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Tribological Behaviour of Cast In-situ Al-Al_2O_3 Composite Developed by Stir Casting Using V_2O_5 Particles

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Keywords: Al-7Si alloy; V_2O_5; in situ; Hardness; dry sliding wear; Al_2O_3.

ABSTRACT

The reinforcement of Al_2O_3 in aluminum metal matrix composites is very popular these days because of their large number of applications. Al-Al_2O_3 composites covers a lot of sectors like automotive, aerospace, aeronautical and defense due to their low weight & excellent mechanical properties like strength, hardness etc. In the current study, Al- Al_2O_3 composites have been produced by adding a different amount of V_2O_5 particles in Al-Si alloy. The influence of V_2O_5 addition on wear has investigated. The influence of sliding distance, amount of V_2O_5 addition and sliding velocity effect on wear behavior have been analyzed experimentally and discussed. An improvement in wear behavior has been observed in developed composite as compare with base alloy. The development of hard Al_2O_3 particles within the melt increases the composite hardness which in turn improves the wear behavior. The coefficient of friction of cast in-situ Al- Al_2O_3 composites was determined at different loads by tribotester. The research revealed that the coefficient of friction and wear loss increases with the load.

INTRODUCTION

Al-Si alloys are famous for the great fluidity. These alloys are also known as foundry alloys. Commercially they are available in the form of hypoeutectic & hypereutectic alloys (Torabian et al., 1994). In industries, Al-Si alloys contribute more than 70% of casting. Despite their large number of application, these alloys exhibit unpromising tribological properties.

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The addition of oxide particles considerably helps in eliminating these problems and enhance mechanical and tribological properties altogether. These embedded Aluminum alloys also known as Aluminum matrix composites AMC. These AMCs because of said properties have gained popularity and interest of researchers from various backgrounds (Gruzleski and Closset, 1990; Kumari et al., 2002)

As the response of these AMCs towards weary action not only depends upon hardness or strength but also depends on sliding velocity, the load applied, and operating conditions (Clarke and Sarkar, 1979; Dwivedi et al., 2001). Many studies have also pointed to the rate of solidification, grain refinement, and chemical composition as the main factor in wear behavior (Chandrashekharaiah and Kori, 2009).

There are multitudes of ways to prepare AMCs like mechanical alloying, stir casting, squeeze casting etc.(Tjong and Ma, 2000). Among all these various ways there are two ways which deserve to be worth mentioned, In-situ fabrication and exsitu method. The former method involves the chemical reaction of oxide particles with molten metal and the development of alumina particles inside the melt. While in the latter method the particles are added externally to the liquid metal. The main advantage of the In-situ method over the other is that the surface of the particles believed to be bereft of contamination, which in turn leads to enhanced interfacial bonding strength (Mandal et al., 2007; Sivaprasad et al., 2008)

Many studies have been carried out for ceramics, oxides and borides like CuO, ZnO, MoO_3, MnO_2 and (TiO_2) reinforced Aluminum alloys (Banerji et al., 1983; Hamid et al., 2006). A researcher probed the effect of ceramic particle and heat treatment on the wear rate of AA6351 with (0-9%) ZrB_2 in-situ composite and noticed a reduction in wear rate (Maity et al., 1993). TiB_2 acted as a grain refiner as well as a modifier of Si and increases the wear resistance of Al-7Si matrix (Kumar et al., 2008).

Also, Nanoparticles of V_2O_5 increases antiwear properties when mixed in oil and lowest wear rate has been reported by adding 0.2 wt. % in oil(Dai et al., 2017).

In the present work, Al- Al_2O_3 in-situ composite is produced by adding vanadium pentoxide using stir casting method. The significant factors like reinforcement, sliding velocity and sliding distance etc. influencing the rate of wear were studied through experimental means.

EXPERIMENTAL PROCEDURE

Development of composite

For the experimental study, composites were developed by using Al-7Si (ingot) and V_2O_5 particles (extra pure). Table 1 shows the composition of the base alloy. The composition is determined by Spectrometer (AMETEK Germany).

Table1. The elemental composition of base alloy (wt. %).

Si	Fe	Cu	Mg	Mn	Zn	Ti	Cr	Ni
6.98	0.21	0.16	0.42	0.13	0.02	0.01	0.01	0.03

The bottom pouring furnace has been used for the casting of composites shown in figure1. In the stir-casting method, stirring contributes in transferring particles into the molten alloy and helps to disperse and suspend the particles in the melt. For this purpose, a stainless steel stirring blade with three bents was used for stirring. To prevent the dissolution, a very thin layer of graphite paste was applied on the blade surface (Singla et al., 2016). The parameters used are mentioned in table 2.

Fig. 1. Bottom pouring furnace.

Table 2. Process parameters for the composite development

Parameters	Variables used
Melt Temperature	$700^0C \pm 50$
Preheating Temperature for particles	250^0C
Temperature of Mould	250^0C
Stirrer RPM	600-700
Processing time	10 minutes
Amount of V2O5 added	1,3 and 5 wt.%

The temperature for the composite development was selected as per the differential thermal analysis. DTA has been carried out by using EXSTAR TG/DTA 6300. The powder of Al-7Si and Vanadium pentoxide has been used for the experiment. The heating of the sample is carried out in Al_2O_3 Pan at 10^0C min^{-1} in the presence of nitrogen atmosphere.

Fig.2 shows an endothermic peak at 583^0C which represents the melting of Al-7Si alloy. Another peak at 673^0C has been observed shows the melting of vanadium pentoxide. Declined in peak has been observed between $800\text{-}850^0C$, this might be the formation of another phase. In the current study, the casting has been done considering the parameters according to DTA analysis.

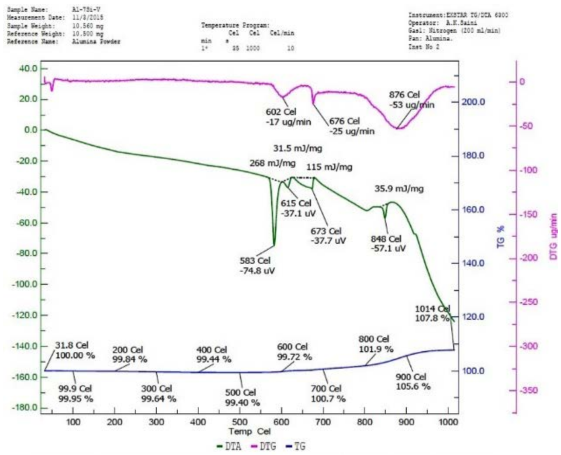

Fig. 2. Differential thermal analysis curve carried out at 10°C per minute.

At 700^0C, 5gm of Magnesium was added in order to promote wettability. V_2O_5 was added in the liquid metal at a very slow rate. For the better dispersion of V_2O_5 particle stirrer was used at a constant position in the crucible. After 10 minutes, melt was poured into a preheated mould. During this process, the argon gas was supplied continuously & degassing was carried out for vacuum casting.

Designation of the developed composite

Adding 1, 3 and 5% V_2O_5 developed three different composites and all the composites have been designated by sample name. The designation given to the composite is shown in table 3.

Table 3. Composite material designation.

Sample Designation	Material
AS	Aluminum-7%Silicon
ASV1	AS-1% V_2O_5
ASV3	AS-3% V_2O_5
ASV5	AS-5% V_2O_5

Where AS represents the Aluminum-7% Silicon alloy,
V followed by the number represents the wt. % of V_2O_5 added.

Pin on Disc Test

ASTM G99-95 test method on Pin on Disc has been used for the experiments. The coefficient of friction and frictional force data has been acquired from tribometer with the help of sensor and LVDT setup. Pin on Disc integrated with a computer is shown in figure 3. The difference of pin weight had been taken into account after each test. Eventually, weight loss had been portrayed as a phenomenon of various applied loads and sliding distance. Weigh machine had been employed for weight measurement.

Fig 3. Pin On Disc Tribotester

Flat cylindrical pins (5mm radius and 30mm height) of the Al-7Si and the composite with 1, 3, & 5 % of V_2O_5 addition has been developed for the test. The counterface disc of 165mm diameter and 8mm thickness was used with 145 mm as maximum track diameter. EN31 was comprised of carbon, manganese, Sulphur, Silicon, Phosphorus, Chromium with 1%, 0.5%, 0.05%, 0.35%, 0.05%, and 1.3% respectively of composition. Ethyl alcohol had been used as an agent for surface cleaning. Test were performed for 1000m distance at 0.83m/s velocity by applying 10N, 20N, and 30N loads. After each test, the disc was cleaned and polished with the help of emery paper of different grit sizes. To prevent the occurrence of corrosion, both disc and pin test samples were spruced ultrasonically with ethyl alcohol after which it was stored in vacuum. The facility of trinocular stereo zoom microscope has been used to detect for any worn surfaces. To retain the accuracy, mean of average value has been used three times following each experiment.

Coefficient of Friction $\mu = \frac{F}{N}$
Where *F* represents frictional force and *N* is the load applied in Newton

RESULTS AND DISCUSSION

Mechanical Properties

Table 4. Shows the properties of base alloy and its cast insitu composites. Hardness has been measured at different positions and the average value has been taken for the results. In case of 1 % V_2O_5 addition, hardness value increased up to about 20%. The trend of hardness variation with respect to the amount of V_2O_5 addition is shown in figure 4. The graph shows the highest value of hardness is obtained in case of ASV1 and it starts decreasing after that at 100gf load. It is well reported by researchers that alumina particles are hard in nature and the presence of hard alumina as well as the refinement of α –Al contribute towards the enhancement in properties. Another reason is the solid solution hardening. In present study, solid solution hardening is attained by reduction of Vanadium from V_2O_5 particles dissolved in molten metal. The solid solution hardening is a result of an interaction among the mobile dislocations and the solute atoms. Dissemination of V_2O_5 particles acts as a hindrance for the dislocation movement and forms the dislocation loops. According to the Orowan mechanism, movement of dislocation is quite difficult in the case of a loop rather than a line (Iwai et al., 2000). Dispersion of Al_2O_3 and intermetallic compound in the matrix also contributed to hardness increment.

With further addition of particles, hardness starts decreasing as shown in table 4. The reason for the decrement is the dendritic growth and release of latent heat. Higher addition of V_2O_5 particles leads to the agglomerations of a large number of Nano-sized alumina particles in the crystal at grain boundaries causing incoherency with the matrix and attributed to low hardness.

Table 4. Mechanical properties of Al-Si and its composites.

S.No	Alloy/Composite*	Microhardness	UTS(MPa)	Elongation
		(HV)		(%)
1	AS	51.7(2.3)	137	8
2	ASV1	64.1(1.8)	184	6
3	ASV3	59.7(1.5)	181	5
4	ASV5	56.3(1.2)	174	4

* Wt. % of oxide added.
# Standard deviations are shown within parentheses.

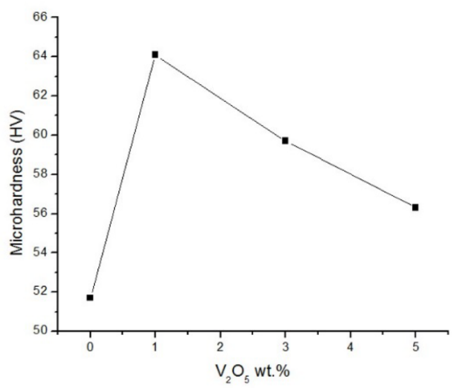

Fig. 4. Micro hardness with respect to V_2O_5 addition.

Coefficient of friction Analysis

The experimental study had been conceded out in order to estimate the variation in the wear rate of different Al-Si- Al_2O_3 composites due to change in reinforcement amount and loads. The obtained results are plotted in graphical form and a trend is observed for each parameter. Elaboration regarding the effect of various parameters on wear rate has been made.

Figure 5(a), (b) & (c) denotes the variation in Coefficient of friction for different Al-Si- Al_2O_3 composites at different loads. 10 N, 20 N & 30 N loads are applied at sliding velocity 0.83m/s It is revealed from the figure that at low load the coefficient of friction increase continuously with sliding distance with one or two exceptions. At intermediate loads, the maximum coefficient of friction is observed at a low sliding distance (200m) and decreases afterward with some exceptions. At higher loads coefficient increases continuously up to a sliding distance of 600m and decreases afterward. Among all the in-situ composites and the matrix alloy, Al-7Si reveals the maximum coefficient of friction whereas Al-7Si-1% V_2O_5 in-situ composite shows the minimum coefficient of friction.

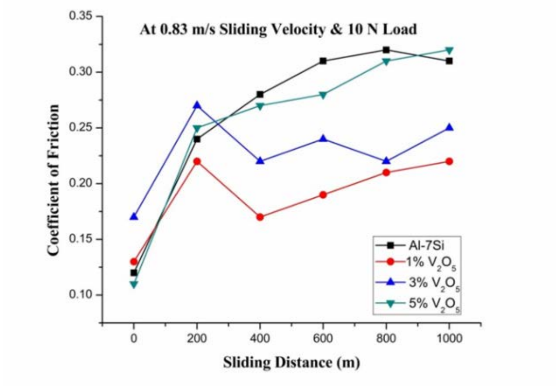

Fig. 5 (a) Coefficient of friction at 10N load.

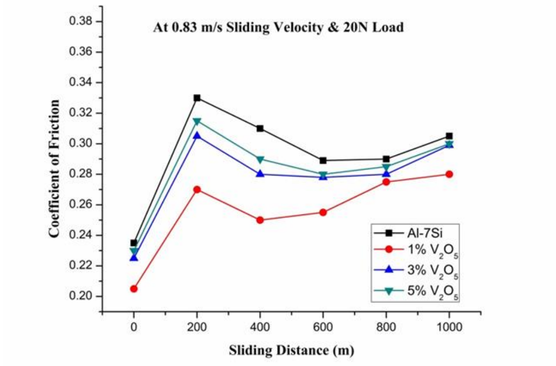

Fig. 5. (b) Coefficient of friction at 20N load.

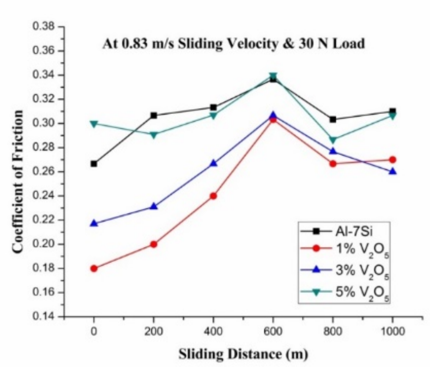

Fig. 5 (c) Coefficient of friction at 30N load.

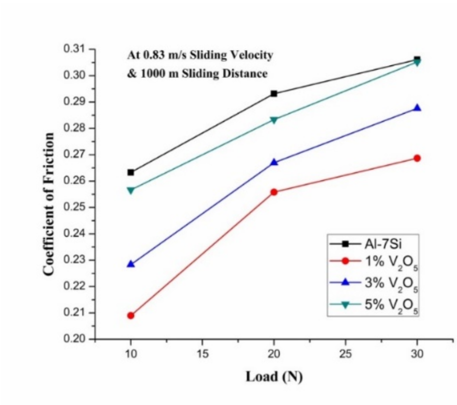

Fig. 5. (d) Variation of COF with different loads at 1000m distance

Generally, friction coefficient has a tendency to increase with increasing load. Addition of oxide particle leads to the formation of hard alumina particles which helps to bring down the coefficient of friction. Significant variation in the coefficient of friction was observed with the sliding distance but in most of the cases, it decreases for large sliding distances at higher loads (Dwivedi, 2010; Sulima and Mikulowski, 2006; XIU et al., 2010)

The figure 5 (d) shows the variation of friction coefficient with the load under constant sliding velocity and constant sliding distance for different Al-Si-Al_2O_3 in-situ composites and Al-7Si matrix alloy. The figure reveals that coefficient of friction increases continuously with a load for all the materials where alloy matrix exhibits the highest coefficient of friction and in-situ composites having 1% V_2O_5 reveals the lowest coefficient of friction at all loads.

Composite developed with 1% addition of V_2O_5 particles shows the maximum hardness among all other composites and contribute to low coefficient of friction. The Significant decrease in the coefficient of friction can be attributed to the decrease in the contacting area of two mating surfaces due to the presence of uniformly distributed fine Al_2O_3 particles in Al-Si matrix. With increases in weight percentage of V_2O_5 particles, more alumina particles are generated which agglomerate to form clusters of the particles. This clustering of agglomerated particles affects the size and dispersion of alumina particles in the matrix that eventually leads to an increase in the coefficient of friction (Iwai et al., 2000).

Figure 5 (d) represents a comparative plot of COF and applied load, the coefficient of friction increases with applied load and obtained results are as per the Archard law of wear (Archard, 1953). Composite with 1wt. % V_2O_5 had a minimum coefficient of friction. A decrease in the coefficient of friction at 1000m was about 32.8% for the 1 wt.% sample, 20.96 % for 3 wt.% sample and in the case of 5 wt.%, it was almost similar to Al-Si alloy at 10 N load. Similar kind of trends has been obtained at 20 & 30 N load also.

Volume loss

Volume loss increases with increasing the load value for all in-situ composite and Al-Si alloy as shown in figure 6. Volume loss declines, for Al-Al_2O_3 composites in comparison to pure Al-Si alloy. Volume loss also increases with increase in V_2O_5 addition, as an in-situ composite with 1% V_2O_5 particle addition exhibits lower volume loss as compared to other in-situ composites having more wt. % of V_2O_5. The drop in volume loss of in-situ composite over the Al-Si alloy credited to the effect of reinforcing particles. Less addition of V_2O_5 leads to uniform dispersion of fine coherent Al_2O_3 particles in optimum quantity. Higher addition leads to agglomeration of Al_2O_3 particles causing incoherency with the matrix and may detach easily during wear testing. The average decrease in volume loss observed for Al-7Si-1%, 3% and 5% composite was 47.3. %, 36.3 % and 27.5 % respectively.

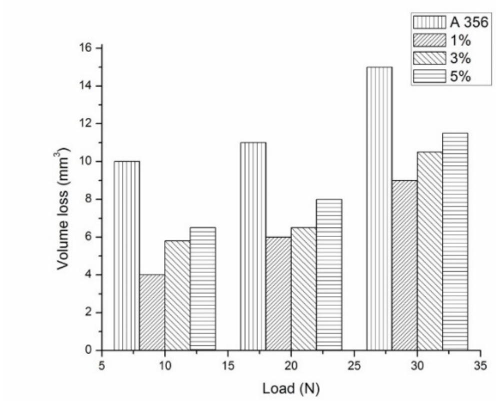

Fig. 6. Variation of volume loss with load at 1000 m Sliding distance.

Wear

Figure 7 (a) & (b) clearly depicts the wear response of Al-Si and cast in-situ composites under dry conditions. Wear increases with a load for all the composites and alloy with an increase in weight percent of V_2O_5 additions. Wear of in-situ composites decrease enormously by the reinforcing particles is in good agreement with literature. Hard particles act as a load bearer and in case of in-situ; it produces the pure interfaces, which in turn enhance interfacial bonding strength (Dinaharan and Murugan, 2012).

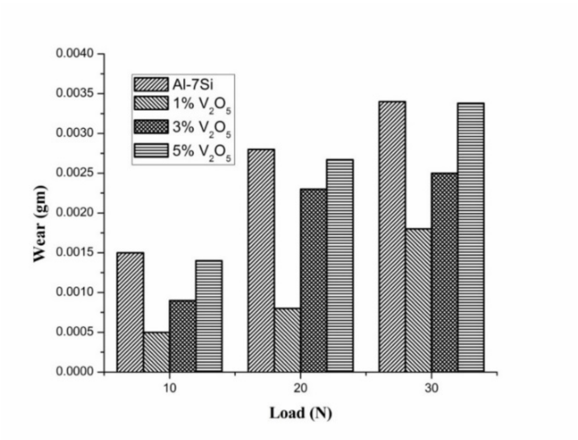

Fig. 7. (a) wear of different composite with respect to the different load applied

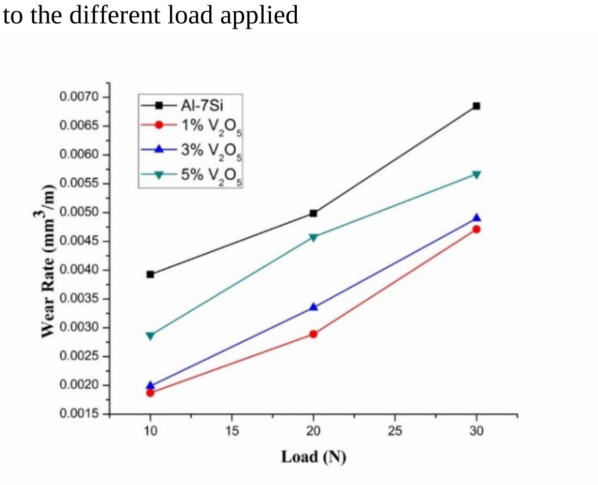

Fig. 7. (b) wear rate of the different composite at different loads.

A higher percentage of V_2O_5 particles increases the alumina content and shoots up the hardness as compare to the base alloy. During the dry sliding test, oxide debris formed due to oxidation and form a compacted layer. At small loads, this layer act as a protecting layer and led to the deteriorating wear rate (JIANG et al., 2014). However, specific wear rate increase with 5% addition of V_2O_5 particles. It is well known that in the cast composites, porosity increases with increase in particle content which in turn decline their performance against wear. This porosity can be attributed to dismal wetting of reinforced particle in molten Aluminum (Yılmaz and Buytoz, 2001).

Porosity also influences hardness and tensile properties. At dry sliding condition, high porosity in composite increases the real area of contact and ultimately wear rate increases. Hence, porosity not only soften the material but it also increases the probability of delamination and cracks.

Increase in applied load eventually resulted in the worn-out surface of the material. In case of the small load because of micromachining effect, a part of counterface material gets separated and oxidized. The oxidized material (Fe_2O_3) contribute as a protective layer between the mating surfaces. Wear studies has established that this temporary reduction of wear rate is due to the formation of this tribo layer. This layer acts as a solid lubricant when low loads are applied. High loads, pull apart this tribo layer and leads to delamination. High load increases heat at the near surfaces, weaken the shear strength and ultimately promotes excessive wear. The formations of grooves are shown in figure 7. Various investigators specifically in case of aluminum-based composites have perceived similar kind of transfer layers (Al-Qutub et al., 2008; Yang et al., 2011; Zhu et al., 2012)

The most favorable results of wear rate have been observed with the condition of 1% addition contrary to 3 & 5% addition. Because of abrasion mechanism, tiny grooves were formed on the worn surface in the sliding direction at low load. But in case of higher load delamination happens due to more real area of contact and finally resulted in an increase in fracture stresses of the reinforced particle as shown in figure 8 (a) & (b)

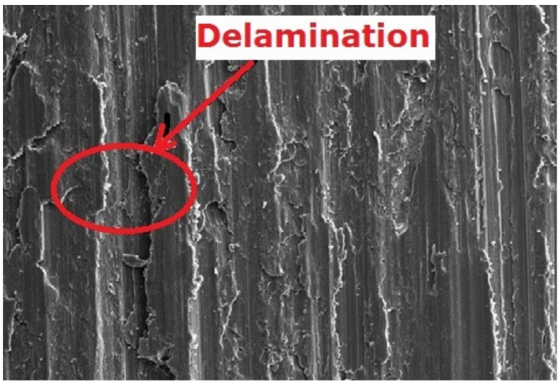

Fig. 8. (a) SEM of 5% V_2O_5 composite.

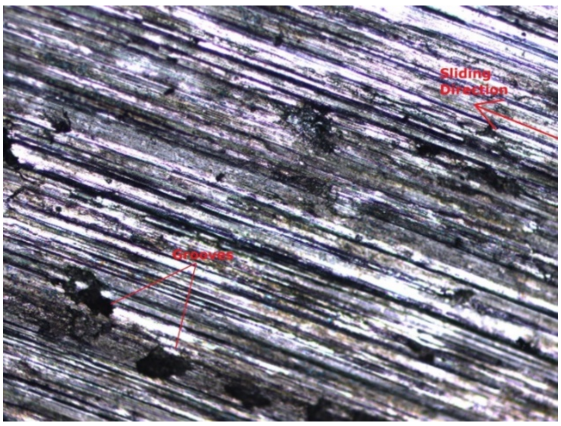

Fig. 8. (b) worn surface image of 5% V_2O_5 composite

Effect of reinforcement on the hardness

The addition of V_2O_5 particles ameliorates the hardness of composite as a whole which resulted in lower wear rate compared to a low mass fraction of V_2O_5. The severe adhesive wear largely depends on the hardness of the material as reported by researchers [19]. Further evidence & support from the practical work suggested that, scuff & seizure, the onset of adhesive process stunting when the hardness of mating parts increased (Deuis et al., 1997).

There is the pure and clean interface between the matrix and V_2O_5 particle as shown in previously published work (Singla et al., 2016) Which clearly resulted in better load-bearing capacity and the ability of the composite, which in turn bring down the rate of wear of composite with a swell in a mass fraction on V_2O_5 particles. The reaction of V_2O_5 with molten aluminum results in the formation of alumina. Alumina particles are hard in nature and contribute in hardness.

Effect of sliding velocity

The rate of wear increases abruptly but linearly with increase in sliding velocity. High sliding velocity leads to increase in generation of heat at the surface contacts. This generation of heat results in mellowing down of surface this, in turn, increases the penetration of counter surface into the pin surface.

Different thermal expansion values between the V_2O_5 particles and the matrix is vital in wearing down of the composite. This incongruity in terms of thermal expansion leads to appearing of interface stress. As the sliding velocity rises, the heat generation also surges to a high value, which in turn leads to increase in interfacial stress, and when this interface stress surpasses interface bond strength crack or particle also may leave its place and leaves a vacancy.

The presence of Si & Al_2O_3 hard phases (secondary) restricts the mental flow during the dry sliding process. Also, in case of Al/ Al_2O_3, Si addition plays an important role .it has a significant effect on interfacial bond strength. Hard particles decrease the real contact area between the mating surfaces and decrease material removal (Ramesh and Ahamed, 2011)(Yang et al., 2010). Fig 8 (b) portrays the eroded surface of the composite under study at sliding velocity of 0.83m/s. However, the not much damage has been inflicted upon the subsurface at this sliding velocity but at a higher sliding velocity of around the subsurface has received comparatively more damage.

CONCLUSIONS

- Wear rate in Al-Si alloy decrease by addition of particles and 1% addition of V_2O_5 shows the better results as compared to the composites having a high percentage of particles.
- At higher loads and sliding velocity more heat is generated which dismantle the tribo layer formed between the contacting surfaces and ultimately the wear rate increases.
- The great reduction in volume loss has been detected in composite with 1% addition of V_2O_5 particles as compared to other cast composites.
- A reduction in the coefficient of friction at 1000m was about 32.8% for the 1 wt.% sample, 20.96 % for 3 wt.% sample and in the case of 5 wt.% it was almost similar to Al-Si alloy at 10 N load
- The great improvement in the wear behavior found which is calculated experimentally.

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