

Effect of heat treatment and ageing on microstructure for hypoeutectic Al-7Si alloy and hybrid metal matrix composites

B.M. Viswanatha^{1*}, M. Prasanna Kumar², S. Basavarajappa³, T.S. Kiran¹ and S. Kanchiraya⁴

^{1*}Department of Mechanical Engineering, Kalpataru Institute of Technology, Tiptur- 572202, INDIA

²Department of Studies in Mechanical Engineering, University BDT College of Engineering, Davangere- 577 004, INDIA

³Registrar, IIT-Dharwad, 580011, INDIA

⁴Department of Mechanical Engineering, Government Engineering College, Hassan-573201, INDIA

*Corresponding Author, Email: vishwanathabm@gmail.com, Tel.: +91 8762018207

ORCID iDs: <http://orcid.org/0000-0001-8805-7383> (Viswanatha); <http://orcid.org/0000-0002-8743-9360> (Prasanna Kumar); <http://orcid.org/0000-0002-3894-0239> (Basavarajappa); <http://orcid.org/0000-0002-9398-6029> (Kiran); <http://orcid.org/0000-0002-3258-5395> (Kanchiraya)

Abstract

In the present investigation on fabrication and microstructure of aluminium based hybrid composites. A356 based aluminium matrix material with varying reinforcement percentage from 0 to 9 wt. % in steps of 3 wt. % silicon carbide (SiC_p) and fixed quantity of 3 wt. % of graphite (Gr) particles were used in fabrication. The specimens were fabricated by stir-cast method. Heat treatment was carried out for the cast specimen at 540°C for 12 hours and further ageing was carried out at 155°C for 3, 6, 9 and 12 hours durations. The specimen after heat treatment and ageing were quenched in water at 60°C. The prepared specimens (as-cast and aged) were examined using optical microscope to know the particle distribution in the matrix. Hardness and tensile were carried out for as-cast and aged specimen. The results were compared with as-cast and aged specimens. There was a significant improvement in hardness and tensile properties due to increase in the weight percentage of SiC_p. The specimen A356-9SiC_p-3Gr aged at 9 hrs showed improved hardness, and tensile when compared to other tested specimen. The presence of reinforcements (SiC_p and Gr) significantly affects the solid state transition kinetics that improves the properties of composites. The presences of reinforcements in the specimens are evident from the electron dispersive spectroscopy (EDS) analysis.

Keywords: Metal matrix composites, Age, Microstructure, Hardness, tensile, EDS.

DOI: <http://dx.doi.org/10.4314/ijest.v13i4.1>

Cite this article as:

Viswanatha B.M., Prasanna Kumar M., Basavarajappa S., Kiran T.S. and Kanchiraya S. 2021. Effect of heat treatment and ageing on microstructure for hypoeutectic Al-7Si alloy and hybrid metal matrix composites. *International Journal of Engineering, Science and Technology*, Vol. 13, No. 4, pp. 1-11. doi: 10.4314/ijest.v13i4.1

Received: September 27, 2021; Accepted: December 31, 2021; Final acceptance in revised form: January 7, 2022

1. Introduction

Man in high seek for making life on earth as simple and as safe as possible has understood the need to be innovative. The search has to lead to new class of materials called “composites”. A composite can be defined as an engineered material consisting of a matrix and a reinforcing material. These two constituents give the composite the superior properties that are expected from that material (Rohatgi, 1993; Prasad and Asthana, 2004). A composite is a macroscopic combination of two or more multiphase distinct materials having an interface between them. A composite exhibits significant properties of both constituent phases such that a better combination of properties is realized. Composites are commonly classified into two distinct levels. The first level of

classification is usually made with respect to the matrix constituents and the second level is based on the type of reinforcements (Anthony, 2006).

The matrix is to provide a stiff structure to the composites. The function of the matrix is to bind the reinforcements collectively by the virtue of its cohesive and adhesive characteristics and further to distribute the load to and from reinforcements and to protect the reinforcements from environmental condition. Matrix selection not only involves desired properties but also decides the material which is best suited for composite manufacturing. In case of matrix selection, factors such as density, ductility, toughness and strength retention at elevated temperature are considered. Generally, aluminium (Al), magnesium (Mg), zinc (Zn), titanium (Ti) and copper (Cu) are matrix materials. There are three types of matrices, such as polymer, ceramic and metal matrix materials (Miracle, 2005).

Reinforcement is considered to be particle, if all its dimensions are nearly equal. Thus, particles are spheres, flakes and any other shapes of nearly equal axes. The particle size and shape has an influence on the property of the composites. For effective reinforcement and better properties, the particles should be small and uniform in size and they should be evenly distributed throughout the matrix (Zong et al., 2007). Particle reinforced composites exhibit isotropic properties. They can be easily processed by using standard metallurgical technique such as liquid metallurgy technique. The most commonly used particles in AMCs are graphite, silicon carbide, alumina and garnet. However, primary disadvantage of all MMCs is that they suffer from low strain to failure and inadequate fracture toughness compared with that of the constituent matrix material (Bindumadhavan et al., 2001; Prasanna Kumar et al., 2006). Liquid metallurgy technique being simple, economical and easily applicable in foundries is gaining wide popularity. This involves incorporation of ceramic particles into liquid Al melt and allowing the mixture to solidify. The important aspect is to create good wetting between the reinforcement and liquid Al alloy. Vortex mixing technique is for the preparation of ceramic.

Hashim et al. (1999) and Hashim et al. (2002a,b) studied the fabrication of MMCs using stir casting method and influence of reinforcement distribution. Particle size, shape, density, speed of rotation of the stirrer and volume fraction influences the reinforcement distribution in the alloy. Increase in 1 wt. % of Mg content increases the viscosity of the slurry by enhancing the wettability characteristics between reinforcement and matrix. Creation of vortex during stirring is essential for immersing the particles inside the melt medium. Two shapes of blades were used to improve the distribution of the reinforcements. The lower speed of stirring causes inconsistent particles distribution which contributes to the porosity within particles clustering at 100 rpm in most MMCs. Ceramic particles reinforcing with alloy were covered with air envelopes and water vapour. Pre-heating the particles prior to mixing was found to be practical in minimizing porosity resulting in increase in the strength of the composites.

The mechanical properties of Al based composites are generally superior to those of base alloys. Compared to high strength Al alloys, SiC_p reinforced composites have higher strength, stiffness and greater fatigue resistance, even at elevated temperatures. The mechanical and physical properties of SiC_p reinforced composites are unique and important features of these materials. By increasing the content of SiC_p in the composite material, corresponding increase in hardness, tensile, yield strength and elastic modulus can be obtained (Wang and Zhang, 1991; Pedersen and Arnberg, 2001). Yu et al. (2007) and Choi et al. (2013) investigated the mechanical and microstructure of A356-SiC_p composite that was fabricated by friction stir processing. The hardness of the stir zone was higher than that of base metal due to reduced defects and the eutectic Si and SiC_p are dispersed over the stir zone. The elastic constant and yield strength of the composites were found to be higher than the base alloy.

The increase of the elastic constant in the composite material is only due to the addition of the SiC_p. The dislocation around the SiC_p produced by the coefficient of thermal expansion (CTE), not only strengthens the matrix by the conventional strain hardening mechanisms, but also can decrease the elastic constant (Elomari et al., 1998; Huber et al., 2006). Heat treatment affects the transition from elastic to plastic behavior; hence peak aged MMCs (T6) exhibits superior yield and tensile strength than in as-cast condition. Increase in the flow stress of the composite with heat treatment is likely to be an indication of the additive effects of the dislocation interaction with both the alloy precipitate and reinforcements. Ceramic particles when added to an alloy increase the CTE between the ceramic particles and the matrix which causes thermal stress, large enough to deform the soft matrix plastically. The dislocations are created at the particle-matrix interface and the matrix (Caceres, 2000; Muratoglu et al., 2006). The heat treated (450°C) composites (Al6061-SiC_p) improved hardness in 3 hours, while the same hardness was attained for base alloy (Al6061) after 10 hours. During natural ageing, the improvement in hardness is small compared to the base alloy. But during artificial ageing, the MMCs reached peak hardness after 7 to 8 hours, in contrast to base alloy which reached at 50 hours. The ageing behavior of the composites is varied between the solutionizing temperatures. The variations between hardness are small as the difference in solutionizing temperature is small (Lee et al., 2001).

Thimmarayan and Thanigaiyarasu (2010) studied the effect of aged base alloy (Al6082) and SiC_p reinforced composites of different particle sizes (22, 12 and 3 µm) on mechanical properties. The result reveals that increase in hardness and tensile strength was observed with decrease of particle size and increase of ageing duration. Abarghouie and Reihani (2010) studied the effect of heat treatment on composites (Al2024-SiC_p) fabricated by powder metallurgy method. The solution treatment of composites and base alloy was carried out at 495°C for 1, 2 and 3 hrs followed by ageing at 191°C for 1 to 10 hrs. The peak hardness was obtained for 2 hrs solution treated for both composites and base alloy. The hardness and tensile properties of aged Al 6061-SiC_p composites were studied. The results revealed that the age-hardenable composite improves the strength and stiffness compared to the base alloy (Liu and Samuel, 1998; Ehsani and Reihani, 2004). Akhter et al. (2007) and Bekheet et al. (2002) studied the effect of ageing on hardness behavior of Al-SiC_p composites. The alloy was reinforced with 5, 10 and 30 wt. % by squeeze casting technique. The

presence of SiC_p in matrix material accelerates the precipitation process in the formation of GP zone and 'S' precipitates. The precipitation would not contribute much during natural ageing and the formation of S-precipitation in artificial ageing was observed at 170°C due to higher rate of decomposition and formation of dislocation density. Artificial ageing exhibits faster precipitation and peak hardness was achieved for maximum (30 wt. %) SiC_p content. Cavaliere et al. (2004) studied the effect of T5 and T6 heat treatment on mechanical properties of A356 thixo-cast alloy. The specimen aged (T5 and T6) at 160°C and 200°C increases the mechanical properties. The specimen aged with T6 (with solution treatment) exhibits higher hardness and tensile properties compared to T5 (without solution treatment).

Ranganatha et al. (2003) and Kim (2011) studied the effect of heat treatment on mechanical properties and microstructure of Al7049 alloy. The results indicated that fine precipitates distribution in matrix was obtained at T6 heat treatment. Seah et al. (1997) studied the mechanical properties as-cast and heat treated (280°C at 1, 2, 3 and 4 hrs) of ZA-27-Gr ranging from 0 to 5 by wt. % and particles size of 100-150 μm . The results revealed that the increasing graphite content in ZA-27 matrix significantly increases the ductility, ultimate tensile strength and compressive strength but decreases the hardness of the composites for both as-cast and heat treated specimens. As graphite being a soft reinforcement, it does not contribute positively to the hardness of the composites.

Westermann et al. (2012) studied the effect of quenching rate on microstructure and mechanical properties of Al7108 alloy. The large deviation in strength depends on cooling and holding time of the material in the T6 heat treatment. The material was solution treated at 480°C temperature with independent holding time. There was no change in microstructure and slight decrease in mechanical property was observed. Kalkani and Yilmaz (2008) studied the mechanical properties of SiC_p (10, 15, 20 wt. %) reinforced using squeeze cast and grain refined of Al7075 composites. The results were compared with as-cast and heat treated specimens. The heat treated composites containing 10 wt. % of SiC_p shows maximum strength when compared to the as-cast composites.

Leng et al. (2008) worked on mechanical properties of Al-SiC-Gr composites fabricated by squeeze casting technique. The Gr volume fractions of 3-7% and different particles size (1, 6, 10, 20 and 70 μm) were used. The microstructure and mechanical properties of the composites were evaluated. The results suggested that the tensile and elastic module depends on volume fraction and the size of the Gr particles. As the volume fraction of particles increases, the tensile strength of the composite decreases (Guo and Yuan, 2009).

Aluminium-silicon (Al-Si) alloys have found wide application because of their wide range of properties. These alloys are quite compatible with almost all ceramic reinforcements. It is possible to produce reliable Al-Si castings because of their excellent castability. Aluminium alloy alone shows poor mechanical and tribological properties that led to the development of new materials (Kearney, 1990; Surappa, 2003). Most of the research work on MMCs is carried out on silicon carbide particle (SiC_p), aluminium oxide (Al_2O_3) and graphite (Gr) particles alone while few researchers have worked on the combination of reinforcements (hybrid composites) (Hanumanth and Irons, 1993; Ames and Alpas, 1995; Srivatsan et al., 1999; Miracle et al., 2001; Aqida et al., 2003; Shabestari et al., 2004; Basavarajappa et al., 2006; Leng et al., 2008; Viswanatha, 2017).

2. Materials and Experimentation

The materials and experimentation carried out for the processing of the base alloy and composites are described. The characterization of microstructure, hardness and tensile properties were carried out.

2.1 Materials

2.1.1 Aluminium matrix material: The base alloy (A356) is the popular matrix among all aluminium (Al) alloys because of its low density, superior thermal, electrical properties, corrosion resistance and improved damping capacity. The details of matrix material composition and properties are shown in Table 1 and Table 2 respectively (Miracle and Donaldson, 2001).

Table 1 Composition of A356 base alloy

Elements	Cu	Mg	Mn	Si	Fe	Zn	Ti	Others	Al
Weight %	0.1	0.4	0.06	7.0	0.1	0.04	0.1	Traces	Balance

Table 2 Mechanical properties of A356, T6 treatment

Material	Density (g/cm^3)	Yield strength (MPa)	Tensile strength (MPa)	Hardness (BHN)
A356,T6	2.685	185	262	80

2.1.2 Particle reinforcements: The prime purpose of the reinforcement is to provide strength and stiffness to the composite. The characteristic of particles depends on the size and distribution of particles; matrix-particles interface bond strength. MMCs are used for high temperature applications to provide creep strength and high temperature tensile strength. Silicon carbide particles (SiC_p , average size of 25 μm) are used in the fabrication and the properties are shown in Table 3 (Miracle and Donaldson, 2001). It is a compound of silicon and carbon that is used as abrasive.

Table 3 Mechanical properties of SiC_p

Material	Density (g/cm ³)	Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio	Hardness, (BHN)
SiC _p	3.2	400	100	0.19	81

Graphite (Gr) is one of the allotropes of carbon. Gr holds the distinction of being the most stable form of carbon under standard conditions. Graphite powder is valued in industrial applications for its self-lubricating and dry lubricating properties. The mechanical properties of Gr are shown in Table 4 (Miracle and Donaldson, 2001).

Table 4 Mechanical properties of graphite

Material	Density (g/cm ³)	Yield strength (MPa)	Tensile strength (MPa)	Hardness, (BHN)
SiC _p	1.82	292	371	40

2.1.3 Fabrication of composites using stir-cast technique: Fabrication of the base alloy and composites were carried out by stir-casting technique and as shown in fig. 1. A known weight of a356 billets were placed inside the graphite crucible and the electrical furnace temperature is set to 750°C (liquidous temperature of base alloy). The SiC_p was varied from 3, 6 and 9 wt. % and fixed quantity of 3 wt. % of gr was added to the base alloy. The reinforcements were preheated to avoid the oxide formation and improve the bonding between matrix and reinforcements. A mechanical stirrer is used to stir the liquid alloy (500 rpm) to create a vortex and the preheated reinforcements are added to the melt. The degasification agent hexachloroethane (C₂Cl₆) is added to remove the entrapped gas from the molten mixture. The preheated mold box is placed on sand bed in order to avoid spilling of molten metal while pouring. After solidification, the castings were removed from the mold box and the specimens were prepared as per ASTM standards.

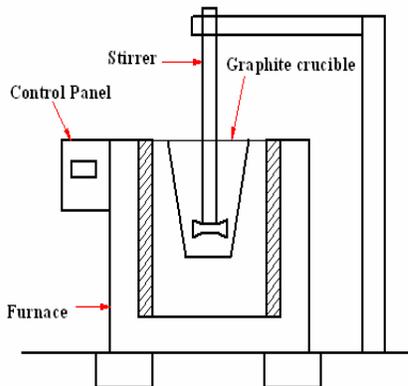


Figure 1. Electrical crucible furnace

2.1.4 Heat treatment: The prepared specimens were solution treated at 540°C for 12 hrs in a furnace and quenched in water at 60°C. The temperature of the furnace was maintained within ± 5⁰ C of the set point by means of an automatic temperature controller.

2.1.5 Ageing treatment: The heat treated specimen were artificially aged (T6) at 3, 6, 9 and 12 hrs at a temperature of 155⁰ C and quenched in water at 60⁰ C. The details of ageing of the cast specimen are mentioned in Table 5 (Miracle and Donaldson, 2001).

Table 5 Heat treatment of cast specimen

Alloy	Temperature	Solution heat treatment		Ageing treatment	
		Temp ^o (C)	Time (hr)	Temp ^o (C)	Time (hr)
A356	T6	540	6-12	155	6-12

2.2.1 Microstructure: To evaluate the microstructure of the base alloy and composites, polishing was carried out on Mecapol P230 polishing machine. Fine polishing was done to get mirror like finish using alumina powder. Keller's reagent was used as etchant.

The polished specimens were used to study the distribution of reinforcements in the matrix. Nikon Microscope LV150 with Clemex image analyzer was used to evaluate the microstructure of the specimen.

3. Results and Discussions

The fabrication, microstructure and mechanical properties of the as-cast and aged specimen results were compared.

3.1 Microstructure and mechanical properties of as-cast specimen: In this section, brief discussion of the microstructure and mechanical properties of the base alloy and composites of as-cast and aged specimens were studied.

3.1.1 Microstructure: Microstructure of as-cast specimen is shown in Fig. 2. The microstructure of A356 base alloy (Fig. 2a) and A356 reinforced with fixed 3wt. % of Gr and varying 3 to 9 wt. % in steps of 3 wt. % of SiC_p are shown in Fig. 2(b-d) respectively. Microstructure of base alloy (Fig. 2a) consists of fine dendrites of aluminium solid solutions (α) with fine eutectic silicon particles having needle shape at interdendritic regions. The uniform distribution of the reinforcements is as shown in Fig. 2(b-d). In Fig. 2(b-d) coarser SiC_p was observed and Gr particles were well associated with SiC_p . The inter particle spacing is found to play a crucial role in determining the properties. The finer microstructure and homogeneous particle distribution improves the properties of the composites. The amount of reinforcements present in 9 wt. % of SiC_p (Fig. 2d) is more compared to 3 and 6 wt. % of SiC_p (Fig. 2, b and c).

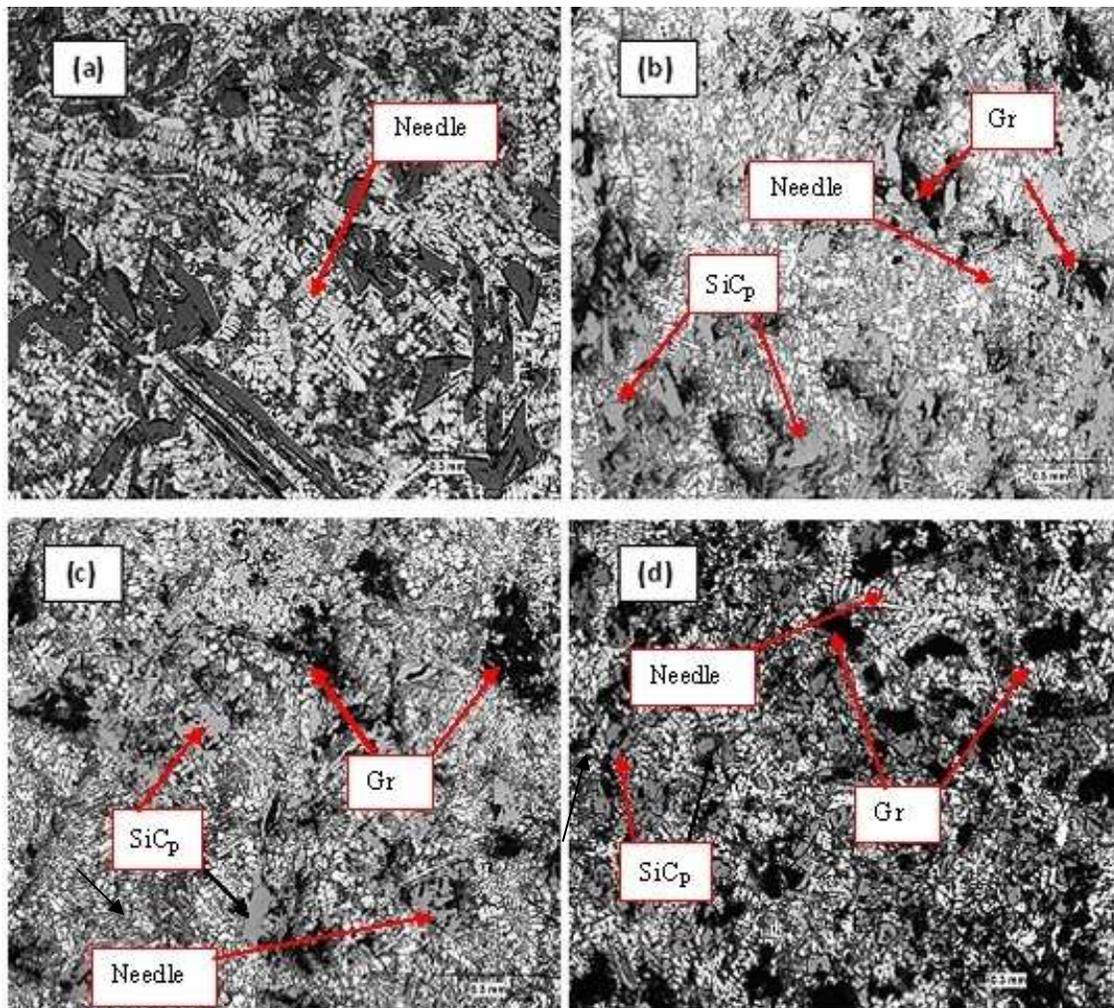


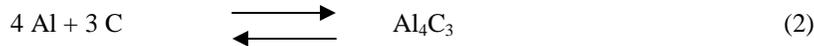
Figure 2, Microstructure of (a). A356 alloy (b). A356-3%Gr-3%SiC_p (c). A356-3%Gr- 6%SiC_p (d). A356-3%Gr-9%SiC_p

3.1.4 Discussion: By liquid metallurgy technique (vortex method), particle size of 25-44 μm (SiC_p -Gr) were dispersed in the matrix. The uniform distribution of particles in the composite is influenced by the type, shape of reinforcement and speed of rotation of the stirrer ((Ames and Alpas, 1995; Basavarajappa et al., 2006). The creation of vortex during stirring is essential for piercing of the particles inside the melt medium. Suitable aerofoil shaped blades were used for improvement in dispersion of

reinforcements. The distribution of reinforcements is dependent on the solidification rates. Longer the solidification rate, more uniform is the distribution of the reinforcements in the matrix (Shabestari and Shahri, 2004; Viswanatha, 2017).

The uniform distribution of SiC_p and Gr (Fig. 2, b-d) is observed within the interdendritic region. The reinforcements are found to be pushed by α -Al dendrites to the interdendritic regions. Thus, reinforcements are segregated along dendritic boundaries with higher cooling rate leading to finer dendrite cell size which gives finer inter particle spacing (Aqida et al., 2003).

In case of composites, when the SiC_p and Gr particles are added to Al matrix, extensive interfacial reactions are present (Eqn. 1 and 2). Interfacial reactions enhance the load bearing capabilities and lubrication properties of MMCs. Extensive interfacial reactions are accelerated by high processing temperature. SiC_p and Gr react with molten aluminium and the following products were obtained.



In case of first reaction (Eqn. 1), aluminium carbide (Al_4C_3) layer is formed through solid state diffusion and in the second reaction (Eqn. 2) by the dissolution of Gr (C) into liquid Al to form Al_4C_3 . The brittle Al_4C_3 phase results from the reactions between SiC_p or Gr with Al. Al_4C_3 deteriorates the mechanical properties of the composites, thus avoiding the formation of Al_4C_3 as the primary concern for successful fabrication (Hanumanth and Irons, 1993).

The formation of Al_4C_3 is avoided by decreasing the possible reaction between molten Al and reinforcements. The SiC_p and Gr reinforcements are preheated to 600°C , which induce the formation of silicon oxide (SiO_2) layer on the SiC_p . The oxide layer prevents direct contact between the SiC_p and molten Al and this inhibits the formation of Al_4C_3 . The Gr particles with high degree of graphitization do not readily react with molten Al because their chemical properties are relatively stable that inhibits the interfacial reaction of Al-Gr composites (Aqida et al., 2003; Shabestari and Shahri, 2004). The interface formed between the matrix and reinforcement is important since the characteristic of this region determines the load transfer and crack resistance of the MMCs during deformation. It is accepted that in order to maximize the interfacial bond strength in MMCs, it is necessary to promote wetting and control chemical reactions (Srivatsan et al., 1999).

The interaction may be in the form of chemical bonding between matrix and the reinforcements, which improves the hardness (Fig. 4) and tensile strength of the composites with increasing of wt. % of SiC_p (Fig. 5). The presence of SiC_p along with flow lines act as barriers to the movement of dislocations within the matrix. In composites, SiC_p acts as a load bearing member that enhances the hardness of the material. Similar results were observed for A356- SiC_p (Ames and Alpas, 1995) and Al-Si- SiC_p (Abarghouie and Reihani, 2010; Thimmarayan and Thanigaiyarasu, 2010) by earlier researchers. Hardness of the specimen increases with increase in SiC_p and decreases with increasing e reinforcement of Gr (Seah et al., 1997). Inclusion of both SiC_p and Gr will not yield as good result when reinforced with SiC_p alone, as Gr is a soft reinforcement (Leng et al., 2008; Guo and Yuan, 2009). The presence of reinforcement in matrix generates dislocation across the span of lattice (Bekheet et al., 2002; Akhter et al., 2007). The generation of dislocation as a result of heavy pile up of dislocations at the grain boundary as well as the particle-matrix interface causes increase in the strength of composites (Seah et al., 1997; Cavaliere et al., 2004; Kim et al., 2011; Ranganath et al., 2013).

3.3 Microstructure and mechanical properties of aged specimen: The objective is to study the influence of heat treatment and ageing on the microstructure and mechanical properties of base alloy and composites. The results were compared with as-cast specimens.

3.3.1 Microstructure: Fig. 6 shows the microstructure of base alloy and composites with 9 hr aged specimens. The microstructure consists of rounded eutectic silicon and fine precipitates of alloying elements in the matrix of Al solid solution (Fig. 6). The refinement of microstructure is a common phenomenon to improve the mechanical properties of cast materials. It leads to benefits such as fine equiaxed grain size and improves the properties and machinability (Seah et al., 1997; Westermann et al., 2012; Kalkani and Yilmaz, 2008). The 9 hr aged specimens showed improved microstructure in all the combination of specimens. Fig. 6a shows the microstructure of base alloy without dendritic structure and with equiaxed grain structure. Fig. 6 (b-d) shows the microstructure of composites with varying quantity of reinforcements in the matrix. Fig. 6d contains 9 % SiC_p that shows more reinforcement when compared with other microstructures (Fig. 6, b and c). Fig. 7 and 8 shows the electron dispersive spectroscopy (EDS) of A356 base alloy and A356-9 SiC_p -3Gr composite. Fig. 8 shows the presence of reinforcements and is evident from EDS that the composite contains SiC_p and Gr with matrix material. The graphite is shown as carbon (C) in the EDS (Fig. 8).

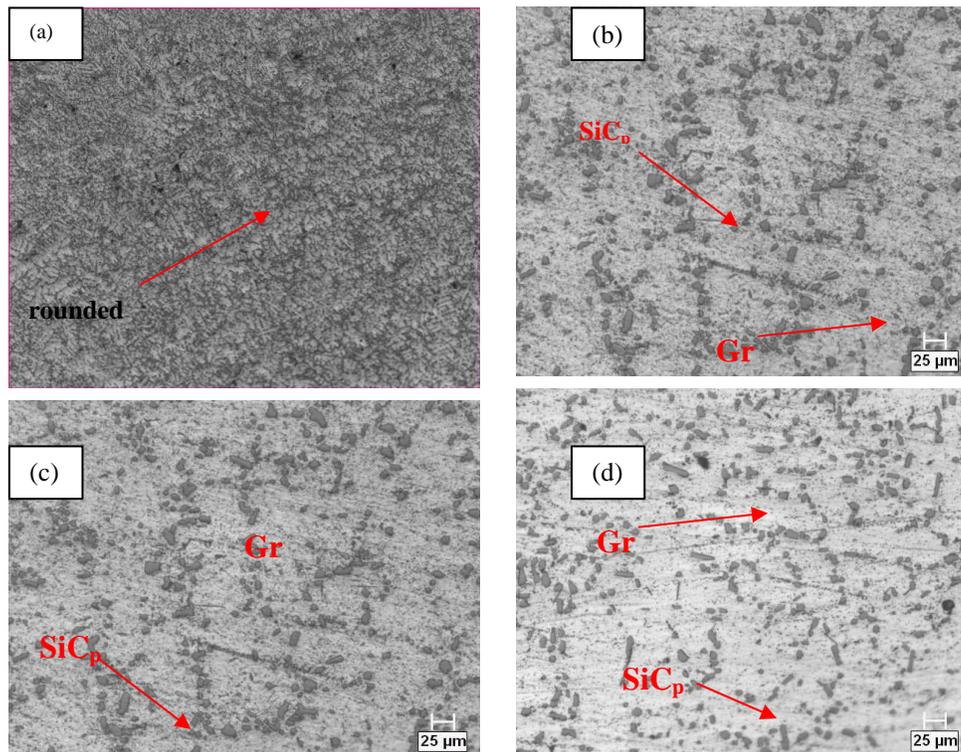


Figure 6, Microstructure of 9 hr aged (a). A356 alloy (b). A356-3SiC_p-3Gr (c). A356-6SiC_p-3Gr (d). A356-9SiC_p-3Gr composites

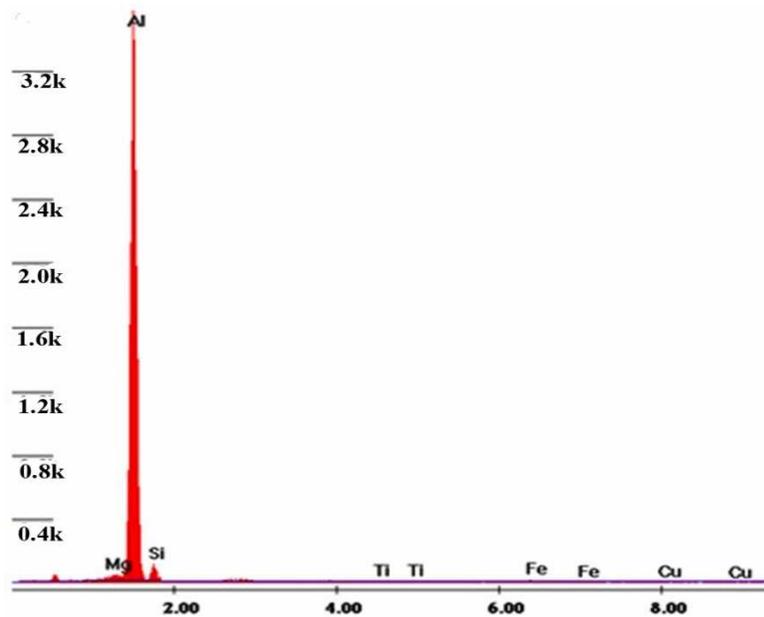


Fig. 7 EDS of A356-9 hr aged specimen

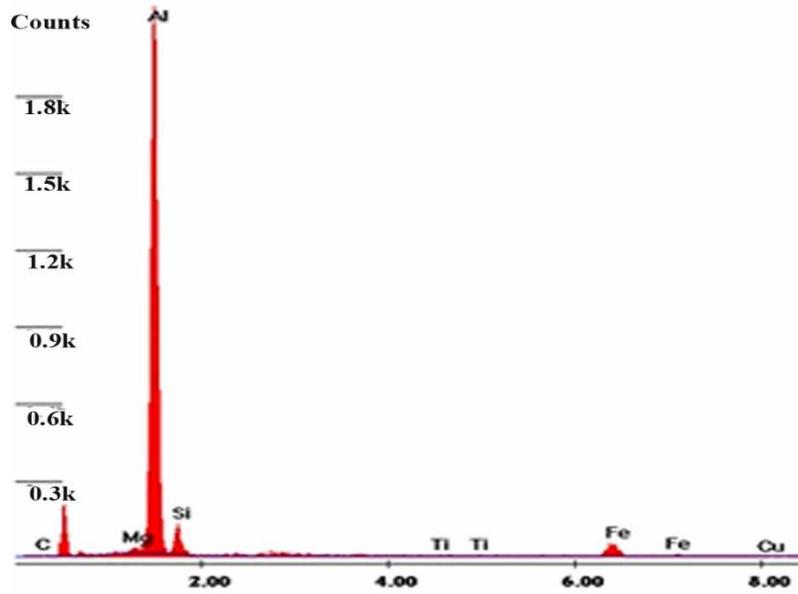
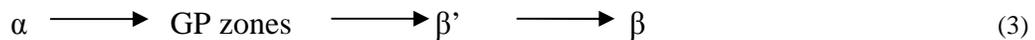


Fig. 8 EDS of A356-9SiC_p-3Gr- 9 hr aged specimen

3.3.4 Discussion

The mechanical properties are highly influenced by microstructure of the material. Consequently, the improvements in mechanical properties were related to duration of ageing (3, 6, 9 and 12 hrs). Fig. 2a shows the dendrite structure of A356 base alloy where the structure consists of primary phase α -Al and eutectic mixture of Al and Si along grain boundaries. After quenching, solute atoms of the base alloy were in supersaturated (α) condition and tend to precipitate during ageing (155°C). The precipitation phase consisting of rearrangement of atoms within the crystal lattice, constitutes to form clusters and Guinier-Preston zones (GP zone) (Bekheet et al., 2002; Cavaliere et al., 2004; Akhter et al., 2007; Kim et al., 2011; Ranganath et al., 2013). The absence of dendritic structure and reinforcement’s distribution is clearly observed from the Fig. 6. The ageing sequence of age hardenable alloys (Bekheet et al., 2002; Ehsani and Reihani, 2004; Akhter et al., 2007) is as follows (Eqn. 3).



Where,

- α - Supersaturated solid solution
- GP - Guinier–Preston zones
- β' - Semi coherent phase
- β - Stable, incoherent (Mg₂Si)

The specimens were aged at 155°C by holding at different durations. The early stage of precipitation is characterized by GP zones, as enrichment of solute atoms (Si, Mg) in the Al matrix. Further decomposition process is characterized by β' phase that have the composition of Mg₂Al. The next stage of decomposition process is equilibrium phase, β (Mg₂Si), which is a stable phase. The transformation of β' to β phase is a minor atomic re-arrangement which improved properties to the specimens. The Mg₂Si phase formation is at ageing duration of 9 hour. The increasing of Mg₂Si phase increases the hardness of the specimen (Caceres, 2000; Muratoglu et al., 2006). The hardness of the specimen tends to decrease upon further increase of ageing duration (12 hrs). This is due to the precipitation hardening process which greatly depends on ageing time (Fig. 9). The initial increase of hardness is due to the diffusion assisted from the particles. At the beginning of ageing, the solute atoms diffuse and locally form clusters to form the GP zone throughout the matrix. GP zone formation increases the mechanical properties [Fig. 9 and 10] due to high stress required to force dislocation through the coherent zone (Liu and Samuel, 1998; Lee et al., 2001; Thimmarayan and Thanigaiyarasu, 2010; Abarghouie and Reihani 2010). The alloy after heat treatment improves the mechanical properties by forming Mg₂Si phase. Large Mg₂Si particles are formed during heat treatment of base alloy. In quenching of the solution treated (12 hrs at 550° C) specimens, magnesium stays in the matrix as the supersaturated solid solution and it will be ready to precipitate during ageing that will enhance the mechanical properties. The mechanical properties of the base alloy are significantly influenced by the presence of β (Mg₂Si) phase and distribution of eutectic Si (Ehsani and Reihani, 2004). In composites, increasing the reinforcement content

decreases the formation rate of GP zones. This can be attributed to the reduction in the energy barrier required for critical zone nucleation. The possible mechanisms may account for the following (Elomari et al., 1998; Huber et al., 2006; Choi et al., 2013).

- An increase in the internal lattice energy
- Thermal enhancement in solid state diffusion

The above mentioned mechanisms are interrelated inherently. The internal lattice energy is increased by an increased dislocation density at matrix-reinforcement interface. This will promote strain induced solid state diffusion process. Further, the low thermal conductivity of reinforcements compared to the highly conductive metal matrix results in significant microscopic thermal gradients within the material. When the material is cooled from higher temperature, the reinforcement adjacent to the matrix will tend to cool at a rate slower than the matrix. Consequently, solute atoms will migrate to these interfacial zones of higher solubility enhanced by the increased thermal activation. On subsequent ageing treatments, GP zones tend to form at 9 hrs duration accelerating the ageing kinetics.

Accelerated ageing of MMCs can also be attributed to the increased dislocation in the vicinity of reinforcements or in matrix residual stress field near reinforcements (Hanumanth and Irons, 1993; Srivatsan et al., 1999; Aqida et al., 2003; Shabestari and Shahri, 2004; Leng et al., 2008; Viswanatha, 2017). As the ageing duration increased, the peak hardness increases. The formation of GP zones and their transition from β' to β phase is possible only when the specimen is aged at a temperature (155°C) below the GP zone. So in this case of A356 alloy, during ageing at 155°C , the high density dislocation would provide a short circuit path for heterogeneous nucleation and fast growth of β' precipitates resulting in accelerated ageing of the matrix. Upon quenching, the reinforced composite from solutionizing temperature, the soft matrix undergoes plastic deformation due to the substantial thermal expansion difference between Al matrix and reinforcements. The plastic deformation of the matrix will result in large number of dislocation and vacancies (Liu and Samuel, 1998; Bekheet et al., 2002; Ehsani and Reihani, 2004; Akhter et al., 2007). These dislocations would appear to accelerate the ageing kinetics of the matrix at higher ageing durations (9 and 12 hrs). Such effects do not seem to be effective at lower ageing durations (3 and 6 hrs). The nucleation of GP zones at (9 hrs) duration is homogeneous and excess vacancies introduced by quenching play an important role in their formation, but not the dislocations.

The reinforcements may themselves be affected by the deformation process, they may undergo fracture or realignment during the deformation. The strength of the composites was further improved by heat treatment consisting of the precipitation of metastable phases during the ageing at super-saturated solid solution. At ageing duration of 9 hrs, the precipitation hardening occurs faster in the composite than 12 hrs (Lee et al., 2001; Thimmarayan and Thanigaiyarasu, 2010). Al-Si alloy is known for its good castability and corrosion resistance. In this alloy series, A356 (Al-7%Si-0.3%Mg) has superior properties and it is used to produce parts that require high strength, elongation and light weight (Ames and Alpas, 1995). At an ageing duration (12 hrs), stress relief takes place in the lattice usually at higher ageing durations, which declined the strength of the material Figs. (9 and 10).

4 Conclusions

From the research work, the following conclusions were drawn.

- A356 base alloy and composites were successfully fabricated by stir-cast method.
- Microstructure shows the uniform dispersion of reinforcements (SiC_p and Gr).
- Microstructure of the A356 base alloy and composites consists of primary aluminium-rich dendrites of α phase. The SiC_p and Gr particles are well distributed in the eutectic and interdendritic region in composites.
- After ageing of the specimen, microstructure consists of modified fine rounded eutectic silicon dispersed in the interdendritic region and fine precipitates of alloying elements in the matrix of Al solid solution. The particles are well dispersed in the matrix.

References

- Abarghouie S.M.R.M., Reihani S.M.S., 2010, Ageing behavior of a 2024 Al alloy SiC_p composite, *Materials and Design*, Vol. 31, pp. 2368-2374. <https://doi.org/10.1016/j.matdes.2009.11.063>
- Akhter R., Ivanchev L., Burger H.P., 2007, Effect of pre/post T6 heat treatment on the mechanical properties of laser welded SSM cast A356 aluminium alloy, *Material Science and Engineering, A*, Vol. 447, pp. 192-196. <https://doi.org/10.1016/j.msea.2006.10.148>
- Anthony K., 2006, Composite materials after seventy years, *Journal of Material Science*, Vol.41, pp.905-912. <https://doi.org/10.1007/s10853-006-6569-9>
- Bindumadhavan P.N, Wah H.K, Prabhakar O, 2001, Dual particle size (DPS) composites: Effect on wear and mechanical properties of particulate metal matrix composites, *Wear*, Vol.248, pp.112-120. [https://doi.org/10.1016/S0043-1648\(00\)00546-9](https://doi.org/10.1016/S0043-1648(00)00546-9)
- Ames W., Alpas A.T., 1995, Wear mechanism in hybrid composites of graphite-20 Pct. SiC in A356 aluminium alloy (Al-7 Pct. Si-0.3 Pct. Mg), *Metallurgical and Materials Transactions*, Vol. 26A, pp.85-97. <https://doi.org/10.1007/BF02669796>
- Aqida S.N., Ghazali M.I., Hashim J., 2003, The effect of stirring speed and reinforcement particles on porosity formation in cast MMC, *Jurnal Mekanikal*, Bil. 16, pp.22-30.

- Basavarajappa S., Chandramohan G., Mukund K., Ashwin M. and Prabu M., 2006, Dry sliding wear behavior of Al 2219/SiC_p/Gr hybrid metal matrix composites, *Journal of Material Engineering and Performance*, Vol. 15, No. 6, pp. 668-674. <https://doi.org/10.1361/105994906X150803>
- Bekheet N.E., Gadelrab R.M., Salah M.F., Abd El-Azim A.N., 2002, The effects of aging on the hardness and fatigue behavior of 2024 Al alloy/SiC Composites, *Materials and Design*, Vol. 23, pp. 153-159. [https://doi.org/10.1016/S0261-3069\(01\)00072-3](https://doi.org/10.1016/S0261-3069(01)00072-3)
- Caceres C.H, 2000, Microstructure design and heat treatment selection for casting alloys using the quality index, *Journal of Materials Engineering and Performance*, Vol. 9, No. 2, pp.215-221.
- Cavaliere P., Cerri E., Leo P., 2004, Effect of heat treatments on mechanical properties and fracture behavior of a thixocast A356 aluminum alloy, *Journal of Material Science*, Vol. 39, pp. 1653-1658. 10.1023/B:JMSE.0000016165.99666.dd
- Choi D.N., Kim Y.H., Byung-Wook A.H.N., Kim Y., Jung S.B., 2013, Microstructure and mechanical property of A356 based composite by friction stir processing, *Transactions of Nonferrous Metals Society, China*, Vol. 23, pp. 335-340. [https://doi.org/10.1016/S1003-6326\(13\)62466-8](https://doi.org/10.1016/S1003-6326(13)62466-8)
- Ehsani R., Reihani S.M.S., 2004, Aging behavior and tensile properties of squeeze cast Al 6061/SiC metal matrix composites, *Scientia Iranica*, Vol. 11, No. 4, pp. 392-397.
- Elomari S., Skibo M.D.M., Sundarrajan A., Richards H., 1998, Thermal expansion behavior of particulate metal matrix composites, *Composites Science and Technology*, Vol. 58, pp.369-376. [https://doi.org/10.1016/S0266-3538\(97\)00124-3](https://doi.org/10.1016/S0266-3538(97)00124-3)
- Guo J., Yuan X., 2009, The aging behavior of SiC/Gr/6013Al composite in T4 and T6 treatments, *Materials Science Engineering A*, Vol. 499, pp. 212-214. <https://doi.org/10.1016/j.msea.2007.11.142>
- Hanumanth G.S., Irons G.A., 1993, Particle incorporation by melt stirring for the production of metal matrix composites, *Journal of Materials Science*, Vol. 28, pp. 2459-2465. <https://doi.org/10.1007/BF01151680>
- Hashim J., Looney L., Hashmi M.S.J, 2002, Particle distribution in cast metal matrix composites-Part II, *Journal of Materials Processing Technology*, 123, pp. 258 – 263. [https://doi.org/10.1016/S0924-0136\(02\)00099-7](https://doi.org/10.1016/S0924-0136(02)00099-7)
- Hashim J, Looney L, Hashmi M. S. J, 1999, Metal matrix composites: production by the stir casting method, *Journal of Materials Processing Technology*, Vol. 92 – 93, pp. 1-7. [https://doi.org/10.1016/S0924-0136\(99\)00118-1](https://doi.org/10.1016/S0924-0136(99)00118-1)
- Hashim J., Looney L., Hashmi M.S.J, 2002, Particle distribution in cast metal matrix composites-Part I, *Journal of Materials Processing Technology*, 123, pp. 251 – 257. [https://doi.org/10.1016/S0924-0136\(02\)00098-5](https://doi.org/10.1016/S0924-0136(02)00098-5)
- Huber T., Degischer H.P., Lefranc G., Schmitt T., 2006, Thermal expansion studies on aluminium matrix composites with different reinforcement architecture of SiC particles, *Composites Science and Technology*, Vol. 66, pp.2206-2217. <https://doi.org/10.1016/j.compscitech.2005.12.012>
- Kalkani A., Yilmaz S., 2008, Synthesis and characterization of aluminium alloy 7075 reinforced with silicon carbide particulates, *Materials and Design*, Vol. 29, pp. 775-780. <https://doi.org/10.1016/j.matdes.2007.01.007>
- Kearney A. L., 1990, *Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 10th edition, ASM Handbook, ASM International, pp.164-165.
- Kim S.J, Jang S.K., Han M.S., Kim S.K., Kim J.S., 2011, Effects of precipitations strengthening heat treatment for Al-Mg alloy, *Transaction Nonferrous Metal Society, China*, Vol. 21, pp. 1218-1224. [https://doi.org/10.1016/S1003-6326\(11\)60845-5](https://doi.org/10.1016/S1003-6326(11)60845-5)
- Lee W.-S., Lai C.-H., Chiou S.-T., 2001, Numerical Study on perforation behavior of 6061-T6 aluminium matrix composite, *Journal of Materials Processing Technology*, Vol. 117, pp.125-131. [https://doi.org/10.1016/S0924-0136\(01\)01166-9](https://doi.org/10.1016/S0924-0136(01)01166-9)
- Leng J., Wu G., Zhou Q., Dou Z., 2008, Mechanical properties of SiC/Gr/Al composites fabricated by squeeze casting technology, *Scripta Materialia*, Vol. 59, pp. 619-622. <https://doi.org/10.1016/j.scriptamat.2008.05.018>
- Liu L., Samuel F.H., 1998, Effect of inclusions on the tensile properties of Al-7% Si-0.35% Mg (A356.2) aluminium casting alloy, *Journal of Materials Science*, Vol. 33, pp. 2296-2281. <https://doi.org/10.1023/A:1004331219406>
- Miracle D.B. and Donaldson S.L., 2001, *Composites*, Vol.21, 10th edition, ASM Handbook, ASM International, pp. 838-867.
- Miracle D.B, 2005, Metal matrix composites- from science to technological significance, *Composite Science and Technology*, Vol.65, pp.2526-2540. <https://doi.org/10.1016/j.compscitech.2005.05.027>
- Muratoglu M., Yilmaz O., Aksoy M., 2006, Investigation on diffusion bonding characteristics of aluminum metal matrix composites (Al/SiC_p) with pure aluminum for different heat treatments, *Journal of Materials Processing Technology*, Vol. 178, pp. 211 – 217. <https://doi.org/10.1016/j.jmatprotec.2006.03.168>
- Prasad S.V. and Asthana R., 2004, Aluminium metal matrix composites for automotive applications: Tribological considerations, *Tribology Letter*, Vol. 17, No. 3, pp. 445-452. <https://doi.org/10.1023/B:TRIL.0000044492.91991.f3>
- Prasanna Kumar M., Sadashivappa K., Prabhukumar G.P., Basavarajappa S., 2006, Dry sliding wear behavior of garnet particles reinforced zinc-aluminium alloy metal matrix composites, *Materials Science (Medziagotyra)*, Vol. 12, No.3, pp.209-213.
- Pedersen L., Arnberg L., 2001, The effect of solution heat treatment and quenching rates on mechanical properties and microstructures in AlSiMg foundry alloys, *Metallurgical and Materials Transactions*, Vol. 32 A, pp.525-532. <https://doi.org/10.1007/s11661-001-0069-y>
- Ranganath R., Anil Kumar V., Nandi V.S., Bhat R.R., Muralidhara B.K., 2013, Multi-stage heat treatment of aluminium alloy AA7049, *Transaction Nonferrous Metal Society China*, Vol. 23, pp. 1570-1575. [https://doi.org/10.1016/S1003-6326\(13\)62632-1](https://doi.org/10.1016/S1003-6326(13)62632-1)

- Rohatgi P.K., 1993, Metal matrix composites, *Defence Science Journal*, Vol. 43, No 4, pp. 323-349. <https://doi.org/10.14429/dsj.43.4336>
- Seah K.H.W., Sharma S.C., Girish B.M., 1997, Mechanical properties of cast and heat treated ZA- 27/graphite particulate composites. *Composite Part A: Applied Science and Manufacturing*, Vol. 28, No. 3, pp. 251-256.
- Shabestari S.G., Shahri F., 2004, Influence of modification, solidification conditions and heat treatment on the microstructure and mechanical properties of A356 aluminum alloy, *Journal of Materials Science*, Vol. 39, pp. 2023-2032. <https://doi.org/10.1023/B:JMSC.0000017764.20609.0d>
- Srivatsan T.S., Ibrahim I.A., Mohamed F.A., Lavernia E.J., 1999, Processing techniques for particulate-reinforced metal aluminium matrix composites, *Journal of Material Science*, Vol.26, pp.5965-5978. <https://doi.org/10.1007/BF01113872>
- Surappa M. K., 2003, Aluminium matrix composites: Challenges and opportunities, *Sadhana*, Vol. 28, pp. 319-334. <https://doi.org/10.1007/BF02717141>
- Thimmarayan R, Thanigaiyarasu G, 2010, Effect of particle size, forging and ageing on the mechanical fatigue characteristics of Al6082/SiC_p metal, *International Journal of Advanced Manufacturing Technology*, Vol. 48, pp. 625-632. <https://doi.org/10.1007/s00170-009-2316-0>
- Viswanatha B.M., 20017, Development and characterization of metal matrix composite material for automobile disc brake system, Ph.D. Thesis, *Visvesvaraya Technological University, India*, pp.2-44.
- Wang Z, Zhang R.J, 1991, Mechanical behavior of cast particulate SiC/Al (A356) metal matrix composites, *Metallurgical Transactions A*, Vol. 22 A, pp.1585-1593.
- Westermann I, Haugstad A.L., Langsrud Y., Marthinsen K., 2012, Effect of quenching rate on microstructure and mechanical properties of commercial AA7108 aluminium alloy, *Transaction Nonferrous Metal Society, China*, Vol. 22, pp. 1872-1877. [https://doi.org/10.1016/S1003-6326\(11\)61400-3](https://doi.org/10.1016/S1003-6326(11)61400-3)
- Yu X.-D., Wang Y.-W., Wang F.-C., 2007, Effect of particle size on mechanical properties of SiC_p/5210 Al metal matrix composites, *Transactions of Nonferrous Metals Society, China*, Vol. 17, pp. 276-279.
- Zong B.Y., Zhang F., Wang G., Zuo L., 2007, Strengthening mechanism of load sharing of particulate reinforcement in al metal matrix composite, *Journal of Material Science*, Vol. 42, pp.4215-4226. <https://doi.org/10.1007/s10853-006-0674-7>

Biographical notes

Dr. Viswanatha BM, is currently working as professor and HOD in Department of Mechanical Engineering, Kalpataru Institute of Technology-Tiptur, Karnataka, India. He handles subjects of Thermodynamics, turbo machines, hydraulics and pneumatics, Nontraditional machining, Computer aided engineering drawing etc., He holds Ph.D degree from Visvesvaraya Technological University-Belagavi, Karnataka, India. He has published research articles in reputed international peer reviewed journals. He is editorial member/ reviewers for many international Journals.

Dr. M. Prasanna Kumar is currently working as Associate Professor, Department of Studies in Mechanical Engineering, University BDT College of Engineering, Davanagere, Karnataka, India. He teaches subjects of Material Science and Metallurgy, Manufacturing process, Computer aided engineering drawing, hydraulics and pneumatics, Nontraditional machining, Mechanical Measurements, Optimization Technique etc., He holds Ph.D degree from Kuvempu University, Karnataka, India. He has published research articles/chapters in many reputed international peer reviewed journals. He is editorial member/ reviewers for many international Journals.

Dr. S. Basavarajappa is currently working as Registrar, IIT-Dharwad-580011, Karnataka, India. He worked in various capacities such as academic dean, academic senate member of Visvesaraya Technological University, Belagavi, Karnataka, India. He holds Ph.D degree from PSG-Tech, Coimbatore, Tamilnadu, India. He has published several research articles/chapters in reputed international peer reviewed journals. His research article/chapters having outstanding records in the field of composite materials. He have achieved Awards/Honors/Recognition from many organization/universities/Journals. He is editorial member/ reviewers for many international Journals.

Dr. T.S. Kiran is currently working as Professor, Department of Mechanical Engineering, Kalpataru Institute of Technology-Tiptur, Karnataka, India. He teaches subjects of Design, Finite Element Methods, Advanced Machine Design, Automobile Engineering, Control Engineering, Computer aided Machine drawing etc., He holds Ph.D degree from Visvesvaraya Technological University-Belagavi, Karnataka, India. He has published research articles in reputed international peer reviewed journals. He is editorial member/ reviewers for many international Journals.

Dr. S. Kanchiraya is currently working as Associate Professor, Department of Mechanical Engineering, Government Engineering College –Hassan, Karnataka, India. He teaches subjects of Thermodynamics, Applied Thermodynamics, Heat Transfer, Turbo Machines, Environmental Automobile Engineering, etc., He holds Ph.D. degree from Visvesvaraya Technological University-Belagavi, Karnataka, India. He has published research articles in reputed international peer reviewed journals. He is editorial member/ reviewers for many international Journals.