ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

Study of the Oxidative Wear of the Aluminum Rutile Composites at Higher Contact Pressure

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Abstract
Aluminium alloy matrix composites have found its wide applications in the manufacturing of the various components such as piston, brakes, piston liners and engine where tribological properties are a predominant process. Aluminium alloy reinforced with 5wt.% and 10wt.% of rutile concentration was prepared by liquid metallurgy route. Wear tests were performed at different loads varying from 9.8N to 49N at constant sliding velocity of 1.6m/sec. Materials possessing high wear resistance under dry sliding conditions are associated with a formation of stable tribo-layer on the wearing surface. In this work, a systematic experimental study was performed to analyse the effect of contact pressure on the formation of the tribo oxide layers during sliding. The shape and size of the wear debris clearly demonstrated that how the particles were fractured and comminuted, losing their role as load supporters.

Keyword
Rutile, SEM, Oxide layer, Composite

I. Introduction
Aluminium alloys offer a suitable alternative to weight sensitive structural applications in the aerospace and automotive industries owing to low density and high specific strength. Wear causes a serious problem when Al alloys are subjected to sliding motion [1]. Alminium based metal matrix composites has been established as potential material especially for sliding wear applications. Various type of ceramic reinforcements are generally used to enhance the tribological properties of the composite. In these days, mineral reinforced composites are gaining popularity as minerals have excellent thermal stability, low cost abundance availability as well as environment friendly. Liquid metallurgy route, stir casting is used for the preparation of the composite. Stir casting route is generally practiced commercially [2]. Its advantage lies in its simplicity, flexibility and applicability to large quantity production.
The aluminium composites operate under high temperature conditions. Wear resulting from the elevated temperature introduces the functional incompetency in the tribosystem. However, oxidation of the aluminium occurs in the operating components where atmospheric conditions are the elevated temperature and high contact pressure. So oxidative wear should be one of the predominant mechanism under the dry sliding conditions. The formation of oxide on the metal surface under the prevailing conditions prevents metal-metal adhesion, thus reducing the wear rate. In this wear regime, wear is termed as mild oxidative wear [1]. The oxidation plays a significant role, causes change in the overall wear rate. Wilson and Alpas [3] at the high applied load, mixing of the wear debris and the counterface material could takes place and which can be oxidized with the rise of temperature at the contact surface forms a oxidized layer. This oxidized layer covers the surface and also known as the tribo layer which considerably reduces the wear.

In the present work, systematic experimental study is performed to analyse the effect of contact pressure on the formation of the tribo oxide during sliding. Aluminium composite is reinforced with 5 and 10% of coarse size (106-125µm) rutile particles (5Ccoarse, 10Ccoarse) using stir casting route. The prepared samples are subjected to the wear tests under the different loading conditions from 9.8N to 49N. The wear behaviour is correlated with the morphological studies of the wear tracks and debris.

II. Material Used and Experimental
In the present studies, a well known aluminium alloy LM13 is used as matrix material and rutile particles as reinforcement. The composite was made by step stir casting route. Required quantity of LM13 alloy was taken in a graphite crucible and melted in an electric furnace at temperature 800˚C. This molten metal was stirred using a graphite impeller at a speed of 630 rpm to create the vortex. Particles prior to mixing were preheated at 300˚C to drive off the moisture. After the formation of vortex in the melt, the particles were charged inside the vortex at the rate of 20–25 g/min. into the melt during stirring by impeller with the help of funnel kept on top of vortex. Rutile particles of coarse (106-125µm) were selected for present work. The wear tests of specimen from each set of composite have been conducted up to 3000 m of sliding distance at a constant sliding velocity of 1.6 m s-1 and at two different pressure 9.8N and49N. Wear rates for the pin are calculated from the volume of material lost during the test.

III. Results and Discussions

A. Surface Morphological Analysis
For the morphological analysis of composites, samples having dimensions 20mm × 20mm were cut from the different areas of the cast alloy and composites. These samples were mechanically polished and etched with Keller's reagent. The surface morphology of each sample was studied with the help of optical microscope (Eclipse MA-100, Nikon) and scanning electron microscope (JOEL, JSM-6510LV) at different magnifications. Elemental analysis of the composite at different phases was done with SEM-EDS (Oxford Instrument INCAACT Energy). Microstructural features of the composite are strongly governed by the distribution of the second phase dispersed particles in the alloy during solidification. The optical micrographs of 5 and 10% rutile reinforced with coarse particles (106-125µm) in the composites are shown in Fig1(a, b), respectively. Figure 1a shows that 5wt.% coarse rutile particles are nearly uniformly distributed in the composite. This kind of distribution of particles is achieved by the constant stirring action of the impeller which provides the normal shear strain and delays the particle settling tendency during stirring [2].

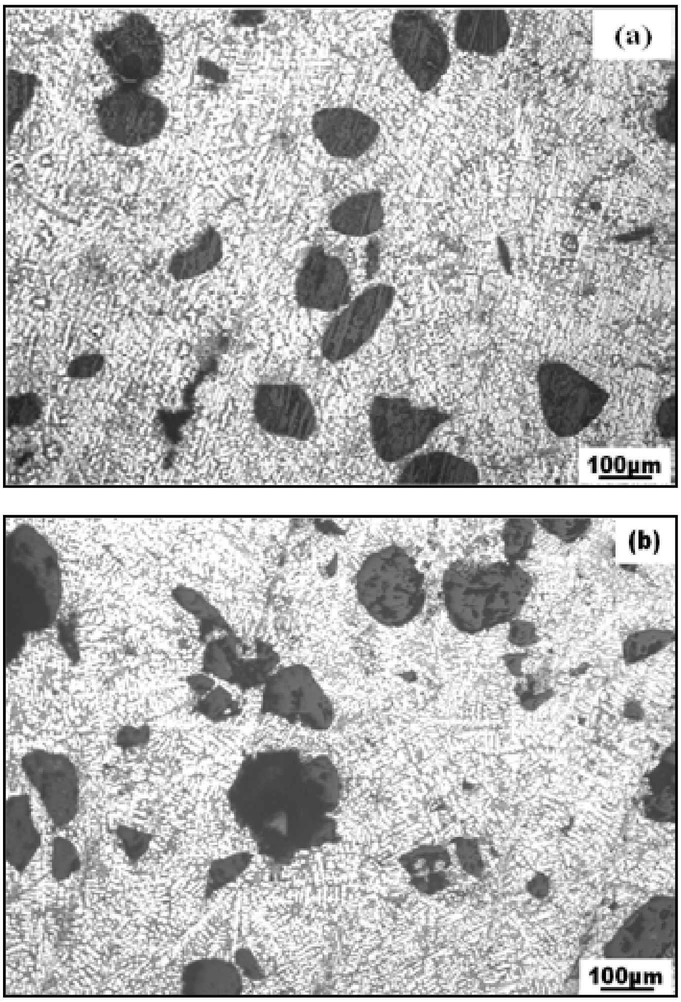


Fig. 1: The Optical Micrographs of Composite With Coarse Reinforced Size at Different Amount (a) $^{5}C_{coarse}$ and (b) $^{10}C_{coarse}$.

The change in surface morphology can be explained on the basis of fact that the rutile particles are pushed by the solid liquid interface during the solidification of the melt that results the particles to occupy the space in the inter-dendritic regions. The dendritic morphology changes to cellular one in composite as reinforced particles restrict the solute transport processes by diffusion and flow [4-5]. The long dendritic growth is clearly observed in the particles depleted regions. Some fragmented dendrites and small broken particles can also be seen due to the stirring action of the impeller during mixing. Dendritic fragmentation can be attributed to the shearing of initial dendritic arms by the stirring action. During particle addition, local solidification of the melt occurs which is induced by the particles as there is a temperature difference between the particle and the melt. It was also found that the perturbation in the solute field due to the presence of particles can change the dendrite tip radius and the dendrite tip temperature. These effects give rise to a dendrite-cell transition as the density of particles is increased. Also the length of the dendrite is reduced in the presence of the particles [4]. The enrichment of Si phase is observed in the vicinity of the particles.

The uniform distribution of 10wt.% coarse size rutile particles can be noted from the Fig 1b. The termination of the dendritic growth on approaching the particle reveals that the inclusion of particles causes the hindrance to the dendritic growth. The restricted dendritic growth enhances the strength thus provides more hardness to the composite [4]. Even the fragmentation of dendrites during rotation gives rise to the growth of cellular structure. In certain areas, the segregation of the particles leads to the clustering. These overlapped segregated particles are loosely bonded to the matrix thus reduces its strength. Presence of rutile particles in the matrix provide hindrance to the dendritic growth and strengthen the composite by giving more hardness which also improves the wear rate.

B. Effect of Applied Load on yhe Wear Rate

Wear rate of 5 and 10% coarse size (106-125µm) rutile reinforced composites ($^{5}C_{coarse}$,$^{10}C_{coarse}$) as a function of sliding distance at variable loads from 9.8N to 49N is shown in fig.2(a, b). At a particular load, two types of wear behaviour are displayed by the composites during the dry sliding. In the initial stages of run, the abrasive wear between the two surfaces in relative motion is dominant. The abrasive wear is accompanied by the formation of thin and shallow grooves on the specimen. So the initial stages of run have shown very heavy wear loss due to the statistical fluctuations in wear. The continuous grinding of these abrasive particles while sliding reduces the sharpness of the asperities. These blunt shaped smooth abrasives cause fall in wear loss and the steady state is attained. The similar type of wear behaviour is also observed by Kumar et al. [6] and Chaudhary et al. [7]. For both the composites the wear rate is mild at low loads (9.8N). Formation of oxide layer prevents the contact between the sliding surfaces which suppresses the wear loss [8]. However, the continuous increase in wear rate is observed with the increase in load from 9.8N to 49N (Fig.2 a,b). Increase in wear rate with the increase of load is on the same pattern as observed by Das et al. [9]. High pressure during sliding fractures the oxide film covering the surface and leads to the exposure of the substrate material thus causing plastic deformation beneath the surfaces which changes the wear mode from mild to severe. This close contact welds the removed materials which can be transferred to the counterface and some of material may fall out as wear debris

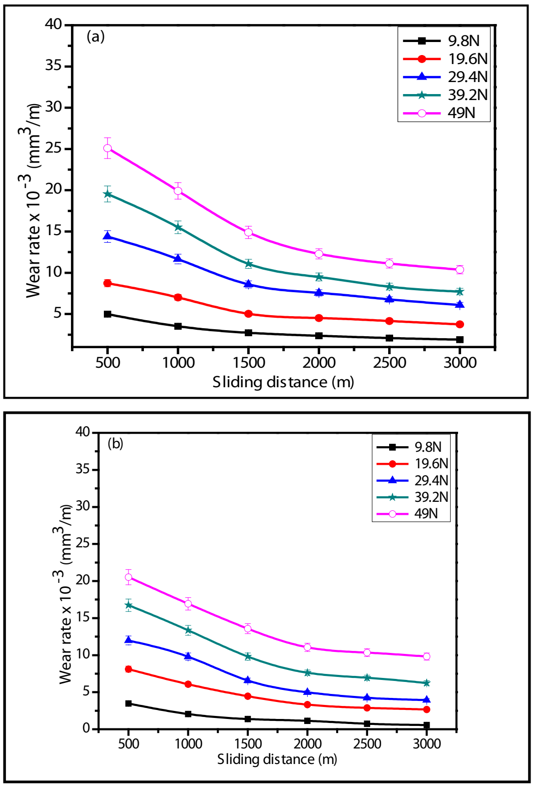


Fig. 2: Wear rate of rutile reinforced composites against sliding distance at different loads for (a) composite-$^{5}C_{coarse}$ and (b) composite-$^{10}C_{coarse}$.

On increasing the amount of rutile particles in the composite from 5 to 10wt.%, reduction in wear rate is observed which is shown in Fig1a and b. According to Archard's wear law [10], volume loss is inversely proportional to the hardness, and is described by the relation, ,where V is the volume loss in mm3, K is wear coefficient, W is the applied load in N, S is the sliding distance in meter and H is the bulk hardness. Rama et.al observed that the increase in amount of the rutile particles increased the hardness and hence it reduces the wear rate [11]. The more number of rutile particles act as a barrier to dislocations and enhance the load bearing capacity to the material. . Under the effect of all loads, the composite 10Ccoarse exhibited better wear resistance as compared to the composite-5Ccoarse.

C. Analysis of the Worn Surfaces and Wear Debris

The removal of the material from the contacting surface during the dry sliding conditions leaves numerous permanent impressions on the surface of the composites. Wear mechanism can be easily understood from the studies of the SEM micrographs of the worn surfaces and the wear debris.

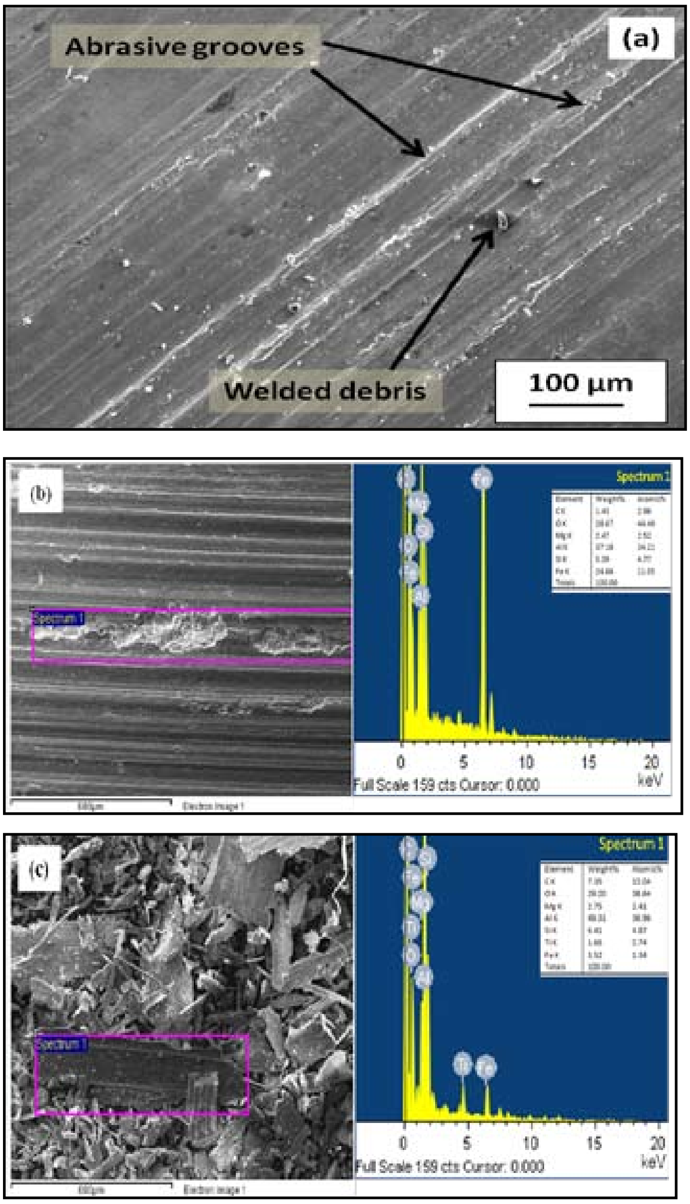
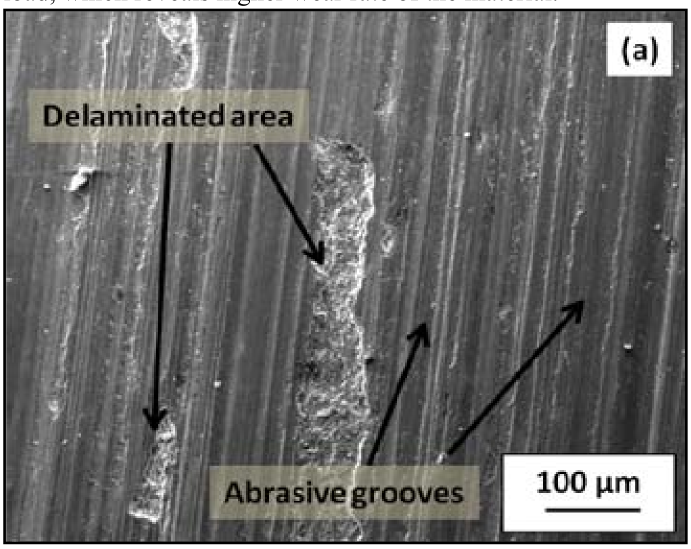


Fig. 3: SEM micrographs of composite-$^{5}C_{coarse}$: wear tracks (a) 9.8N, (b) 49N loads: EDS of wear track, and (c) debris at 49N loads.

Three type of wear are identified by Alpas and Zhang [12]. These are mild wear, severe wear and seizure wear. The SEM micrographs of the worn surfaces and wear debris of 5Ccoarse and 10Ccoarse at room temperature under the low load (9.8N) and high load (49N) are shown in Fig. 3(a) and 4(a). Due to the presence of rutile particles in the matrix, abrasive grooves are created on the surfaces during the continuous sliding of the materials at low load of 9.8N. Larger delaminated area with deeper grooves at high load 49N indicates the higher wear rate as compared to the low load having increased depth of the grooves due to the change in shape of asperities because of plastic deformation that has left more patchy scars on the surface. Presence of adhesive wear during the sliding can be seen clearly on the wear tracks as material adheres along the sliding direction during the wear test. EDS analysis of wear tracks and debris at high load of 49N indicates the presence of O, Mg, Al, Si, and Ti elements. The delaminated area shown in the SEM micrographs depicts the presence of an oxide layer on the worn surface. This supports the formation of a wear protective oxide layer on the load bearing surfaces. The oxide layer poses a greater resistance to sliding wear and friction, as oxide debris reduces the extent of direct metal to metal contact Figure 3 c shows the micrograph of collected debris of the composite-5Ccoarse for 49 N loads. Flake type debris observed in micrographs indicates the adhesive delamination of the materials during sliding wear test at different loads [13]. Wear is governed by delamination which gives plate-like morphology of debris with micro-cracks [6]. The micro-cracks are the main source of delamination or removal of the material during the wear test. In the area around the cracks where delamination has occurred, a 'mechanically mixed layer' containing Fe from the counterface as well as oxides and other elements from the test pin are clearly seen in EDS spectrum of the wear track (Fig3 b).

Figure 4c shows the debris collected after the wear test 10Ccoarse with 9.8N load. Fig 4c reveals that wear is governed by delamination which gives plate-like morphology of debris with microcracks. The pull-out of ductile aluminium having thread-type morphology is also seen. Ribbon type morphology of the debris is produced by the fine abrasives leaving grooves on the wear track [14]. Large plate type debris clearly indicates that adhesive wear occurs during wear test for the composite-10Ccoarse when tested at higher (49 N) loads. However, size and amount of debris increases at higher load, which reveals higher wear rate of the material.



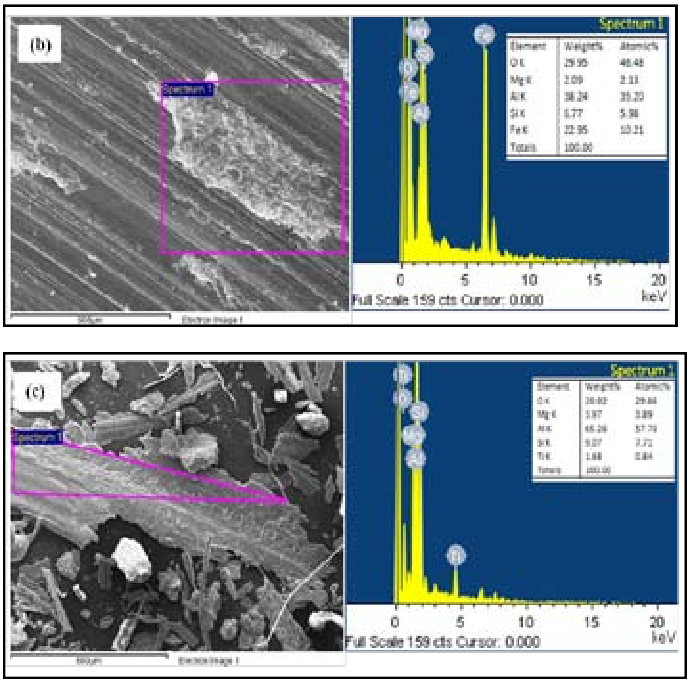


Fig. 4: SEM micrographs of composite-$^{10}C_{coarse}$: wear tracks (a) 9.8N, (b) 49N loads: EDS of wear track, and (c) debris at 49N loads

Corrugated structure observed on the wear debris is due to the continuous rubbing of materials during the wear test. Wavy pattern observed on the debris indicates the delamination of material during continuous rubbing. Some thread like debris corresponding to α Al are trapped in between the grooves and acquire round shape. Due to continuous rubbing action, these get heated and reached the melting point of metal. Large damaged regions due to delamination are covered by the oxide layer due to exposed surface to the environment, which is confirmed by the EDS of wear track (Fig 4b). The distinguish feature of the high load wear loss is due to the detachment of very large size plate type debris generated under the high applied load [11]. From the EDS micrograph, presence of the oxygen in the spectra confirms the formation of oxide layer on the wear tracks during the sliding at 49N load (Fig 4c).

From the studies of the wear tracks and wear debris it is concluded that at low load of 9.8 N the abrasive wear is the cause of the wear loss which generates thread type debris. On increasing the load delamination wear is dominant which produces flat plate type debris with sharp edges. EDS analysis reveals that at intermediate load, mild wear occurs as mechanically mixed layer (MML) covers the surface and safeguards the matrix. Plastic deformation accompanied by the huge removal of the material occurs due to the fracturing of the tribo oxide layer under the higher contact pressure. In the severe wear mode at high load of 49N, the combined adhesive, delamination and plastic deformation governs the wear mechanism.

IV. Conclusion

The studies have revealed that the aluminium composite reinforced with rutile particles exhibit better wear resistance which further increases with the increase in amount of reinforcement from 5 to 10 %. Refinement in silicon morphology from needle shaped to globular takes place in the vicinity of reinforced particles. Low contact pressure support formation of oxide tribolayer between the contacting surfaces causing mild wear in the composite. The transition in mild to severe wear is observed at high contact pressure because of the removal of material by the fracturing of the tribo oxide layer. At high contact pressure, the observed wear mechanism comprises of adhesive, oxidative, delamination and plastic deformation.

V. Acknowledgment

The authors are thankful to Armament Research Board (ARMREB), Terminal Ballistics Research Laboratory (TBRL), Defence Research and Development Organization (DRDO), India for providing financial support under the letter no. ARMREB CDSW/2012/148 for this study.

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