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Studies of the High Temperature Resistant Stir Cast LM13 Aluminum Alloy-Rutile Composites for Industrial Applications

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Abstract - **Present study deals with the development of high temperature wear resistant rutile reinforced aluminum composite material. Simple stir casting, a low cost technique is widely used for production of industrial composites. This was used to prepare composite material by charging the rutile reinforcement proportion from 5 to15 wt.% in cast LM13 aluminum alloy composite. The wear characteristics the developed composite has been studied at elevated temperatures using a pin-on-disc machine at different loads. The study revealed that increase in amount of reinforcement not only improves the wear rate but also enhances the wear resistance of the composite at elevated temperatures. Wear mechanisms studies were done with the help of scanning electron microscope (SEM) and EDX by analyzing the morphology of the wear track and wear debris. The developed composition has exhibited the mild wear up to 200°C at applied load 49N thus making it a high temperature wear resistant material. Beyond 200°C transition in wear mode mechanism from mild-to-severe has been observed.**

Keywords — SEM, Rutile, Aluminium, Wear, Composite.

I. INTRODUCTION

Aluminum matrix composites (AMC's) are the advance and attractive materials being used in several industrial applications due to their unique combination of light weight, high strength, improved wear resistance and excellent mechanical and thermal properties [1-4]. The AMC's can be safely used in automotive brake systems, connecting rods, piston, cylinder liners etc. As these components are exposed to high temperature and pressure during their operating conditions superior wear resistance at high temperature becomes a key factor.

In AMC's, the primary constituent is aluminum alloy termed as matrix phase and the other constituent is namely reinforcement non-metallic and ceramic is embedded in the matrix phase. Addition of ceramic reinforcements serves as load-bearing elements, thereby, restricting the strains in the matrix. The wear behavior of the composite can be studied with huge number of possible material combinations and various processing techniques as it results in variety of wear mechanisms [4, 5]. Sharma et al. [6] investigated the tribological behavior of Al6061-garnet particulate composite prepared by the liquid metallurgical technique. The hardness and wear resistance of the composite was found to increase with increasing content of garnet particulate. It was observed that mechanically mixed layer (MML) was responsible for the decrease in wear rate and coefficient of friction which improves the tribological behavior of the Al-6061 to a greater extent with the addition of garnet reinforcement. Arora et al. [7] predicted the effect of rutile particle content on the wear rate of Al alloy. The reinforcement was strongly bonded with the matrix and the high temperature wear resistance increases with the reinforcement volume fraction. Kumar et al. [8] found that fine size ceramics particles was more efficient in improving wear resistance of the hybrid composites Al-12Si alloy reinforced 15% $ZrSiO_4$. The dominant wear mechanisms shifted from mild to severe wear when the applied load exceeds the critical load. Kumar et al. [9] related the transition temperature with growing predominance of Fe_3O_4 in the oxide film which is due to the oxidation growth from

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logarithmic to parabolic thereby, reducing the wear significantly. This is also in consistent with the high temperature resistance studies of stir cast with the mineral zircon reinforced Al composites [10]. Solid state and liquid state processing routes for example are generally used for the fabrication of composites. Liquid state casting of the metal matrix composite is preferred over the solid state processing because of its low cost and ability to produce large complex shapes. Stir Casting,Spray Deposition, SqueezeCasting, In-situ Processing are the liquid melt casting processes are used to study the wear mechanism and wear transition with applied pressure and the high temperature of aluminium matrix reinforced with SiC and TiB2 [10-13].

The environment friendly, low cost and abundance in availability of minerals is the suitable choice as reinforcement for the development of composites. Among the various casting routes, stir-casting is widely used for the development of industrial composites [9]. So far, limited work has been reported on the high temperature wear resistant studies of Al alloy using as matrix. The proposed work of this study is to evaluate high temperature wear resistance of the Stir Cast LM13 Aluminum Alloy-Rutile Composites for Industrial Applications

II. Experimental Details

In this study, piston alloy LM13 was used as matrix material and high-purity rutile mineral as reinforcement. LM13 alloy was obtained in the form of ingots from Emmes Metal Pvt. Ltd., Mumbai. Rutile particles of Coarse size (106–125 µm) with 5, 10, and 15wt.% were used to study the effect of amount of reinforcement on the wear damage and wear mode transition of the materials.

The composites were developed by stir casting route. The detailed description of the casting process is given in other works [7]. Dry sliding wear tests of the composites were done by using pin-on-disc method. Effect of applied load was observed by varying the load from 9.8 to 49 N. To study the effect of ambient temperature on the wear behavior of the composites, wear tests were conducted at 50, 100, 150, 200, 250 and 300 ºC with 9.8 and 49 N loads. All the developed composites and base alloy were tested at a constant speed of 1.6 m/s against EN 32 steel disk having hardness 65 HRC. To get an average value of wear rate, each test was run three times. Before each test, the track was cleaned with acetone. Wear rate was determined by measuring specimen height change using a linear variable displacement transducer (LVDT). To study the wear behavior, wear rate was calculated by using the formula, [W (mm3/m) = height change (mm) × pin area (mm2)/sliding distance (m)]. To get a better idea about the wear mechanism during the wear tests in different conditions, wear tracks of some selected composite materials were studied with the help of SEM (JOEL, JSM-6510LV).

III. Results & Discussion

Figure 1(a) and (b) shows the variation of wear rate at constant sliding distance for the base LM13 alloy and composites measured at temperature 50 °C to 300 °C .

To study the dependence of temperature on the wear behavior of the rutile reinforced composites, wear tests were carried out by varying temperature from 50 °C to 300 °C in steps of 50 °C. Although the behavior of wear has been studied at all loads but considering the fact that the transition in wear mode takes place at high load (49 N), so more emphasis is given to the studies at high load in the present paper. Murakami et al. [11] suggested that ‘‘strong adhesion’’ between two surfaces in contact occurs at a temperature which lies between 0.4Tm-0.5Tm. Zhang and Alpas [12] suggested that the critical transition temperature in an alloy corresponds to 0.4Tm. At this critical temperature, thermally activated deformation process is expected to become active and lead to softening of the material adjacent to the contact surfaces. Hence critical temperature of the material plays significant role on wear rate.

Figure 1(a) shows the wear rate of the aluminum LM 13 alloy and the developed composites at low load (9.8N) with the variation in ambient temperature from 50 °C to 300 °C. As the steady state wear occurs at a sliding distance of 1500 m, the average wear rate of the material was taken during the sliding distance from 1500 m to 3000 m. Figure 1(a) reveals that there is a reduction in wear rate slightly in elevation in temperature from 50 °C to 200 °C (near the critical temperature for LM 13 alloy).Wilson and Alpas [13] suggested that the formation of mechanically mixed oxide layer resulting from the high temperature near 200°C reduces the wear rate by forming an interface between the metal surfaces in contact. After 200°C, the softening of the matrix weakens the bonding between the matrix and particle and hence increases the wear rate. There is a continuous increment in the wear rate up to 300°C for the base alloy and the composites, but the composite displays improved wear resistance in comparison to the LM 13 alloy.

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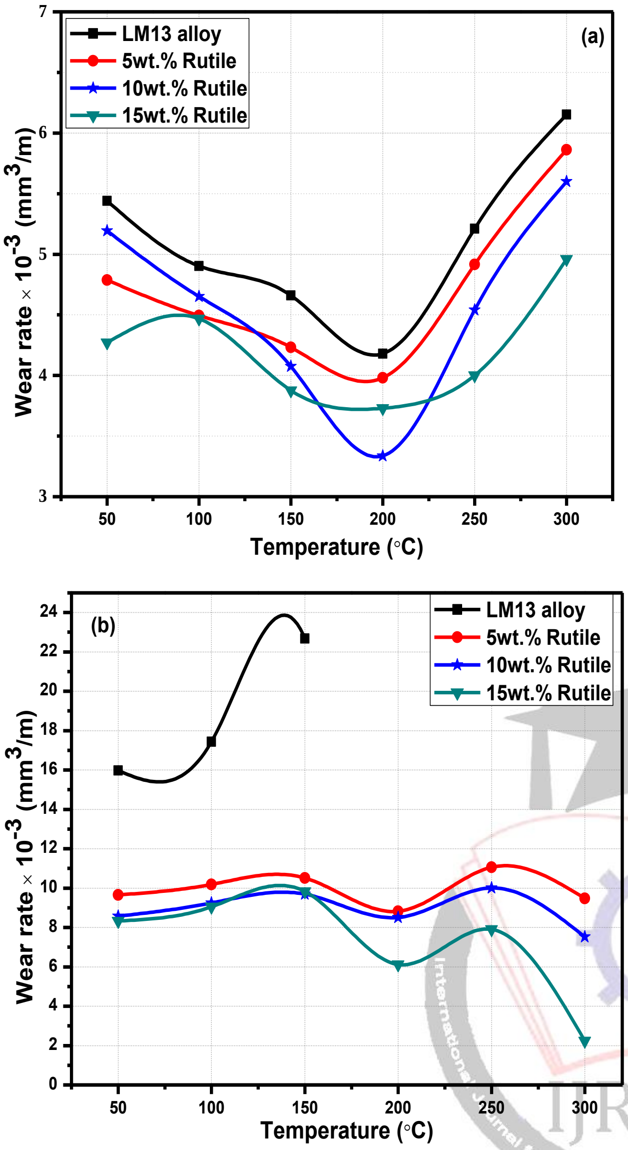
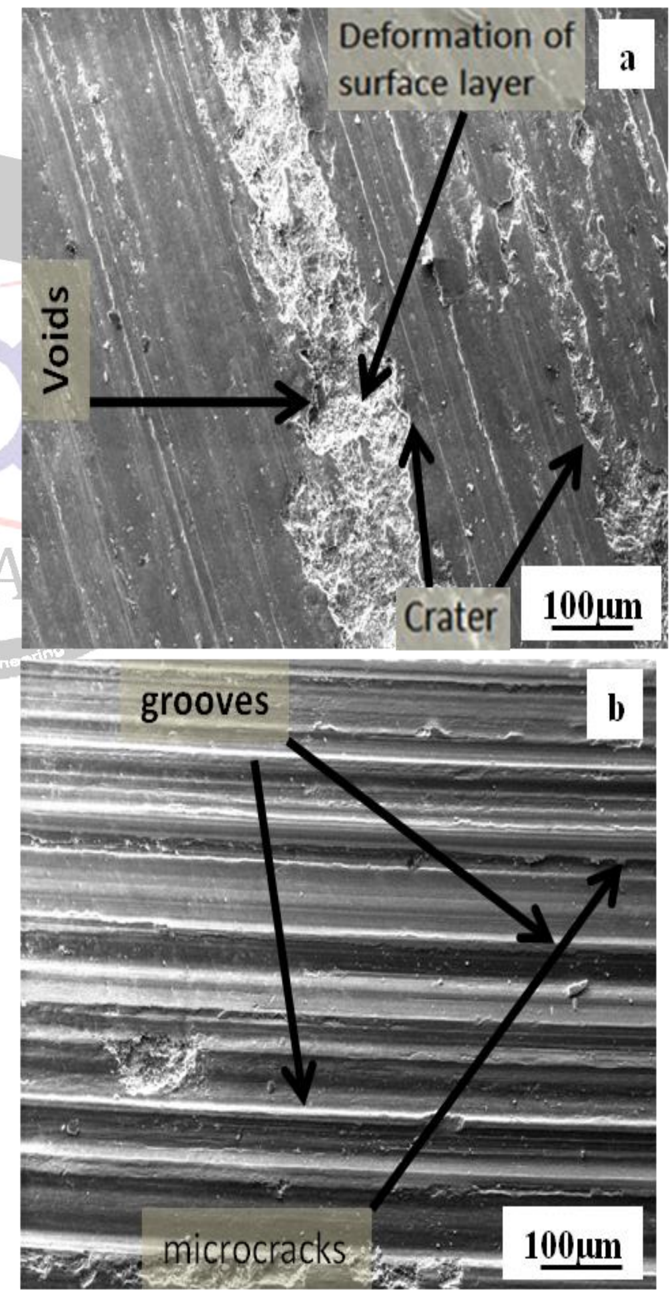


Fig. 1: Comparison of wear rate against the sliding distance at different loads for (a) 9.8N, and (b) 49N.

Figure 1(b) depicts the change in wear rate for LM13 alloy and the composites at higher applied load (49 N). For the cast LM13 alloy, there is an abrupt increase in wear rate with temperature from 50 °C to 150 °C. However, the base alloy was completely worn out with the rise in temperature from 200 °C to 300 °C. So, massive removal of material in the form of large chunks of debris observed which signifies the severe wear loss. At higher load, there is a continuous increase in wear up to 200 °C and beyond this temperature; the decrease in wear rate may be due to formation of oxide layer. Further, increase in temperature (up to 250 °C) led to tearing of oxide layer, hence exposing new area to delaminate. These freshly exposed surface layers undergo oxidation and hence rapid formation of oxide layer is formed. Once equilibrium is achieved in the process of oxidation, the mixing of debris and material which is removed from the disc creates a mechanical mixed layer (MML) on the surface of pin, thus protecting it from further oxidation. So, this reduction in wear rate at high temperature (300 °C) is also supported by Wlison and Alpas [13]. They observed that at high temperature (300 °C) and high applied load of 49N, there is a generation of debris within the steel disc which is the cause formation of MML. This formation of layer enhances the wear resistance of the composite at high temperature.

IV. WEAR TRACKS ANALYSIS

The wear track analysis of developed composites and the base alloy was done after performing wear tests at higher load and temperature. The wear rate at higher temperature is found higher as compared to the wear at room temperature.



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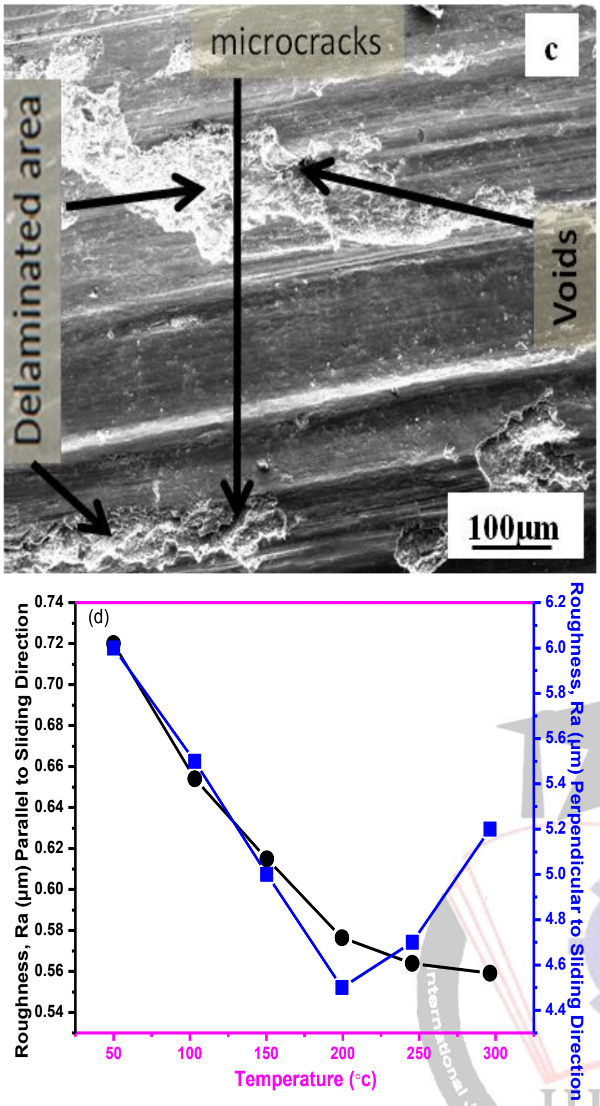
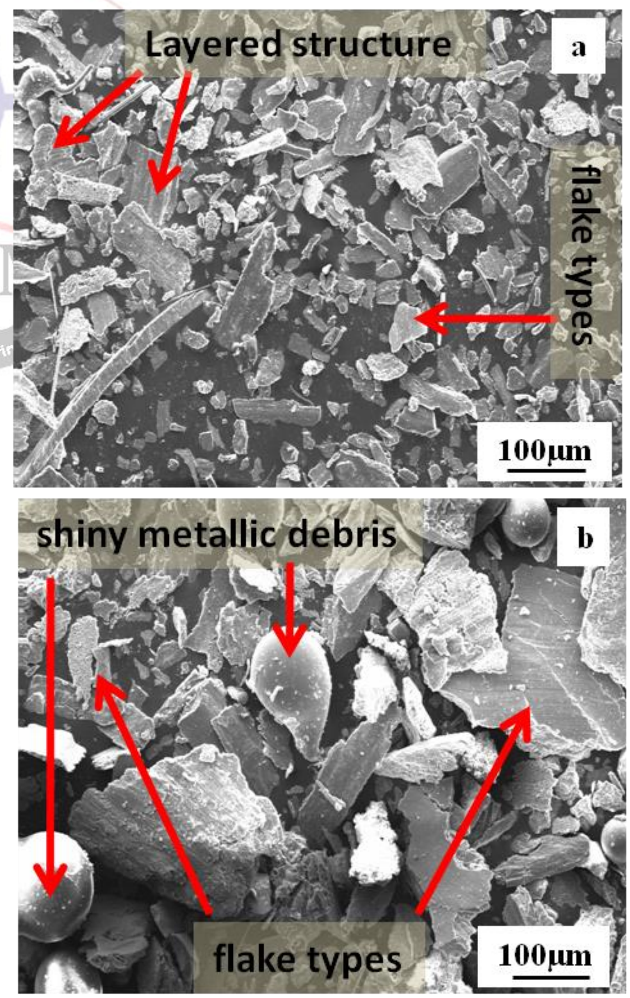


Fig. 2: SEM micrographs of composite-5Ccoarse: wear tracks at different temperatures (a) 200 °C, (b) 250 °C, (c) 300 °C and (d) roughness of wear tracks at 49N load.

The movement of the pin during the dry sliding between the contact surfaces pushes the material to flow along the sliding direction which can be seen as the damaged area. The abrasive action of the asperities of the counter surface causes heavy damage which further enhances the depth of the grooves [Fig. 2(a)]. The adhesive wear because of the softening of the composite forms wavy patterns as can be seen in the wear tracks in Fig 2 (b-c). The delamination and the adhesive wear are the dominant wear mechanism in these testing conditions as large damaged areas and chipping of the material is common feature in all the wear tracks[13]. In the Fig 2.d, surface roughness decreases with increase in temperature from 50 °C to 200 °C but surface roughness increases with increase in temperature from 20 °C to 300 °C in both the parallel and perpendicular. The lower wear resistance of the thin oxidative layer at high temperature leads to the increase in roughness. At elevated temperature (300 ºC), Figure 2(d) indicated the increase in depth and width of the groves which can also be confirmed from the surface roughness of the material in parallel and perpendicular direction to the sliding direct.

SEM micrographs of wear debris of the composite with 5wt.% coarse size at 200 °C, 250 °C and 300 °C at 49N loads are shown in Fig 3. Figure 3a shows (200 °C) the flake type delaminated debris along with the layered structure due to continuous rubbing caused by constant sliding between the pin material and counterface. In each rotation, deforming forces help to get these cracks interconnected [14]. At 250°C, the oxidative wear is dominant which can be seen as white shiny metallic debris (Fig 3b).Small plate type debris with micro cracks on the surface indicates the onset of the delamination wear whereas the micrograph with the debris at 250 °C shows the droplets of molten liquid of irregular shapes (e.g. rod, spherical and dumbbell shape) with rough edges. The increase in size of the metal balls (Fig 3c) at 300 °C is because the increase in temperature aggravates the change of state of metal from solid to semi-solid [15]. The oxide film is composed of several layers on the debris (Fig 3d). The outermost layer consists of Al_2O_3/Fe_2O_3 oxide layer which enhances the wear resistant property of the composite.



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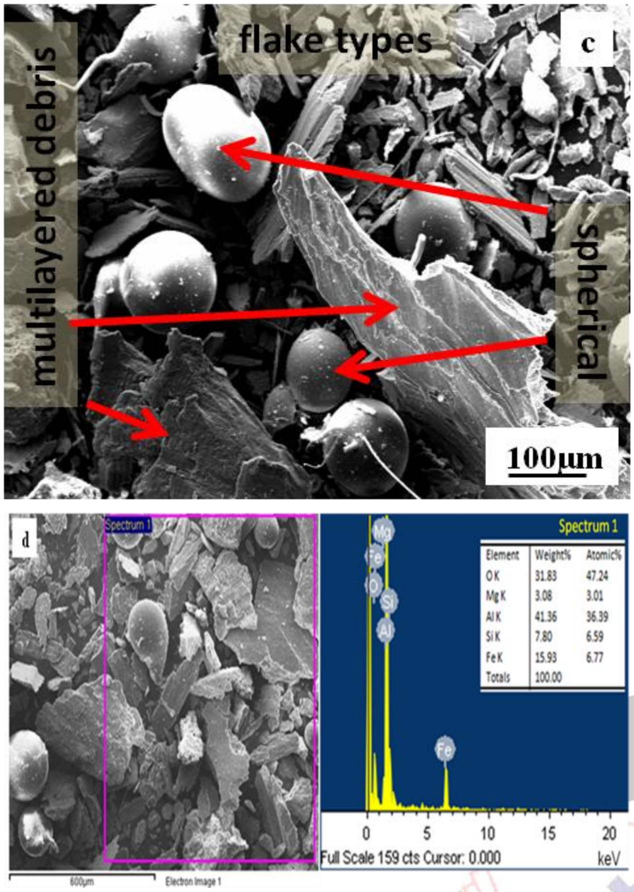

Fig. 3: SEM micrographs of composite-$^{5}C_{coarse}$: wear debris at different temperatures (a) 200 ºC, (b) 250 ºC, (c) 300 ºC, and (d) EDS spectrum of debris with 49N load at 250 ºC.

According to Sudharshan and Surappa [2], delamination of the specimen surface is because of the crack nucleation in the voids around the particles and crack propagation. High temperature generates frictional heat which causes the higher degree of softening of surface material and specimen pin responsible for the mild to severe wear transition of the composites.

Wang et al**.** [3] performed the dry sliding wear test of Mg alloy AZ91D alloy under the variation in loads from 12.5 to 300 N at the ambient temperatures of 25-200 °C. The XRD patterns of the worn surfaces for the AZ91D alloy showed that there always existed a predominant tribo-oxide ($MgAl_2O_4$) on the worn surfaces. It was found that less amount of $MgAl_2O_4$ was formed at the high load as compared to the low load. The mild to severe transitions could be delayed because of the thick and hard Mechanical Mixed Layer (MML) on the worn surface which undoubtedly hindered gross plastic deformation or thermal softening of the matrix under low loads [16], even at high temperature of 200 °C prevented the severe wear due to the formation of substantially thickened layer of MML. Thus, the wear at 200 °C fell in the mild wear regime which qualifies the developed composite to be used in industrial applications as a high temperature resistant material. Under high loading conditions the increase shear stress between the particle and the matrix interface leads to brittle interface leads to decoherence of the particles. The large sized flag types debris indicate the delamination of the large pieces of materials from the contact surface. Many letter shear dimples observed in the sub surface region shows the shear deformation.

V. Conclusion

1. The wear resistance values were observed in the the LM13-rutile composite.
2. The depth of deformed zone in LM13-15wt.% rutile composite was lower than that of the other LM13-rutile composites.
3. The formation of cavities due to delamination of surface materials, tearing of surface and abrasive grooves were observed on the wear tracks at higher temperatures.
4. Reinforced particles act as a load bearing constituents in composite materials which transfer the load from the matrix to reinforcement. The oxide layer formation around 200 ºC improves the wear rate of the composites even at high load thus providing this material high temperature resistant property to be used for industrial applications.

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