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Sliding Wear of Cryogenic Treated Al6061Aluminium Hybrid Metal Matrix Composite

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Abstract
The sliding wear behavior of cryo treated hybrid aluminium matrix composite of Al6061 and its reinforcement with 2.5% SiC + 5% TiO_2 is carried out to ascertain which constituent and parameter is having more influence on the wear resistance of the metal matrix composites. The cryogenic treatment on metals and nonferrous metals gives a new born crystal structure of uniformly dispersed molecules at micro level. This favors for longer wear and durability of material. The hybrid composite material is prepared by stir casting process. The wear and frictional properties of hybrid metal matrix composite are studied by performing dry sliding wear test using a pin on disc wear tester. The experiments are conducted at a constant sliding velocity of 1.04 m/s and a sliding distance of 628 m over a various loads of 3, 4 and 5 kg. The result shows that, the reinforcement SiC and TiO_2 has improved the wear resisting property of Al6061 alloy composite. Influence of cryo treated hybrid composite shows improved wear resistance property compared with untreated cryo samples. The coefficient of friction decreases with the increasing load and particle reinforcement. The microstructure analysis reveals that SiC and TiO_2 particulate are uniformly distributed in the matrix. The wear surfaces are examined by Scanning Electron Microscope which indicates an abrasive wear mechanism due to hard ceramic particles exposed on the worn surface.

Keywords: *Al6061 alloy hybrid composite, Dry sliding wear ,wear mechanism, cryogenic processing*

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I. Introduction

The hybrid metal matrix composite is the reinforcement with two or more different type of substances to get the improved property of the combination favoring the desired application. This gives high degree of freedom in material design[1]. The advantage of increased performance of light weight material in the automoyive, aerospace, nuclear energy and structural application made the researches to concentrate on hybrid metal matrix composite, also the conventional metals has some limitation in mechanical properties like specific strength, stiffness, and wear rate[2-5]. The wear resistance is influenced by the addition of hard reinforcement particles like Al_2O_3, SiC, TiO_2etc in the metal matrix composite shown to reduce the wear loss compared to base alloy[6]. The wear resistance increases with the increase in addition of hard phase as reinforcement and the particle size of the hard phase[7]. The experimental study[8] also proves as wear loss decreases as two-fold when the reinforcement particle size of Al_2O_3 reinforcement increases from 5 to 142µm at the same volume fraction. The wear rate also decreases with increase in reinforcement hardness as is evident by low wear rate of SiC (2600 VHN) than Al_2O_3 (1800 VHN) with the same base alloy composition[8].

The addition of nonmetallic phase in composite, a change in wear mechanism from purely adhesive to a mixed mode of oxidative-abrasive has been reported[8].This results in the wear of the disc surface due to the hard non metallic phase. The experimental work [9] has been made to access the factors that influence dry sliding wear behavior such as slide speed, reinforcement coefficient using Aluminium/Fly ash/Graphite hybrid metal matrix composite. The finding of the research work indicate that load was the more influencing factor on wear rate of hybrid metal matrix composite followed by sliding speed and reinforcement content.

The comparative work was done by the researchers between binary and hybrid composite of Aluminum alloy reinforcing with silicon carbide and Aluminium alloy reinforcing with silicon carbide and graphite. The composites were made using powder metallurgy technique. The results shows that the hybrid composite possesses significant level of tribological characteristics with blackish and smooth worn surfaces[10]. than the binary composite. The metal matrix composite is prepared using the stir casting tehniques for its advantages of simplicity, flexibility and applicability to a large quantity production. Its attractive principle allows for the conventional metal processing route to be used and reduces the final cost of the product. The liquid metallurgy technique is the economical of all the metal matrix composites manufacturing[11] and allows for the very small size components to be fabricated.

The quality of the liquid metallurgy technique depends upon the solidification of the melt that contains suspended dispersoids. This is achieved under selected condition that could ensure desired distributing of the dispersed phase in the cast matrix. These selective parameter conditions are obtained by resorting to stir casting in which considerable attention is paid to achieving a uniform distribution of the reinforcement material, ensuring wettability between the two main substances. Thus optimum properties of metal matrix composite could be achieved through uniform distributing reinforce material and optimum wet ability or bonding between these substances. The aluminum metal matrix composite having particles of discontinuous phase has desirable properties like low density, high specific strength, stiffness, controlled coefficient of thermal expansion, increased fatigue resistance and excellent dimensional stability at the elevated temperature etc [12,13]. The sliding wear behavior is characterized by the factors such as volume fraction, particle size of the reinforcement its hardness and strength of matrix alloy, applied load and environmental temperature etc. This wear characters is investigated in aluminum MMCs with reinforcement such as SiC, Al_2O_3,TiC, TIB_2 and graphite in [14-18]. The hybrid aluminium matrix composite shows improved mechanical properties than the single reinforcement and increases with the increasing reinforcement percentage [18].

Cryogenic processing

The cryogenic treatment is basically carried out using a cryogen (liquid nitrogen, liquid helium etc.) in cryostat, followed by holding it for a programmed time (i.e. freezing/soaking time) and then progressively leading it back to the room temperature. As one of the common arts to improve the hardness and wear resistance of metal products: i.e. motor racing parts, gun barrels, surgical and dental instruments[20-22], the mechanism has been reported as transformation of unstable phase (austenite) to stable phase (martensite), precipitation of fine dispersed carbides[21, 23, 24] and changes of the residual stress state[25]. These decades, the mechanical properties of some polymers such as PI, PEI, PTFE, PC, PU and epoxy resin were investigated at low temperature conditions [26-31]. In addition, the property changing of high performance fiber reinforced composites under cryogenic temperature condition was also investigated by scholars [32-34].

On the other hand, cryogenic treatment, also known as subzero treatment, is a very old process that has been used widely for high precision parts and objects and especially for the ferrous materials mentioned earlier [35]. Subjecting materials to extreme cold hardens and strengthens; this method has been used for centuries [36]. Now cryogenic treatment is widely used in the automotive, aerospace, electronic and mechanical engineering industries to improve mechanical strength and the dimensional stability of various components [37]. For the past few years, in order to improve properties, a cryogenic treatment for nonferrous metals such as aluminium and magnesium alloys has been used [38].

The mechanical properties and microstructure of metals and alloys in cryogenic treatment have drawn the attention of researchers. [39] and Jiang et al. [40] showed the beneficial effects of cryogenic treatment on nonferrous metal aluminium. When considering the wear performance of copper alloy, cryogenic treatment yields the least significant changes [41]. However, Woodcraft and Adam [42] showed a significant improvement in the mechanical properties of the strength, hardness, and toughness of aluminium alloy when subjected to cryogenic treatment. This has led to the idea of analyzing individual alloys' properties when MMCs undergo cryogenic treatment. This field is rapidly growing and is being used by many manufacturers. The present work provides a way for the researchers to construct a facility to research the process and results of cryogenic treatment in order to create standards for both processing and testing, which are currently unavailable. Hence it is important that mechanical properties of MMCs being developed are evaluated at cryogenic temperatures. The crogenic processed hybrid composite has improved hardness and mechanical property compared with alloy and similar hybrid composite Jeyachandran et al.[43]

The aim of the present investigation is to evaluate the dry sliding metal- metal wear behavior of Al6061 alloy, discontinuously reinforced with unequal volume fraction (SiC 2.5% & TiO_2 5%). With cryogenic treatment and without cryogenic treatment.The stir casting method is chosen for the manufacturing of hybrid metal matrix composite. The effect of unequal volume fraction of the reinforcement and the applied load on the dry sliding metal-metal wear behavior of composite was investigated using a pin on disc wear tester. The microstructure was studied for the particle distribution and worn surfaces were examined by scanning electron microscope.

Manufacturing of hybrid composite material

The stir casting method is used for preparing hybrid composite material Al6061+(SiC 2.5% & TiO_2 5%) Under this method particle reinforcement is added into liquid alminium melt and the mixture is allowed to solidify. Preheated reinforcement is added to the vortex created by a rotating impeller in the molten alloy. The process ensures a good wettability between the particle reinforcement and the molten liquid aluminium alloy. The industries prefer this method as it is quite flexible and yields a product with homogenously suspended reinforcement besides allowing moving solid liquid interface while solidification[44,45].

The induction type of electric furnace is used for melting aluminium Al6061alloy in a crucible. The temperature was maintained at 850°C. The power operated stirrer was introduced into the aluminum melt. The stirrer was coated with alumina material and immersed to about two third of the aluminum melt. The stirring speed was kept at 400 to 500 rpm to form a vortex in the molten metal for the addition of reinforcement. The other parameters like pouring temperature, preheating of reinforcement particles were suitably chosen. The average diameters of the reinforcement particles were 25μm and 50μm. They were preheated to 300°C and added inside the vortex formed by vigorous stirring.

The molten composite material after complete adding of reinforcement particles was tilt poured into the preheated 250°C permanent steel mould and allowed to solidify in atmospheric temperature. Billets of unequal volume fraction of reinforcement material of the hybrid Al60615 composite were thus produced and wear test specimen were machined from them. The nominal chemical composition of Al6061 alloy is given in Table 1.

Table 1 Nominal chemical composition of Al6061 alloy

Elements	Cu	Si	Mg	Mn	Fe	Ti	Ni	Zn	Sn	Al
Percentage	0.17	0.8	1.2	0.15	0.15	0.13	0.006	0.06	<0.001	Balance

Cryogenic treatment

The Al6061 hybrid metal composite prepared by stir casting method is subjected to cryogenic processing Cryogenic treatment of samples is performed by placing Al6061/SiC-TiO_2 specimen in a cryogenic chamber. The cryogenic treatment is done in nitrogen reservoir. The sample temperature is monitored by a K type thermocouple which was used to operate a stepper motor which lowered the sample and maintained a temperature decline at the rate of 1°C/min. The temperature is lowered to - 196°C the time taken to reach is nearly 4 hours.

The pain stacking method is very slow microprocessor controlled process which eliminates the probability of thermal shock and micro-cracking..Specimen were held at -196°C for time duration such as 20 hours and slowly brought up to approximately +25°C. The cryogenic processing is followed as per Kaveh Meshinchi et al [30]. After the completion of cryogenic processing the specimen is prepared for microstructure analyzes according to ASTM E3 standards. The samples were subjected grinding and polishing followed by etching by nital. The optical microscope was taken using metallurgical microscope and then the specimen is washed with acetone and dried thoroughly for the dry sliding wear test.

Experimental procedure

A pin on disc wear testing machine (Wear and Friction monitor TR-201) was used to conduct the sliding experiments at room temperature. A dead weight loading system kept the pins 8mm diameter and 20mm length with the flat ends on the disc. The disc test piece size was 100mm diameter and 10mm thick they slide by a diameter of 50mm on the disc made by hardened steel HV 698. The sample specimen Al6061+(SiC 2.5% & TiO_2 5%) of cryogenic treated, uncryo treated composite samples and unreinforced Al6061 alloy were tested separately under varying applied loads of 29.43N (3Kgf), 39.24N (4Kgf), 49.05N (5Kgf) for a total sliding distance of 628m at constant sliding speed of 1.04m/sec for all samples. Test were conducted at atmospheric conditions of 50% relative humidity and 25°C. The entire test was conducted for 10 minutes at a constant disc speed of 400 rpm.

The vertical height of the specimen was continuously measured to note the vertical displacement of the specimen during the test this was taken as the wear of the specimen. Linear variable differential transformer (LVDT) was used for this purpose. The photographic view of the pin on disk wear tester used in this investigation is shown in Fig 1. An experimental graph showing the height loss or wear in μm against sliding time in seconds obtained from wear testing is shown in fig 2. The hardness of the composite material and Al6061 alloy specimen at room temperature was measured using Vickers hardness testing machine.

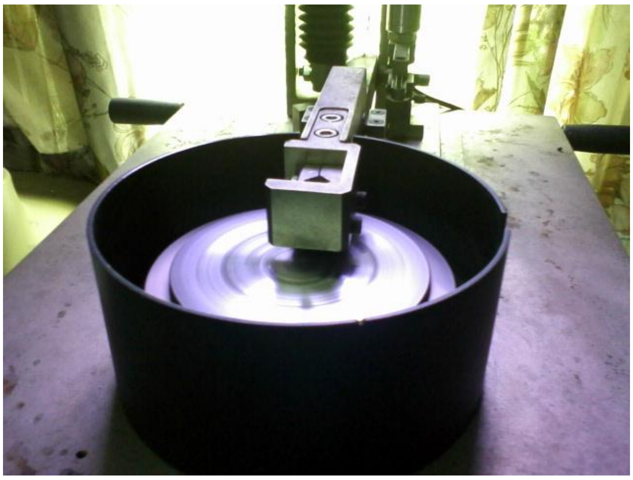


Fig. 1 Photograhic view of pin on disk wear testing machine

The sliding speed and the sliding distance travelled by the test specimen on complete travel of the experiment or in a particular interval of time is calculated by substituting in the equation below,

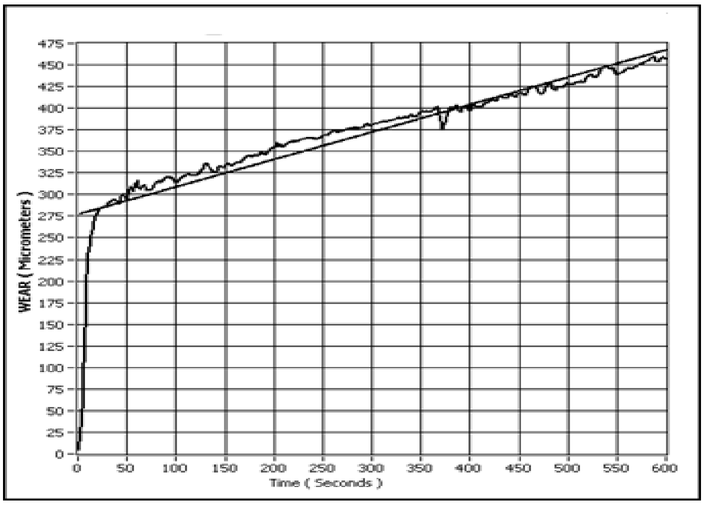
Sliding speed in m/sec = $\pi DN/60$

Sliding distance in meters = $\pi DNT/60$

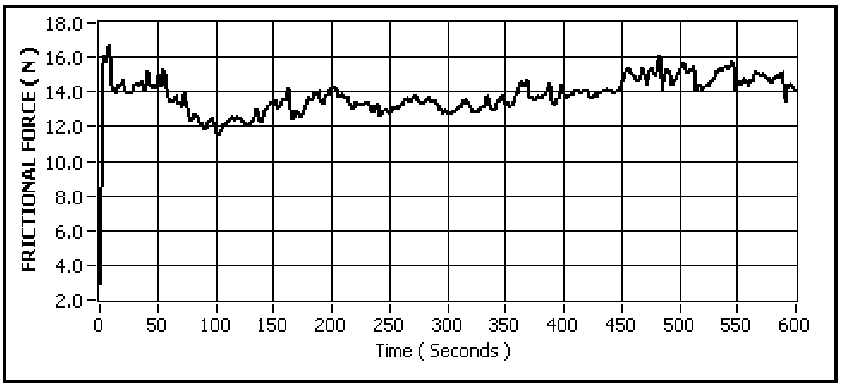
Where D = Diameter of wear track

N= Disc speed in rpm

T= Test duration in seconds



(a)



(b)

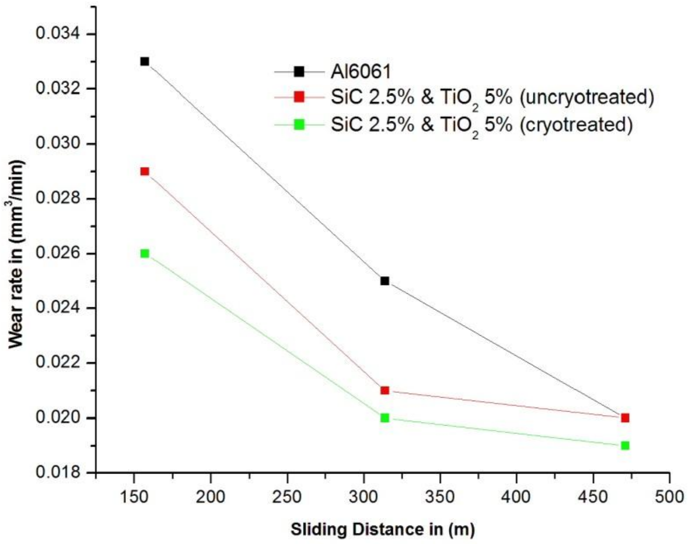
Fig. 2 Typical graphical result from pin on disk type wear testing machine (a) wear in µm and (b) Frictional force in N

II. Results and Discussion

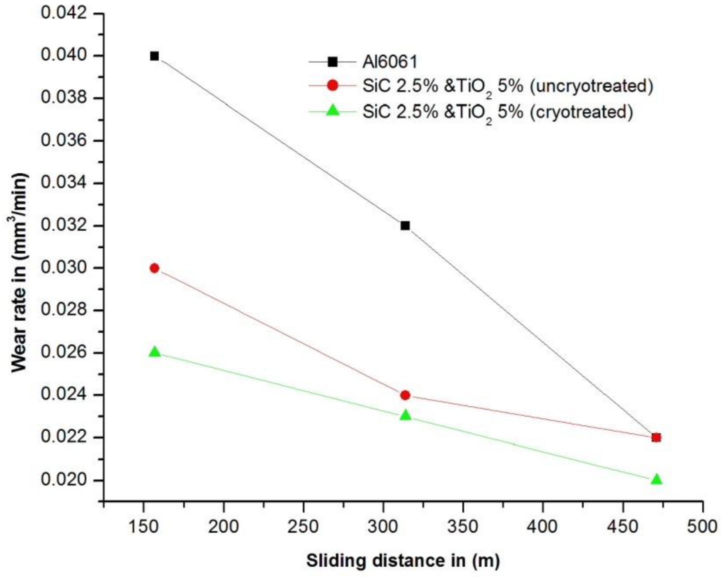
The hybrid composite material prepared is subjected to dry sliding wear and their response to the wear and other function was analyzed.

Influence of cryogenic treatment and its effect of load, sliding distance and particulate SiC and TiO_2 percentage on wear rate

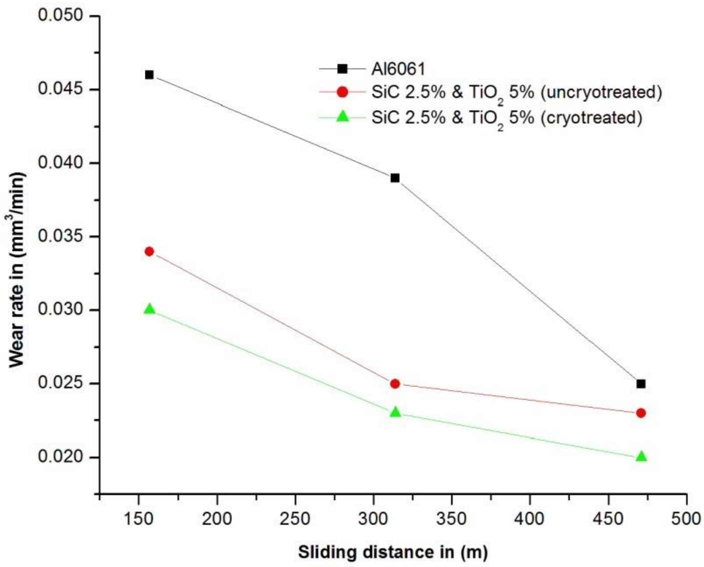
The wear performance graph depicts the wear of hybrid composite material of cryogenic processed and uncryo processes (Al6061+2.5%SiC &5%TiO_2) and unreinforced Al6061 alloy specimen under dry sliding condition are presented in the Fig.3. When the load applied is 29.43N (3Kgf) in Fig.3 (a) the variation of the wear rate with sliding distance for different cryogenic processed samples of hybrid composite material is shown. The graph shows two region which is "running in" and "steady state" periods The "running in" period is the time of start that is initial stage in the wear testing the wear rate is more due to the adhesive nature of the sample to the sliding disc[48]. During "steady state" period the wear progressed at a slower rate and linearly with increasing sliding distance. The hybrid composite specimen subjected to cryogenic processing shows decrease in wear rate as seen in graph. This is due to the high wear resistance of the particulate TiO_2 incorporated in the hybrid composite mixture. The results also explains that increase of sliding distance reduces the wear rate, due to the smoothening of the composite material after 100m which in turn reduces the wear rate. Fig. 3 (b) show the variation of wear rate with respect to sliding distance at a load of 39.24 N. The result obtained is almost same as the result obtained before, but the increase of load increases the wear rate in composite material. Fig. 3 (c) for 49.05N shows the same trend as observed for 29. 43 N load and 39.24 N load. The results of the above graph tell that increase of load increase the wear rate in hybrid composite material. The increase of volume fraction of TiO_2 in hybrid reinforcement decreases the wear rate of hybrid composite material due to the lubricating property of the TiO_2 particulate [46]. The cryogenic processed specimen shows enhanced wear resisting property compared to the uncryotreated composite specimen. This shows that materials microstructure at the molecular level is improved and evenly dispersed to have improved wear resistance of the hybrid composite.



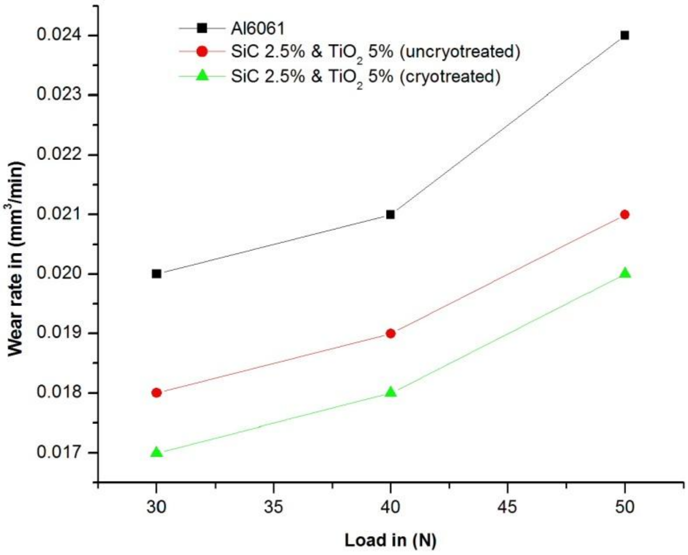
(a) 29.43N



(b) 39.24N



(c) 49.05N



(d) at the end of maximum sliding distance(628 m)

Fig. 3 Wear rate of unreinforced alloy and composites at applied loads of (a) 29.43N (b) 39.24N (c) 49.05N as a function of sliding distance (d) at the end of maximum sliding distance(628 m) as a function of volume percentage of reinforcement.

Fig. 3 (d) shows wear rate with respect to load and volume reinforcement for the hybrid composite material. The results are taken for the maximum of 628m specimen travel in the disc. The results clearly tell as the load increases the wear rate increases. The maximum wear rate is seen in the unreinforced alloy. The influence of the reinforcement in the matrix Al6061 alloy and the TiO_2 volume percentage along with cryogenic processing has the marked effect in the wear resistance property. It has been ascertained that increases of volume fraction of TiO_2 in a particular volume fraction say $3/4^{th}$ in a 7% reinforcement shows good wear resisting property. As expected, the wear rate of the composite specimen with a fixed volume percentage of reinforcement increases with increasing applied load and is depicted in Fig.3 (d). At the constant applied load the hybrid composite shows lower wear rate than the unreinforced Al6061 alloy. The Fig.4 the photographic view of the wear surface of the reinforced alloy specimen at the end of the maximum sliding distance for the subzero treated and untreated hybrid metal matrix composite. The width of the scratches decreases with increases in reinforcement and harder particulate reinforcement and increases with the increase in applied load.

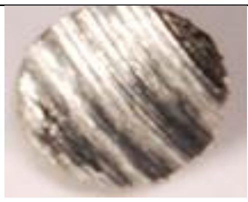
Reinforcement in volume %	**Load**		
	3kg	**4kg**	**5kg**
2.5% SiC+5% TiO_2 Uncryo treated sample	 1”x1.26”	 1”x1.26”	 1”x1.26”
2.5% SiC+5% TiO_2 Cryogenic treated sample	 1”x1.26”	 1”x1.26”	 1”x1.26”

Fig. 4 The photograph of the wear surfaces of the reinforced Al6061 alloy composites specimen at the end of the maximum sliding distance

4.5 Microstructural studies

The optical micrographs of unreinforced Al6061 alloy and its composite with (SiC 2.5% & TiO2 5%), subjected to cryogenic processed and untreated sample is shown in Fig. 5 The figure proves that the reinforcement is uniformly distributed in the matrix alloy. The porosity of the composite specimen increases with increase in volume fraction of the reinforcement material. The impact of cryogenic processing has significant changes in the microstructure of MMCs and led to the transformation of α-Al to β (Mg17Al12) phase. In the Al6061 alloy the β phase exhibited irregular morphologies (eutectic β phase) and tiny laminar shaped morphologies. The β phase has main strengthening effect on Al-Mg based alloys at room temperature proved by Mehta et al. [49]. The lower mechanical properties at elevated temperature is due to the low melting point of these alloy Kaveh meshinchi et al. [30].

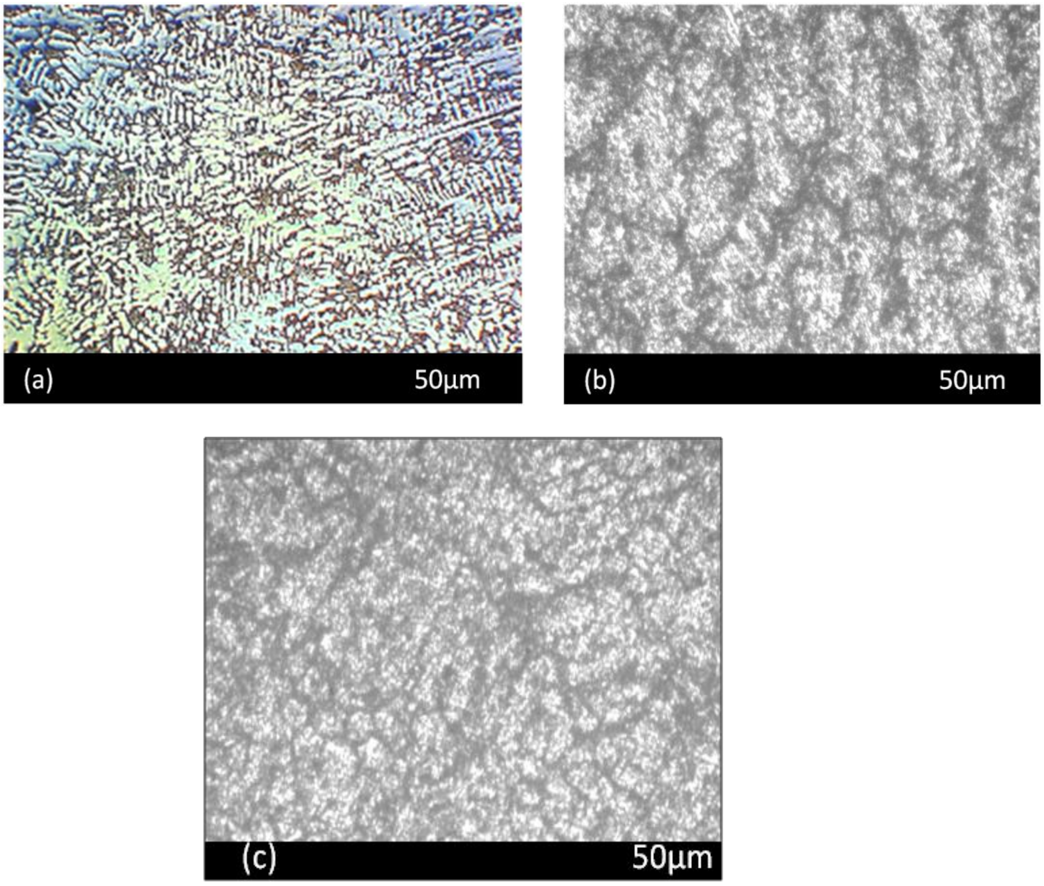
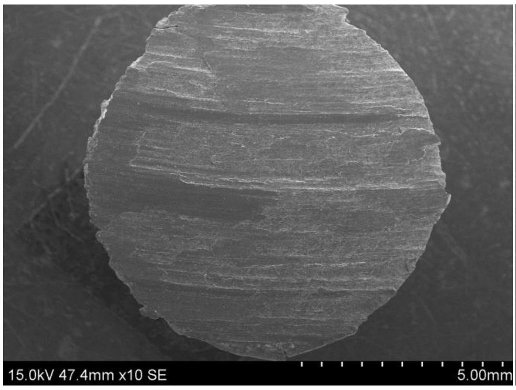
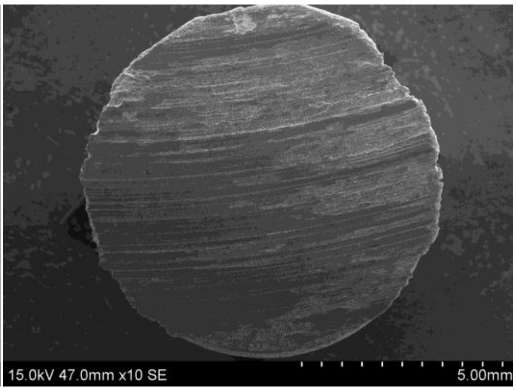


Fig. 5 Optical micrograph of (a) unreinforced alloy, (b) uncryotreated Al6061+ (SiC 2.5% & TiO_2 5%), (c) cryotreated Al6061+ (SiC 2.5% & TiO_2 5%)

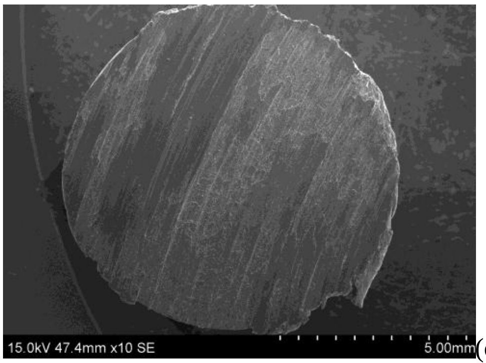
The examination of the worn surfaces in Fig.6 and Fig.7 reveals that composite material has much coarse surface than the unreinforced alloy. The cavities and large groove regions are seen in the surface subjected to testing. The samples when subjected to 5Kg load the width of the grooves and size of the dimples is larger than on the 3kg load. The change from mild to severe wear with increase in load due to the greater plastic flow in sliding surface of the specimen at the higher loads[46]. In composite material the Fig.8 (b) is subjected to severe wear and Fig.8 (c) is subjected to mild wear due to cryogenic processed and also high TiO_2 particulate volume fraction having high hardness and resisting the delaminating process. The dimples are formed due to the removal of material. The particle pull out due to the poor particle/matrix bonding [46]. The abrasive wear mechanism is exhibited in the experimental investigation and the wear resistance is more in case of composite material and further increases with cryo treated composite.



(a)

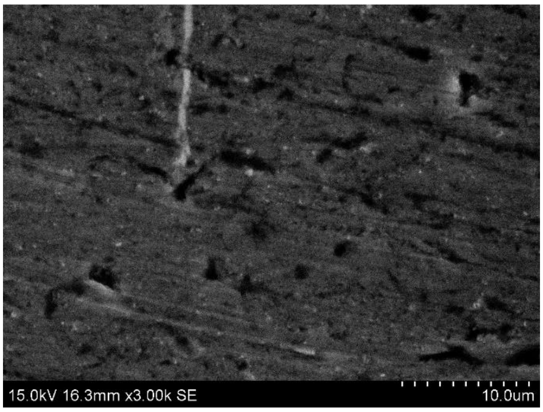


(b)

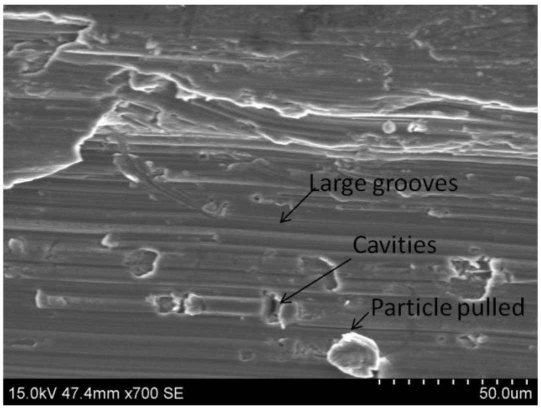


(c)

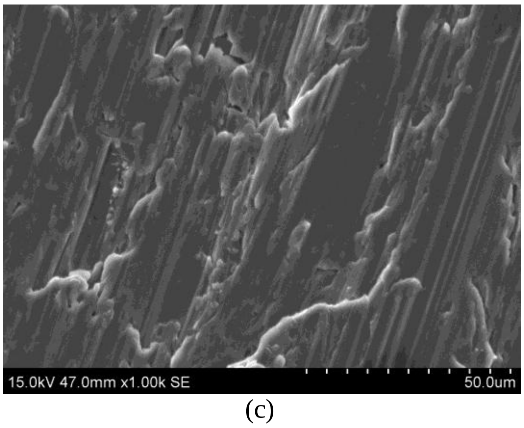
Fig. 6 SEM photographs of the wear track in 5mm (a) unreinforced alloy and composites with (b) Al6061+2.5%SiC & 5% TiO_2 uncryo treated (c) 2.5%SiC & 5% TiO_2 cryotreated cryogenic processed vol. fraction after complete sliding distance with maximum load of 5kg.



(a)



(b)



(c)

Fig. 7 SEM photographs of the worn surfaces in 50µm (a) unreinforced alloy and composites with (b) Al6061+2.5% SiC & 5% TiO_2 uncryo treated (c) Al6061+ 2.5% SiC & 5% TiO_2 cryotreated vol. fraction after complete sliding distance with maximum load of 5kg.

III. Conclusion

The experimental investigation on the effect of SiC and TiO_2 reinforced with and without cryogenic processing of unequal percentage content on the wear behavior of Al6061 alloy hybrid composite led to the following conclusion:

1. In general wear rate decreases with increasing volume content of the reinforcement, the increase in TiO_2 percentage by $3/4^{th}$ in a 7% volume fraction of (SiC & TiO_2) the wear rate decreases compared with unreinforced aluminium alloy and also due to increased percentage of TiO_2. This depicts the influence of TiO_2 having lubricating property and formation of mechanical mixed layer of the reinforcement particulate as the temperature increases while sliding[46]. The wear resistance increases in TiO2 dominating volume percentage reinforcement due to the lubricating property of the TiO2 while incorporating highly in the hybrid composite material.
2. The results of this unequal volume percentage of hybrid composite subjected to cryogenic processing also have enhanced wear resistance property compared with untreated cryogenic samples of hybrid composite. This also creates an quantity factor of the reinforcement particle regards to property while developing an hybrid composite
3. The results reveals that wear resistance is also influenced by lubricating property compared with harder property of reinforcement.
4. As load is increased, the change from mild to severe wear takes place much faster in alloy than composites.
5. The wear rate of the hybrid composite are less when compared with the matrix alloy and the binary composite.
6. The results of the scanning electron microscope show that composite material has much coarse surface than the unreinforced alloy. This indicates the abrasive wear mechanism which is due to hard ceramic particles on the worn surfaces.

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