Microstructure, mechanical and wear behaviour of Al7075/SiC aluminium matrix composite fabricated by stir casting

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Application of particulate reinforced composite is being emphasized day by day due to its modified strength, high hardness, less weight, and ductility. This paper deals with the behaviour of physical, mechanical and tribological properties of aluminium matrix composite reinforced by micro-sized silicon carbide particles (in a various quantity such as 0, 3, 6 and 9 wt.%) prepared by stir casting fabrication process. With the increase in weight percentage of SiC reinforcement, the density of composite improves from 2.76 gm/cc to 2.83 gm/cc, and the porosity of composite reduces from 1.78% to 0.56%. UTS and Hardness of SiC particle reinforced aluminium matrix composites developed from 140 MPa to 205 MPa and 66 HV to 84 HV respectively. Microstructure reveals that strong bonding develops between matrix and reinforcement in terms of strength and hardness in all the formed composites compared to its matrix material. Comparatively less wear is observed with enhancing SiC content conducted by the pin on disc dry sliding wear test for all the formed composites.

Keywords: Aluminium, Stir casting, SiC, Wear rate, Mechanical properties

1 Introduction

Application of aluminium alloy enhanced day by day due to its less density, fatigue manners, creep quality, machining and fabrication capability, fracture toughness, wear resistance capacity[1,2]. Metal Matrix Composite (MMC) fortified with ceramic particles has a vast scope of application in automobile parts, aerospace components, defence applications and many more[3]. The selection of matrix alloy and reinforcement particles depends on its end application. Several kinds of reinforcements are added in aluminium alloy matrix such as SiC, Al_2O_3, ZrB_2, B_4C, TiB_2, fly ash, etc. in the form of fibres, particulates, and whiskers. Among all the different forms, the particulate reinforced aluminium matrix composite has a bigger notation to the earlier research work due to its significant properties[4]. Recently the demand for Aluminium Matrix Composite (AMC) increased due to its easy improvement of mechanical properties. Aluminium based metal matrix composite contemplated a better replacement over traditional materials in constructional applications of aerospace and automotive industry. Silicon Carbide particle reinforced composites have better hardness and stiffness due to which its use in fabrication of

automotive engines with cylinder heads, cylinder, pistons, and brake motors is replaced the traditional cast iron and other heavyweight metal alloys make[5,6]. The primary reasons for the fabrication of Al-Si alloys are due to its low density, good wettability of reinforcement in matrix and better corrosion resistance capacity. Wear behaviour of Al-Si composite strongly depends on other alloy composition and reinforcement content, applied load and rotational sliding velocity[7-9]. Mostly three different types of mixing processes are used for making metal matrix composites such as liquid path method, semisolid mixing and powder metallurgy formation. Stir casting is a broadly used liquid rotating fabrication technique for making metal matrix composite by mechanical stirrer or by the conventional method which mixes both matrix material homogeneously and reinforces particles[10]. Stir casting accelerates the mixing of reinforced particles viz. ceramic powders into molten metal by mechanical stirring[11,12]. Al/SiC aluminium matrix composite has become the developed metal for making several parts in the automotive industry. Al/SiC aluminium matrix composite obtain better strength to weight ratio and low wear rate, which reduce overall vehicular weight considerably resulting in fuel economy[13]. The preliminary study explores that an increase in the percentage of

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Nanoparticle Silicon Carbide enhances the major mechanical properties and boosts up to a certain level and then gradually decreased[14]. Stir casting fabrication is very economical for producing metal matrix composite. SiC reinforced aluminium matrix composite significantly developed its strength compared to the unreinforced matrix due to the uniform dispersion of reinforcement particles[15]. Adding some amount of magnesium powder during the mixing of matrix and reinforcement particles enhances the wettability particles into the final composite. It does not only benefit the parent metal but also diminishes the surface tension of liquid metal and oxide formation at the time of mechanical stirring[16,17]. SiC and graphite particle reinforced AA6082 hybrid metal matrix composite enhanced its ultimate strength from 163 to 189 MPa and make better strength to weight ratio with decrease ductility from 8.6 to 5.2[18]. Nanoparticle size Al7075/SiC aluminium matrix composite gain better robustness at 20 minutes stirring time and found a more uniform semisolid microstructure that only upon stirring temp of 615°C and 620°C[19]. Nano-sized SiC particles uniformly distributed in A356 Aluminium alloy by modified stir casting (stirring temperature 750°C and Stirring speed 700 rpm) and significantly developed its tensile and yield strength[20]. Several factors and process parameters can upgrade the dispersion of silicon carbide particles in the Aluminium based metal matrix composite; major factors contain mechanical stirrer applied, stirring speed and stirring time, pouring temperature, gating system used[21]. Specific wear rate reduced of Al7075/SiC composite as the sliding speed enhanced up to travel speed (4 m/s) due to its hardened surface of the specimen, generation of iron oxide, and crumble of the SiC reinforcement particles[22]. Wear rate enhanced simultaneously with the addition of SiC particle reinforced Al7075 based aluminium matrix composite. It can find that the minimum wear rate observed at 15 wt. % SiC reinforced composite[23]. Reducing wear rate, friction force, and specific wear rate have been verified to finding the best optimal combination of wear performance at an applied load of 20 N, covering distance 1570 m and 10.5 wt. % of SiC reinforced composite[24].

Aim of the present study is to investigate the various effects on mechanical and tribological properties of the aluminium matrix composite reinforced with micro particle-sized SiC. Ultimate tensile strength, micro hardness, porosity, and wear analysis have been done to characterization and wear behaviour of aluminium matrix composite.

2 Experimentation

In this experiment, Al7075 alloy used as matrix material with microparticle size SiC reinforcement filler material. The chemical composition of Aluminium alloy 7075 shows in Table 1. Various weight percentages of SiC content (0%, 3%, 6%, and 9%) dispersed with aluminium matrix. Physical properties of silicon carbide micro-sized particles are shown in Table 2. SiC particulates developed from carbon and silicon fabricated by the high-temperature electrochemical reaction of carbon and sand. Stir casting fabrication method is used to prepare aluminium matrix composite reinforced with a various weight percentage of SiC particles. Stir casting technique is one of the best mixing processes to prepare metal matrix composite as supported by earlier research works. Schematic illustration of stir casting setup depicts in Fig. 1. Process parameters are selected based on previous literature survey about stir

Table 1 — Chemical composition of Al 7075.

Components	Cr	Fe	Si	Mg	Mn	Cu	Zn	Ti	Al
Wt. %	0.21	0.22	0.04	2.58	0.03	1.65	5.75	0.03	Balance

Table 2 — Physical properties of silicon carbide (SiC) micro-sized particle .

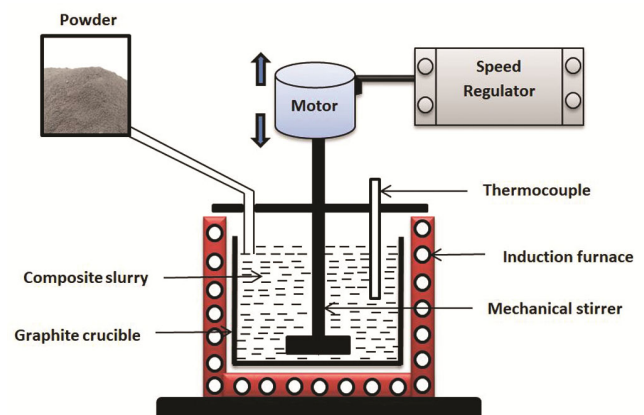| Particulates	Amount
Density	3.21 gm/cm^3
Molar mass	40.11 gm/mol
Melting point	2730°C
Purity	99.92%
Formation	Powder
Size	20 μm

Fig. 1 — Schematic illustration of stir casting fabrication setup.

casting fabrication method[1,3,10,14,18,20,23,25]. Uniform ingots for all the specimens of Al7075 were melted and stirred at 300 rpm for 10 minutes in a graphite crucible at 750°C pouring temperature. In the present work, SiC particles are preheated at 450°C temperature in a muffle furnace to remove moisture content. For better wettability, 2% magnesium is added with the aluminium matrix. After casting Al7075-SiC several composites by varying parameters, all sectioned specimens were surface polished up to mirror finish by using consecutively 400, 600, 800, 1000, 1500 and 2000 graded emery paper. Scanning Electron Microscope (SEM) analyses were conducted to observe the micro structural evaluation of metal matrix composites and the distribution of the reinforced particles of silicon carbide throughout the matrices. Tensile specimens were prepared according to ASTM E08 standard conducted by HEICO HLC 693-35 testing machine and setstrain rate of 0.5 mm/minute. The specimens used for the tensile test are shown in Fig. 2. Vickers micro hardness tester is used to measure the hardness of composite under 3 kg f applied load and 15 second dwelling time. For accuracy at least four hardness reading measured for every sample and calculate the average hardness value. Wear test was conducted in pin-on-disc wear tester (DUCOM's, Model-TR 20LE-M5) as shown in Fig. 3. For wear testing, pin specimen of size 6mm diameter and 40 mm length of pins were rubbed against the counter plate of EN31 steel disc having hardness is 62 HRC. According to the ASTM G99 standard, details of process parameters for the pin on disc wear test are shown in Table 3. All pin specimens and counter plates should be cleaned with acetone before testing.

3 Results and Discussion

3.1 X-Ray Diffraction analysis

XRD pattern of stir cast aluminium metal matrix composites reinforced with silicon carbide micro particlesis shown in Fig. 4. XRD graph was developed by X-Ray Diffractometer along with Cu-Kα radiation (Wavelength=1.54178°A). 2θ range selected in between 10° to 70°. Here, the XRD pattern is identified in six major peaks. Three major peaks indicate Aluminium (Al) which 2θ values are 38.45°, 44.79° and 64.95°. Two major peaks indicate silicon carbide (SiC) which 2θ values are 35.18° and 54.61°. The intensity of SiC peaks enhanced as the addition of SiC content into the matrix. Figure 4 depicts that aluminium diffraction peaks in SiC reinforced

composites are a little bit lower as compared to unreinforced matrix alloy due to the addition of SiC reinforcement. The study revealed that the integrity of SiC particulates is preserved at the time of casting. One major peak identified as intermetallic component magnesium silicon (Mg_2Si) which 2θ value is 40.28°. XRD pattern did not find any other oxide formation. Related kind of peaks found previous literature survey[18,20].

3.2 Physical properties

Density is a physical property that has a great influence on material characterization and ultimate
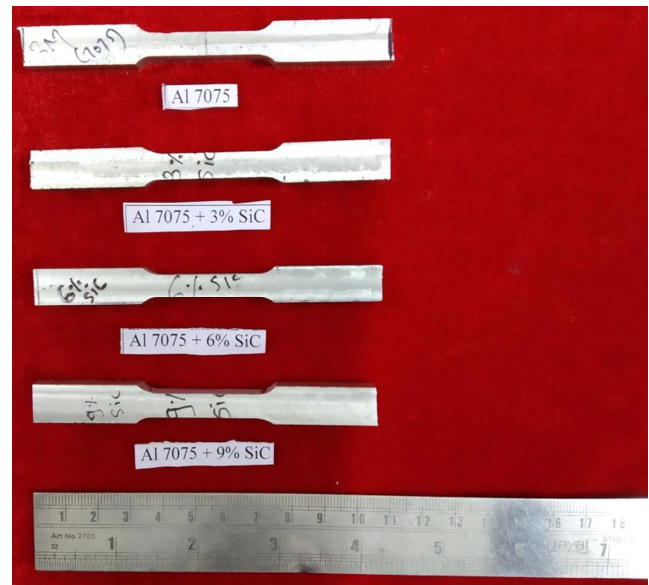

Fig. 2 — All tensile specimens according to ASTM E8 standard.
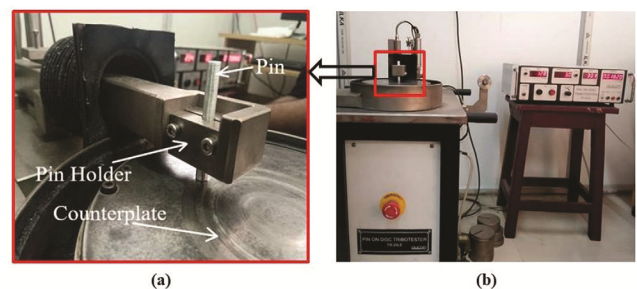

Fig. 3 — (a) Magnified view of wear setup and (b) Pin on disc wear setup (DUCOM's, TR 20LE-M5).

Table 3 — Details of process parameter for the pin on disc wear test.

Parameters	Unit	Value
Applied Load	N	10, 20 and 30
Sliding speed	rpm	300
Sliding distance	m	2000
Track diameter	mm	80

strength. The density of Aluminium alloy Al7075 and SiC particles are 2.81 g/cc and 3.21 g/cc, respectively. The experimental density of all the composite specimens is measured bySAB-224CL density meter. It can clearly understand that experimental density increases simultaneously with enhancing the weight percentage of reinforcement shown in Fig. 5. Theoretical densities of aluminium matrix composites are calculated by the wt.% of the mixture of reinforced particles with base matrix material based upon the order of mixture depicts in Equation (1).

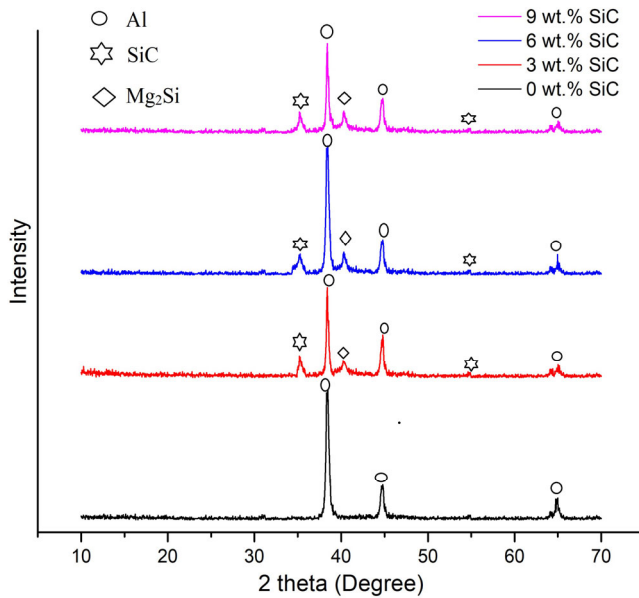$$\rho_t = (\rho_m \times wt.\%) + (\rho_r \times wt.\%) \qquad \dots (1)$$

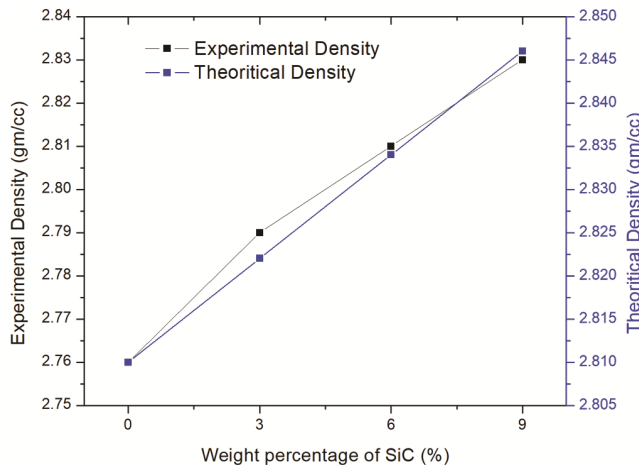Fig. 4 — XRD pattern of Al7075/SiC composite.

Fig. 5 — Variation of experimental density versus weight percentage of SiC as reinforcement.

where, ρ_t = Theoretical density of formed composite, ρ_m = Density of aluminium matrix material and ρ_r = Density of reinforcement particulates.

Porosity percentage is an eminent effect that influences the overall mechanical and fatigue properties of the final composite. Porosity formed inside the composite because of the generation of hydrogen during the solidification period. Composite shrinkage occurs during solidification due to temperature difference between mould and molten metal. Porosity also forms due to water vapour generation and gas entrapment during the stirring period. Porosity percentages of SiC reinforced aluminium matrix composites reduces with enhancing SiC content. Porosity generation depends upon different sources. Porosity associates of separate reinforced particles. On the other hand, porosity formation minimizes because of developing solidification period by the addition of magnesium powder and preheating of ceramic reinforcement before mixing in molten matrix[26]. Porosity percentage of aluminium matrix composites reinforced with 0, 3, 6 and 9wt.%SiC particles are 1.78%, 1.13%, 0.84% and 0.56% that reveals decline trend of porosity percentage as increasing hard and rigid SiC content. However, existence of SiC phase in aluminium matrix promotes interfacial bonding in between ingredients, accordingly porosity generation reduces. The same kind of result also observed in previous literature[27,28]. The porosity of the final composite found minimum while maximum weight percentage of silicon carbide reinforcement used in the present experiment as reflected in Fig. 6. The
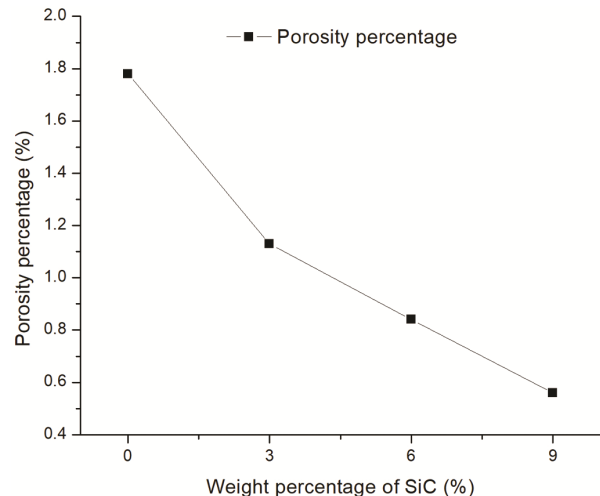

Fig. 6 — Porosity percentage versus weight percentages of SiC as reinforcement content.

formula of measuring porosity percentage in a composite is depicted in Equation (2).

$$\text{Porosity } (\%) = \frac{\rho_t - \rho_e}{\rho_t} \times 100 \qquad \dots (2)$$

where,

ρ_t = Theoretical density of formed composite

ρ_e = Experimental density of formed composite

3.3 Mechanical properties

Vickers micro hardness test of Al7075/SiC aluminium matrix composite samples is evaluated. The hardness of Aluminium alloy 7075 alloys without reinforced any particulates is 66 HV. The variation of composite hardness for different weight percentages of reinforcement particles is displayed in Fig. 7. It can be observed that the overall hardness of composite increases with the maximum amount of addition of silicon carbide. Maximum hardness found at 9 wt. % of SiC filled composite. Hardness inspection did a concentrated load applying on a marking area and particulates density increases those to remain under the indentation region. According to the increase of density, hard particles adjacent to the indentation area developed its hardness. The hardness of SiC reinforced aluminium matrix composite developed by 13.64%, 22.73%, 27.27% compared to unreinforced aluminium matrix. Figure 8 shows the tensile strength behaviour of stir cast composite aluminium alloy 7075 and different weight percentage of silicon carbide particulates. Al7075 aluminium alloy and silicon carbide (SiC) have separate thermal expansion coefficients. Strain fields are formed surrounding reinforced particles due to the variation of thermal expansion coefficients at the time of solidification period[29]. The strain fields bind dislocations. The interconnection in between dislocations and silicon carbide particulates provide resistance to the formation of crack at the time of tensile loading. Grain refinement allotted by silicon carbide particulates presents more regions to resisting load. Better bonding and clear interface of silicon carbide particulates protect the parting of particulates from the aluminium matrix. Reinforcement particulates uniformly distributed throughout the matrix that occurs Orowan strengthening[30]. Therefore, silicon carbide particulates are very active in enhancing the tensile strength of aluminium matrix composite from 140 MPa to 205

MPa due to its high density, high hardness and better stiffness capacity compare to the parent matrix material. Maximum and minimum elongation found in Al7075 parent alloy and Al7075/9 wt.% SiC composite, respectively. This result shows that the percentage of elongation reduces significantly with addition and simultaneously increases in weight percentage of SiC as reinforcement. Elongation percentage of composite exhibits its ductility behaviour.

3.4 Microstructure evaluation

Micrographs of stir cast Al7075-SiC composites conducted by Scanning Electron Microscope (Model - Sigma 300, Carl Zeiss) depicts in Fig. 9. General defects of metal fabrication such as metal shrinkage
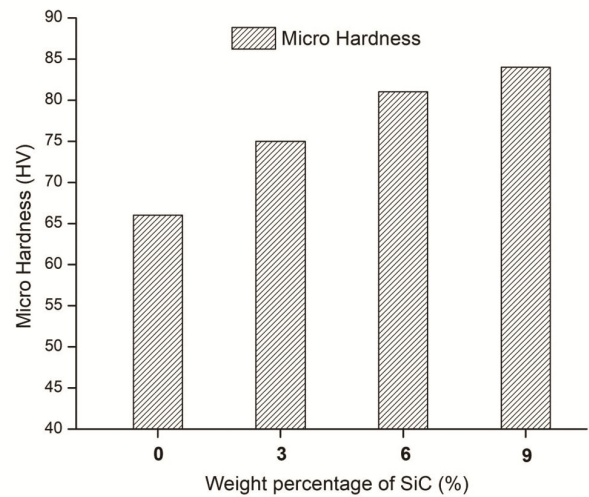

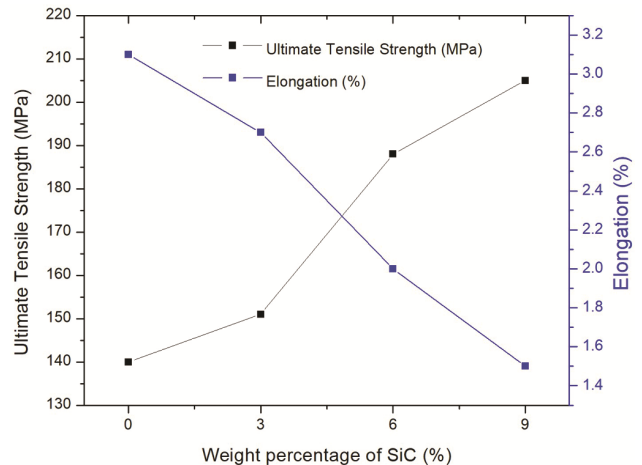Fig. 7 — Micro hardness characteristics Al7075/SiC aluminium matrix composite.

Fig. 8 — UTS and elongation of Al7075/SiC aluminium matrix composite.

during cooling are not displays in SEM micrographs that greatly impact on the quality of the casting[28]. Figure 9(a) depicts as cast micrograph of unreinforced Al7075. Proper distribution of reinforcement particulates plays a vital role in metal matrix composite during the casting process. The uniform distribution between the matrix material and reinforcement particulates are required for getting better quality metal matrix composite that improved properties. Density variation plays a vital role between melt and reinforced agents that reason for non-uniform dispersal because of mixing adequately[25]. Figure 9 (b-d) depicts the uniformly homogeneous distribution of silicon carbide particulates throughout the aluminium matrix. It is observed that aluminium matrix composite with 6 wt. % silicon carbide reinforcement forms cluster in the composite in a random pattern and some pores are also generated in the same way which is due to improper stirring speed, and pouring temperature as shows in Fig. 9(c). It is noticed that lower weight percentage of reinforced composite, developing porosity not obstructed like higher weight percentage of reinforced composite and comparatively better fluidity of molten metal that permit better movement of reinforced particulates and clustering with some

porous content. Aluminium matrix composite with 9 wt. % silicon carbide reinforcement generates some agglomeration of SiC particles which impacts viscosity and surface tension of the molten matrix shown in Fig. 9(d). Indeed, it is also evident that agglomeration of reinforcement particles strengthening casted composite material in case of better bonded with the matrix. Agglomeration of reinforced particulates strongly bonded with a molten matrix with a minimal amount of microvoids and crack formation in the vicinity of aggregates. Moreover, these aggregates provide the strength of the casted composite[31]. Micro-sized reinforced particles and agglomerations are dispersed arbitrarily throughout the molten matrix. It is observed that there is unappropriated dispersion of particles close to grain boundaries or inside the grains. Uniformly distributions of SiC particulates throughout the matrix develop a good mechanical bonding between the matrix material and reinforcement particulates. Forces grow during the stirring process greatly affected by stirring speed. Inappropriate stirring speed formed particulate agglomeration[20]. For determination of maximum force that generates from agglomerate rotating in a shear flow is described below in Equation (3). Hard agglomerate particulate sinduce shear stress
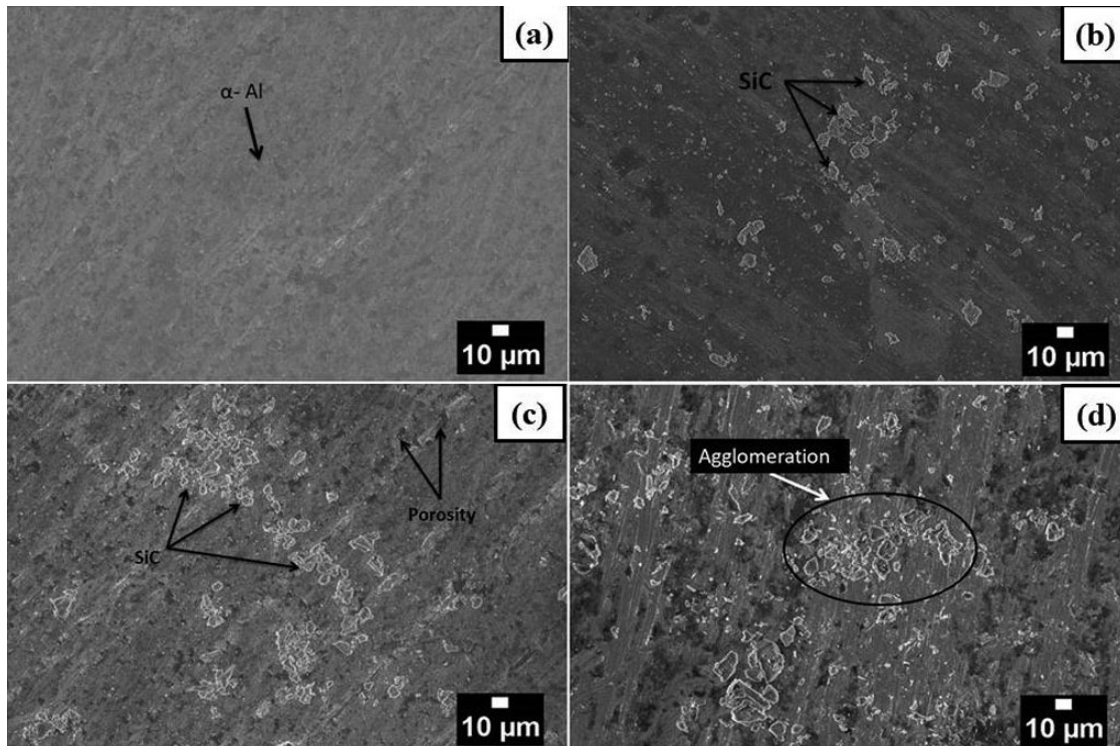

Fig. 9 — Particulates distribution of (a) 0%, (b) 3%, (c) 6% and (d) 9% weight percentages of SiC reinforced Al7075-SiC aluminium matrix composites.

within the fluid that assists split up and blending homogenization.

$$F=6\pi\eta r^2\gamma \qquad\qquad ... (3)$$

where, r= radius of reinforced silicon carbide in agglomeration, η= viscosity of molten metal and ɣ= shear rate in an adjacent liquid medium

3.5 Wear resistance capacity

Wear rate gradually reduces with increasing SiC content in the aluminium matrix. Wear rate rapidly increases with the addition of applied load due to surface penetrates at high load. The higher and lower

amount of wear rate found at unreinforced Al7075 matrix at 30 N applied load, and Al7075/9%SiCaluminium matrix composite at 10 N applied load respectively illustrated in Fig. 10(a). These are happened due to the addition of SiC content throughout the Al7075 matrix that increased overall strength, density, and hardness of final composite material. SiC particles are very hard and rigid compared to the aluminium alloy 7075, which increased wear resistance capacity of filled composites[5]. It is observed that SiC reinforced composite containing wear rate in a decreasing manner due to a huge amount of heat generated in
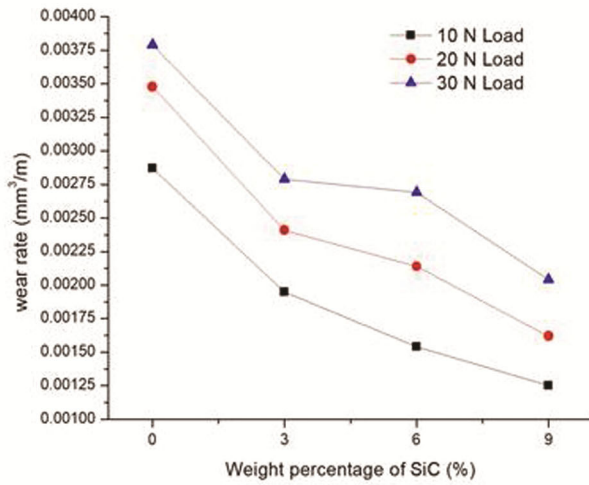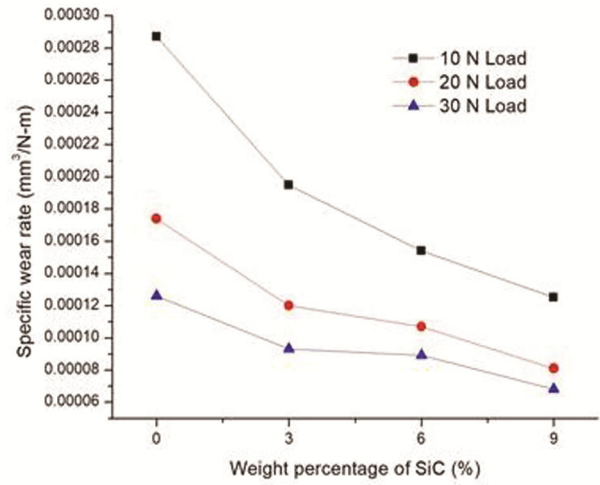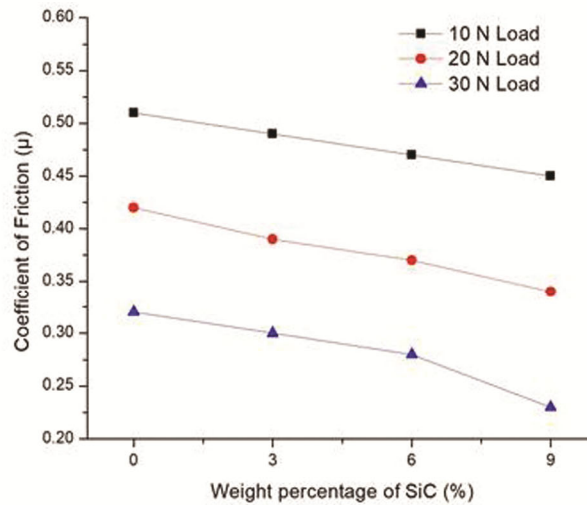
Fig. 10 — (a) Variation of wear rate versus wt.% of SiC with variation of applied load, (b) variation of specific wear rate versus wt.% of SiC with variation of applied load and (c) variation of coefficient of frictionversuswt.% of SiC with variation of applied load.

between two surfaces that form self-lubricated tribo-layer, which reduces wear rate of composites[27]. The specific wear rate simultaneously increased with respect to reduction in applied load depicts in Fig. 10(b). Coefficient of Friction (COF) graph based on the variation of applied load for different composite shows in Fig. 10(c). It is observed that the value of the coefficient of friction enhanced at a lower amount of applied load but at higher load, it reduces due to maximum heat generation and formation of the mechanically mixed layer. The maximum frictional force needed to start initial sliding compared to maintain sliding velocity. Therefore, the coefficient of friction increases at slow sliding velocity and reduces at high sliding velocity. At higher loads, pin asperities get deformed generating a smooth surface layer, and due to prolonged sliding action, high heat is generated between the sliding interfaces which induce tribo oxide layer resulting in a reduction in coefficient of friction[23,25].

3.6 Worn surface analysis

Worn surface behaviour of aluminium matrix composite obtained from the dry sliding pin on disc wear test depicts in Fig. 11. It is noticed that the Al7075 matrix without adding any reinforcement as shown in Fig. 11(a) produce larger grooves and generate the maximum amount of frictional heat and deforms plastically that also called adhesive wear[32,33]. The worn surface characteristics depict in Fig. 11(b-d) represents the result of grooves, ploughing and abrasive wear during the plastic flow of base material produced or the existence of hard and rigid silicon carbide reinforcement particulates[24].It is also observed that sizes of grooves are larger in base matrix compared to SiC reinforced composites because the presence of SiC particles reduce surface roughness and bring smoother aluminium surfaces[14]. Wear resistance capacity of SiC reinforced composites especially influenced by SiC hardness correlative to metal matrix hardness. Reducing inter particulate distances by enhancing SiC particulate size or particle content, results in a better wear resistance capacity compared to base matrix material[34,35].

4 Conclusions

Following observations are established as follows within the present experimental domain.

(i) Al7075/SiC Composite can be successfully formed by using a stir casting fabrication technique.

(ii) X-Ray Diffraction pattern reveals the existence of SiC particulates throughout the aluminium matrix.
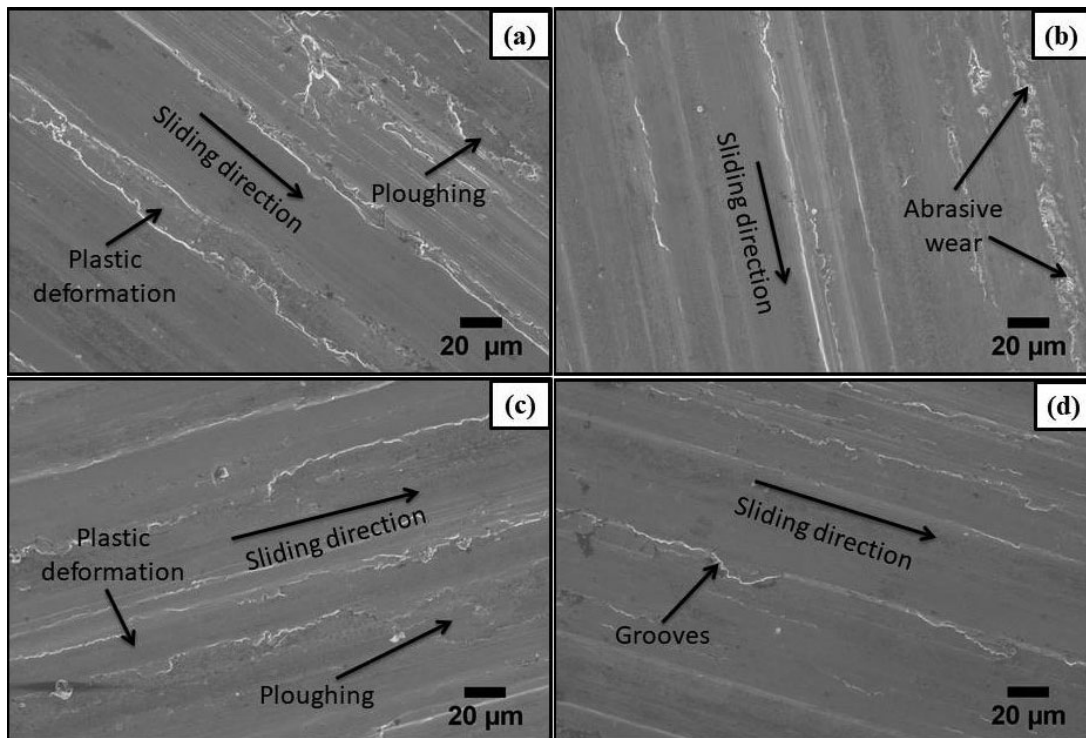

Fig. 11 — Microscopic structure of worn surface on Al7075/SiC composites at 10 N applied load (a) base matrix material of Al7075, (b) 3 wt.% SiC reinforcement, (c) 6 wt.% SiC reinforcement and (d) 9 wt.% SiC reinforcement.

(iii) Percentage of porosity decreased from 1.78% to 0.56%, and experimental density increased from 2.76 gm/cc to 2.83 gm/cc with the addition of wt.% of SiC rein forcement in Al7075-SiC Composite.

(iv) The hardness of the Al7075/SiC Composite was enhanced from 66 to 84 HV gradually with the addition of wt.% of SiC reinforcement in Al7075-SiC Composite.

(v) Ultimate Tensile strength of Al7075/SiC Composite was enhanced up to 205 MPa gradually with the addition of wt.% of SiC reinforcement in Al7075-SiC Composite.

(vi) From SEM analysis it is revealed that stir casting route establishes a uniform distribution of Si Call over the aluminium matrix and minimizes the amount of porosity in the formed composite up to certain limit of stirring speed and duration within a favourable molten material temperature and cooling rate during solidification which is a function of volume and surface area of the cast product.

(vii) Friction wears loss in the measure of loss of volume; through the pin on disc tribological study of Al7075/SiC Composites at different applied load (10, 20 and 30 N) and fixed sliding speed of 300 rpm for fixed sliding distance2000 m; was found decreased with the addition of wt.% of SiC reinforcement.

Acknowledgement

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