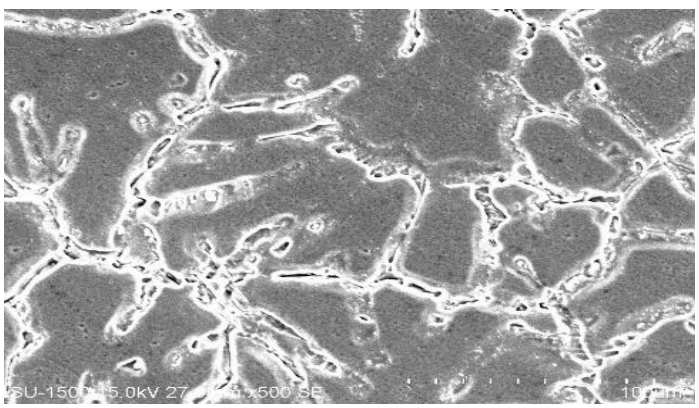
$$\alpha = \frac{k}{\rho C_p} \tag{3}$$

Where k is thermal conductivity (W/m·K), ρ is density (kg/m³), and C_p is specific heat capacity, (J/kg·K)

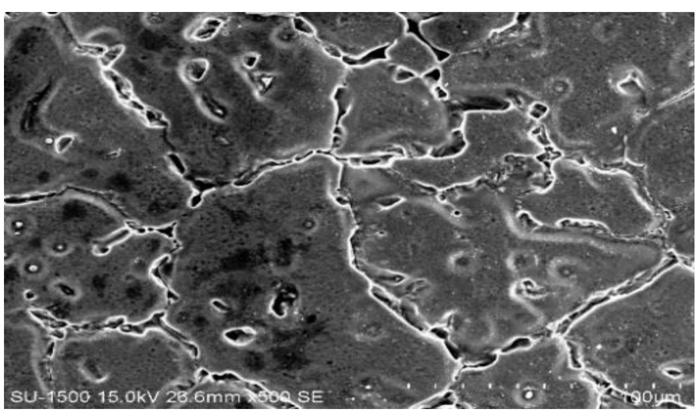
RESULTS AND DISCUSSION

Microstructure

The typical SEM micrographs of pure Al6061 and different percentages of fly ash reinforced Aluminum (Al6061) composite specimens were done. The Figure 4 (a) depicts the microstructure of pure cast Al6061. It was found that no voids were observed and the casting is free from defects. Figure 4 (b) and 4 (c) depicts the microstructures with 4% and 8% weight fractions of fly ash particles sized within 50 µm of Al6061, [9] it was clearly observed that the fly ash particles were present and the fibres were comparatively higher in Al6061 than composites with 4% and 8% weight fractions. The addition of fly ash particles increases the bonding strength, tensile strength, hardness and hence thermal properties could enhanced [15, 24]. Figure 7 (d) and 7 (e) shows that the distribution of fly ash particles were uniform and no clustering of reinforcement was observed in the matrix, and hence the dispersion of fly ash particles were seen uniform [17] and no gap was observed between the particles and matrix. It was also observed that the reinforcing materials are well bonded with matrix and therefore the formation of fiber decreases with the increases in fly ash percentage [17] and thus the mixing of fly ash particles was comparatively better in composite with fly ash particles sized below 50μm [18]. As a result of this uniform mixing of fly ash in aluminum (Al6061) composite specimens, the better the thermal expansion property was observed with fly ash particles sized below 50μm and the clustering of reinforcement was not happened. Due to the proper mixing of base material and reinforcement, the composites exhibit higher specific heat carrying capacity [17] and hence, there is no segregation of particles during solidification process. As a result of this, the formation of fibre were less, with the increased percentage of fly ash. Hence, the thermal conductivity was decreased with the increase in fly ash percentage in the specimens.



(a)



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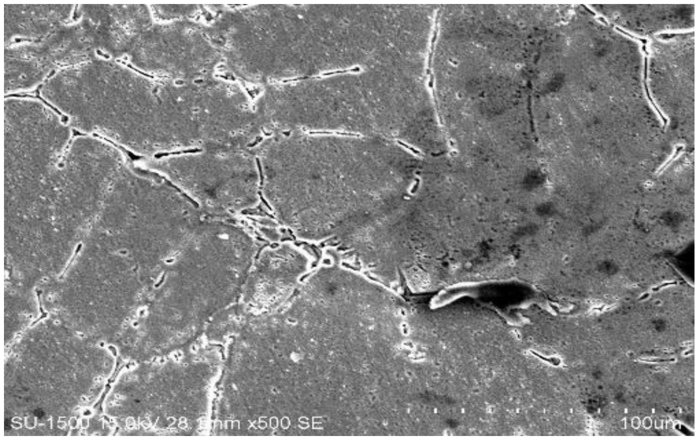

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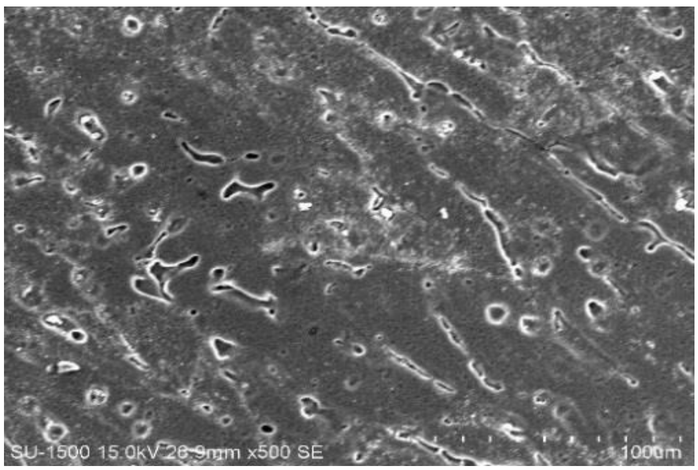

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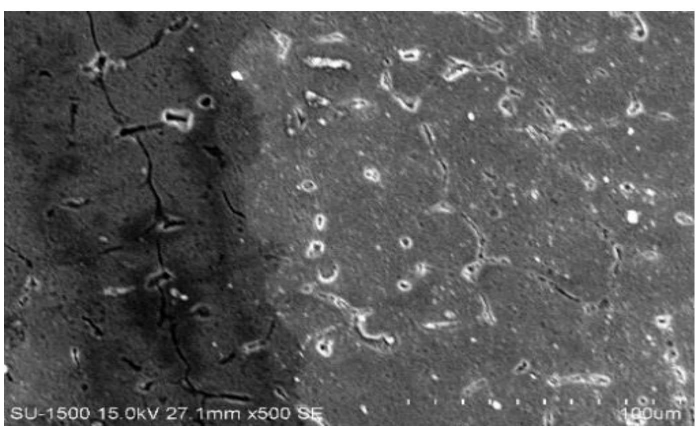
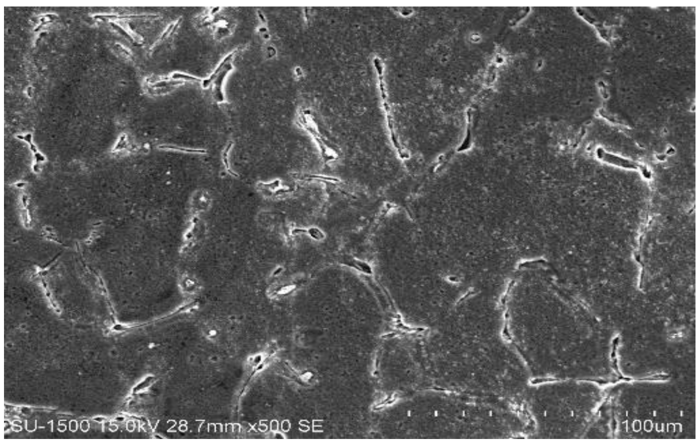


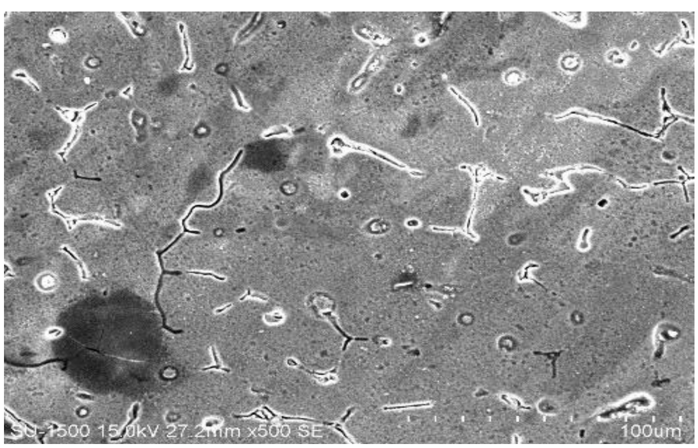
(e)

Figure 4. (a) Microstructure of Al6061, and (b) micrograph of composite with 4% fly ash (below 50µm), (c) micrograph of composite with 8% fly ash (below 50µm), (d) micrograph of composite with 12% fly ash (below 50µm) and (e) micrograph of composite with 16% fly ash (below 50µm)

Figure 5 (a) and 5 (b) shows the micrographs of Al6061 with 8% and 12% fly ash particles sized between 51-100 µm along with the microstructure of cast Al6061 alloy (as received samples) [9]. The Precipitations were evident, in the grains and also along the grains, as shown in figures 5 (a) and 5 (b), respectively. It was observed that the grains were discontinuing by the addition of fly ash in increasing order which leads to improvement in thermal properties. Figure 5 (c) and 5 (d) reveals that the grain size of matrix alloy is larger than that of composites microstructure of Al6061 with fly ash percentage varying from 12%-16% respectively [19]. Micrographs clearly exhibits the minimal micro-porosities in the casting and also there was no gap observed between the particles and matrix as shown in Figures 5 (c) and 5 (d). It was clearly observed that the reinforcing materials are well bonded with matrix [9].



(a)



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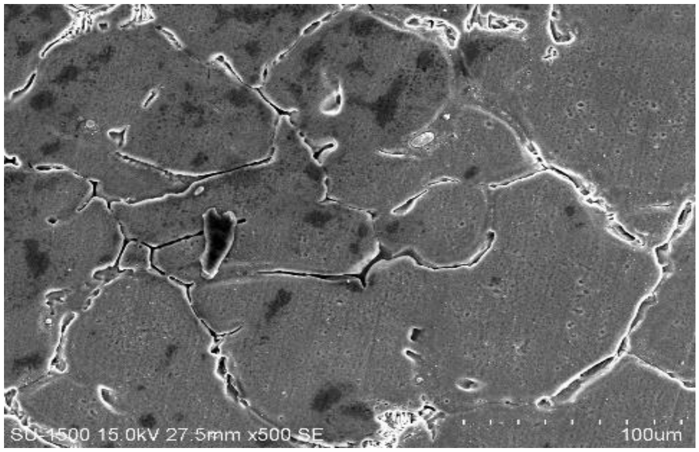

(c)

(d)

Figure 5. (a) Microstructure of Al6061 with 4% weight fraction of fly ash (51-100µm), (b) Microstructure of Al6061 with 8% Weight fraction of fly ash (51-100µm), (c) Microstructure of Al6061 with 12% weight fraction of fly ash (51-100µm), and (d) Microstructure of Al6061 with 16% weight fraction of fly ash (51-100µm)

Coefficient of Thermal Expansion

From literature survey, it was observed that thermal expansion of Al6061 at 250°C is 25.24 $\times 10^{-6}$ m/m-°C [20]. In this work it has been observed that the coefficient of thermal expansion of Al6061 is 24.10 $\times 10^{-6}$ m/m-°C at temperature range of 150-350°C.

Figure 6 depicts the thermal expansion variation of composite material with different fly ash weight parentages. It has been observed that thermal expansion decreases with increase in the fly ash wt. % due to presence of filled microballoons and poor interfacial strength between the cenospheres and matrix alloy [25, 26, 6]. At elevated temperatures, the kinetic energy of molecules increases in the composite which intern increases the thermal expansion of material; it is also known that at lower temperature the molecules exhibit lower kinetic energy [21]. This variation in thermal expansion may also due to the asymmetric (inharmonic) contour of interatomic potential of composite material. If this inter-atomic potential is symmetric (harmonic), then common value of interatomic potential does not change, i.e. no thermal expansion. [21]. Therefore at higher temperature, the common value of interatomic potential changes rapidly. This leads to increase in thermal expansion of material. It also observed that at 150°C, elongation of specimen is less than 0.1mm for different compositions. For higher temperature i.e. at 350°C the expansion of material is around 0.5mm and variations in elongations of composite material are drastic. This variation of thermal expansion of composite material may be due to accumulation of fly ash particles. This leads to decrease in thermal expansion of composite material.

From Figure 6, it was observed that composites with fly ash particles sized below 50µm exhibit better thermal expansion property compared to composites with fly ash particles sized above 50µm. This is due to fact that, as size of fly ash particles increases its tendency to withstand temperature decreases [20]. Hence thermal expansion of material is more in case of second set i.e. composites with fly ash particles sized above 50µm.

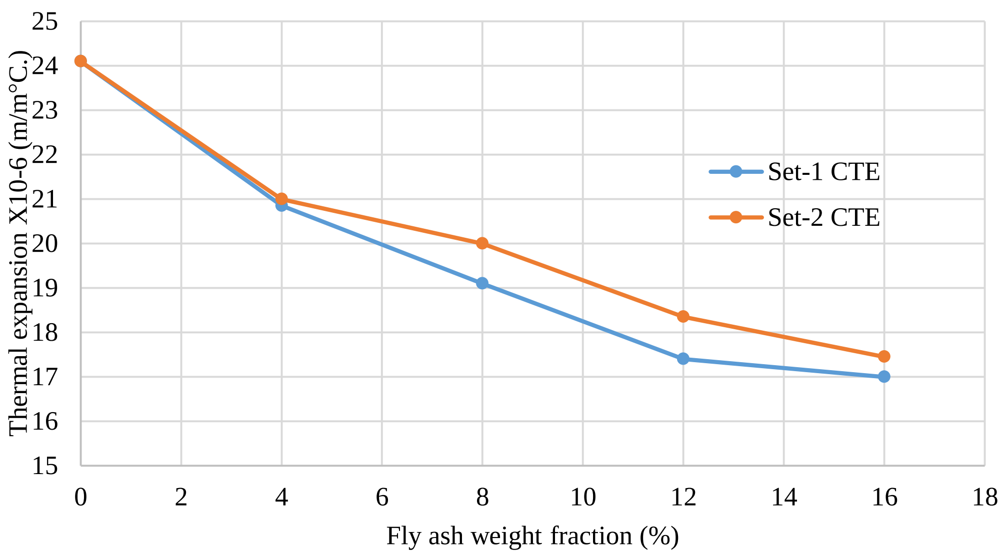

Figure 6. Coefficient of thermal expansion with different fly ash wt. % for two sets of particle size.

Specific Heat Capacity

Figure 10 shows the variation of specific heat with fly ash weight fraction reinforcement. The fly ash particles exhibit the higher specific heat capacity and reinforcing of it in Al6061 alloy enhances the heat capacity of the composite [20,26]. As a result of this, the specific heat capacity of composite also increased. It has been observed that in the Figure 7, the variation of specific heat increases with respect to fly ash particle size. The composite with fly ash wt. % with particle size less than 50µm shows better properties as compared with the particle size of greater than 50µm. The specific hat carrying capacity of specimens increases due to the lower thermal expansion of fine powdered particles of fly ash.

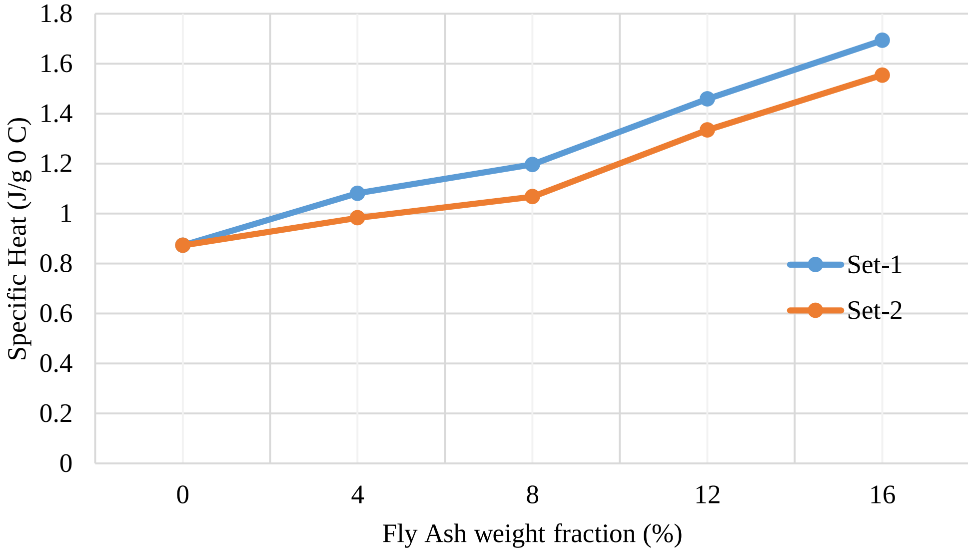

Figure 7. Specific Heat Capacity with different fly ash wt. % for two sets of particle size.

In this present study, the maximum fly ash of 16 wt. % was used as reinforcement in Al6061 [21], because increase in fly ash particles as reinforcement increases the hardness of the material.

Thermal conductivity

The Figure 8 shows the variation of thermal conductivity of composite material with different weight fractions of fly ash in Al6061. It was observed that with increase in fly ash wt. % in Al6061, the thermal conductivity decreases, which is mainly due to an elevated temperature, the thermal conductivity value are higher with higher temperature heat transfer rate [26].

It has been observed from the Figure 11 that for pure Al66061 thermal conductivity of composite was 153.12 W/m-k and at 4%, 8%, 12% and 16% of fly ash percentages thermal conductivity were 147.11, 136.06, 129.94, 124.73W/m-k, respectively. Thermal conductivity of the composite material declining mainly due to low thermal conductivity of fly ash particles [21].

The variations of thermal conductivity for composites with fly ash particles sized above 50µm and below 50µm were shown in Figure 8. Due to high temperature rate, the particles sized below 50µm of fly ash reinforced composite exhibits lower thermal conductivity as compared to composite with particle sized above 50µm of fly ash. It is also known that lower the density of composite lower will be thermal conductivity [20] and due to the higher density of fly ash particles in second set of composites, its thermal conductivity will be higher. Increase of fly ash in Al6061 enhances the machinability of the composite intern reduces the thermal conductivity [29].

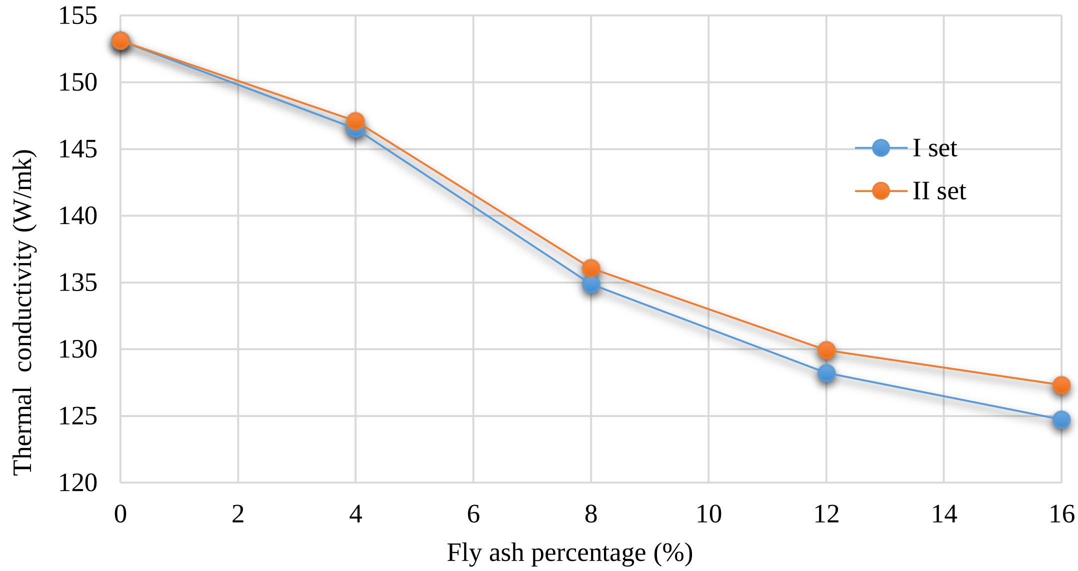

Figure 8. Thermal Conductivity with different fly ash wt. % for two sets of particle size.

Thermal Diffusivity

The variation of thermal diffusivity with weight percentage of fly ash particles reinforced Al6061 as shown in Figure 9. From the Figure 9 it was observed that increase in fly ash reinforcement in Al606l decreases the thermal diffusivity [28]. The composite exhibit low thermal diffusivity, high specific heat capacity, low thermal conductivity and low thermal expansion by the reinforcement of fly ash particle sized below 50µm [22-23].

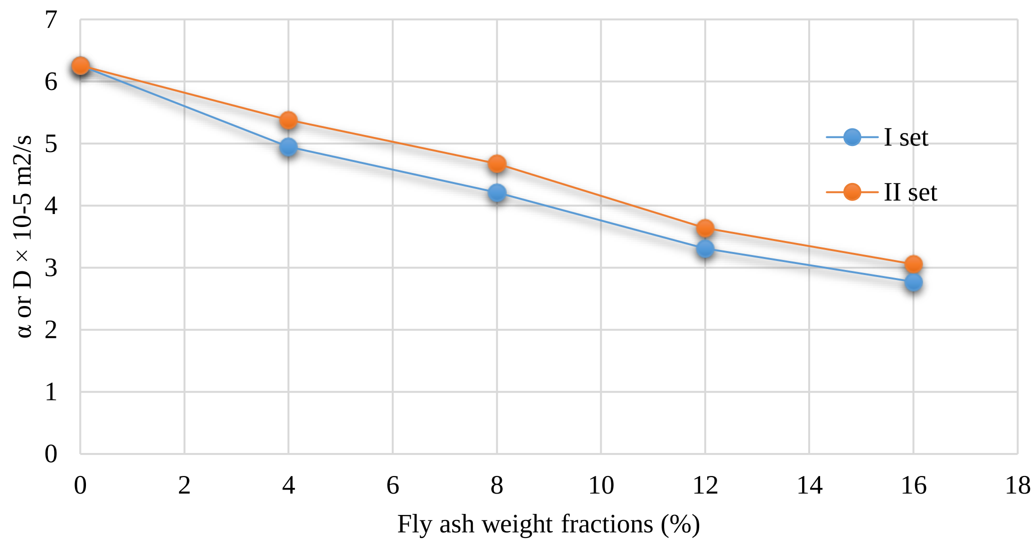

Figure 9. Thermal Diffusivity with different fly ash wt. % for two sets of particle size.

CONCLUSIONS

- Al6061 alloy finds number of applications in variety of engineering application as a high performing component. It has unique characters like lower density and good thermal conductivity property. This Al6061 which is heat treatable and is used in the field of aerospace, marine and automobile industries. As technology advances, materials with lighter density, higher hardness, more strength and better stiffness finds lot of applications in aerospace and automobile field. Different thermal properties for different compositions of Al6061 and Fly ash compositions were studied. It was observed that fly ash with particles sized below 50µm exhibit enhanced thermal properties compared to composite with fly ash particles sized above 50µm.
- The value of thermal expansion are decreasing with addition of fly ash particles. The percentage change or increase in values of thermal expansion is observed more in case of composite with fly ash particles sized above 50µm. It is also observed that percentage change in thermal expansion value is decreasing in both the cases. It is true that addition of fly ash decreases thermal expansion whatever may be the size of fly ash particle size.
- In this present work it was observed that due to proper mixing and higher specific heat carrying capacity of fly ash particles sized below 50µm reinforced Al6061alloy composite, exhibit higher specific heat as compared to fly ash particles sized above 50µm reinforced alloy composite.
- Thermal conductivity was also one of the important thermal property that need to be given preference in the automobile and aerospace applications. It was observed that thermal conductivity of pure Al6061 is 153.12W/m-k with the addition of fly ash thermal conductivity decreases, which was most widely accepted for automobile and aerospace applications. The small difference in the thermal conductivities observed in two different set composites mainly due to fact that smaller fly ash particles exhibit lower thermal conductivity.
- In this present work thermal diffusivity of composite was observed to be $6.4 \times 10^{-5} m^2/s$ on an average decreases with addition of fly ash in Al6061 due to the higher specific heat of composite.

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