
**TRIBOLOGICAL CHARACTERISTICS OF AS-CAST AND AGED
FUNCTIONALLY GRADED COMPOSITES**

7.1. Introduction

A good wear resistance and low co-efficient of friction are two essential property requirements for present day automotive engine components [128]. The most widely used Al alloys for engine components either A356 or A319, are lacking in tribological property requirement. With the development of functionally graded materials (FGM), gradient microstructure and compositions in composite materials could be produced. If the degree of distribution of hard reinforcing particles are changed in the surface layers that will provide more wear resistance. As the middle and the opposite side layers are gradually depleting in reinforcing phase, these layers will result in gradual increase in plasticity and toughness. Functionally graded aluminium based composites reinforced with Mg₂Si is potential candidate material for aerospace, automotive, and other applications. The present chapter has two sections; the first section deals with the room temperature dry sliding wear characteristics of as-cast A356-Mg₂Si in-situ FG composites and the second section is on the evaluation of reciprocating wear characteristics of the FG composites at 200°C in as-cast as well as in T6 condition.

7.2. Dry Sliding Wear Behavior of As-Cast Al-Mg₂Si FG-Composites**7.2.1. Effect of sliding distance**

The cumulative wear loss versus sliding distance plots of the samples from inner zones base alloy and of the composite FGMs with varying percentages of Mg additions are shown in figure 7.1(a). As expected, the wear loss decreases with increase in wt.%Mg in

the composites, which is obvious due to the combined action of grain refinement of α -Al and higher volume fraction of hard Mg_2Si reinforcing particles. The interactions between dislocations and Mg_2Si particles resist the propagation of cracks during sliding wear. Strain fields are created surrounding the reinforcing particles due to the mismatch in the thermal expansion co-efficient during solidification. These strain fields resist the propagation of any crack developed during sliding and subsequent material removal. The in situ formed reinforcing particles are defect free which preserve their integrity during sliding. The clear interface and good reinforcement/matrix bonding delay the detachment of particles from the aluminum matrix resulting in enhanced wear resistance.

The effects of in situ formed Mg_2Si particulate content on the worn surface topography of the composite are shown in (Fig.7.2). The worn surfaces are showing parallel grooves along the direction of sliding which are due to plowing action in the material by the asperities of the much harder steel counterface. The plows have characteristic dislodged material sideways from the groove to form ridges near the grooves. Further repeated sliding action on the hard asperities leads to metal loss. The depth of the grooves and plastic deformation at the edges of the grooves forming plowing are reduced when Mg_2Si particulate content is increased. The worn surface of aluminum matrix (Fig.7.2) shows several plow marks, mechanically mixed layer and a few delamination.

In general, composites are having better wear resistance due to their better load bearing capacity and capacity to maintain a protective stable oxide film protecting metal-to-metal contact. The oxide films are evident from the figure generated on the surface by the frictional heat which significantly affects the wear rate of the composites. The detached

elements namely Al, Si from matrix A356 alloy, the detached Mg_2Si reinforcing particles and Fe from the counter disk, together form a mechanically mixed layer and gets entrapped between the two sliding surfaces resulting in three body wear.

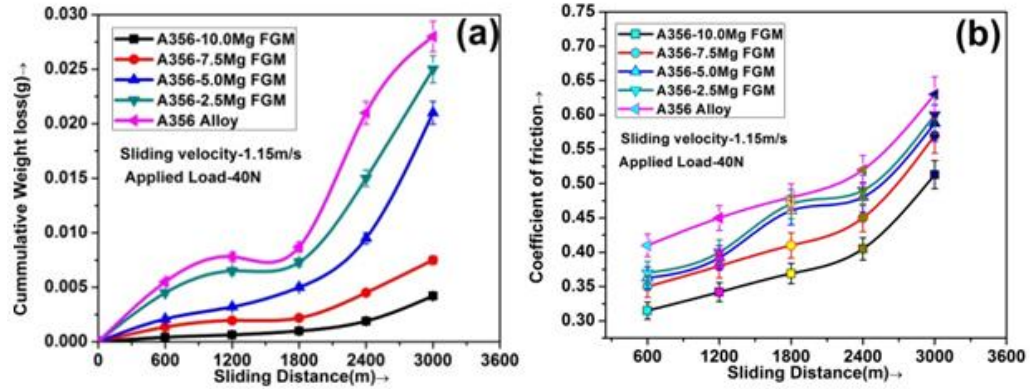


Fig. 7.1. Variation of (a) cumulative wt. loss and (b) COF with sliding distance (m) at inner core to the geometrical center of the FGM tube for both FGM's cast and A356 alloy.

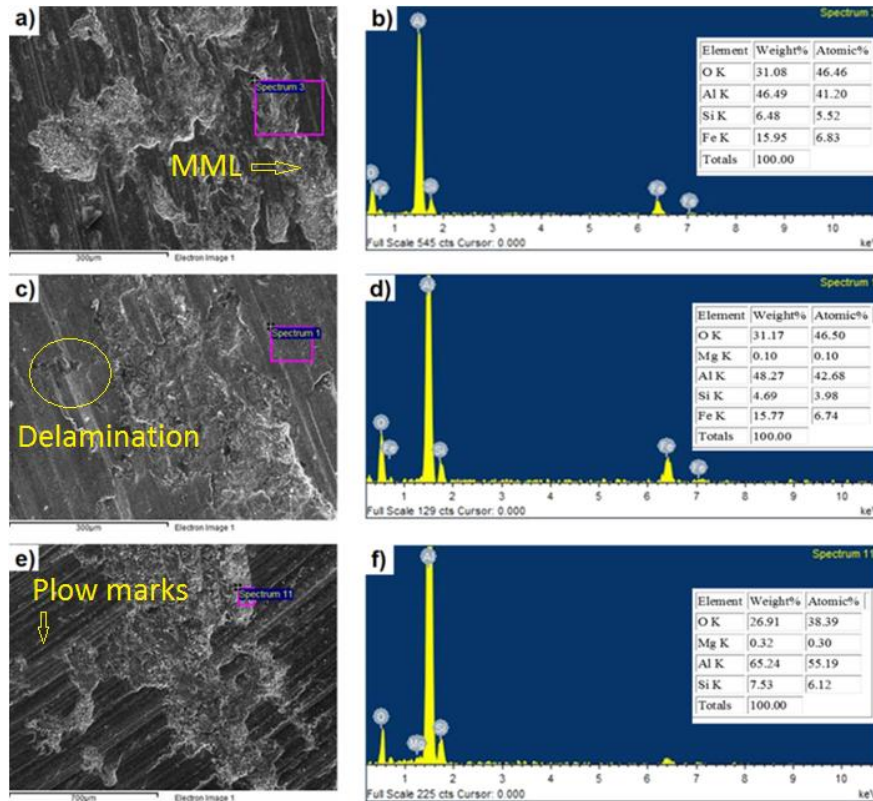


Fig.7.2. SEM micrographs of worn surfaces at constant load (40 N) and sliding distance 3000 m; (a) A356 alloy, (c) A356+2.5Mg FG composite and (e) A356+7.5Mg FG composite at inner position; (b), (d) and (f) are corresponding EDS analysis.

The composition of the sliding surface of the pins was analyzed using EDS (Fig. 7.3 & 7.4). A mechanically mixed layer is formed on the surface of the sliding pin which contains a mixture of Fe transferred from the steel counterface along with composite material. The mechanically mixed layer is acting as a lubricant to reduce the wear rate. Fig. 7.1(b) shows the variation of the coefficient of friction (COF) with the sliding distance of base alloy and composite FGMs at 40 N normal load and for 1.15m/s sliding velocity. It is evident from the figure that, with an increase in sliding distance, the COF values are increasing for both the matrix alloy as well as the FG-composites. The observed increase in coefficient of friction with increase in sliding distance perhaps due to rise in temperature of mating surfaces which leads to higher frictional force.

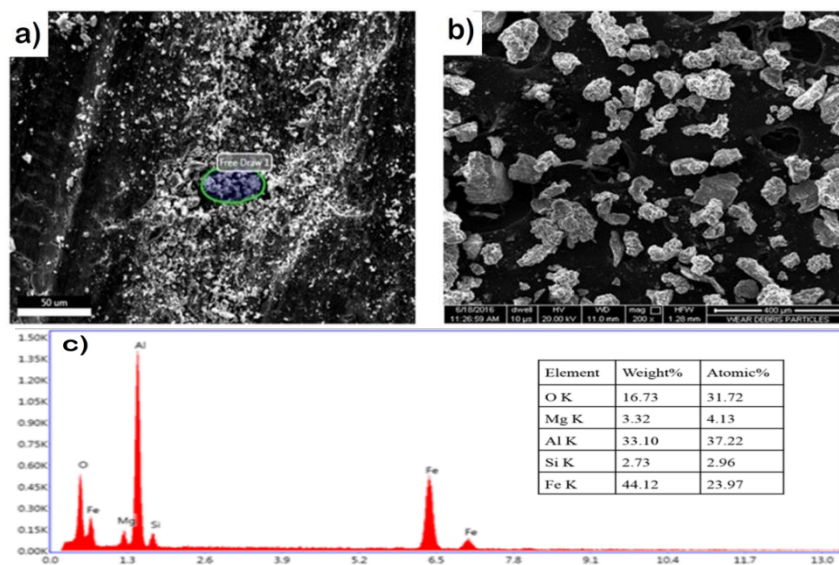


Fig. 7.3. SEM of the worn surface of inner zone of A356%-7.5%Mg FG composite at 40 N load and 3000 m sliding distance showing; (a) wearing of mechanically mixed layer, (b) type of debris formed and (c) corresponding EDS analysis.

Beside this, the coefficient of friction is found to decrease from matrix alloy to FG composites with increasing Mg contents in identical sliding conditions. It may imply that, the wear mechanism is mostly abrasive type and is consistent to the lower mass losses in

composites compared to the matrix alloy. The broken and dislodged, small Mg_2Si particles are resisting the plastic deformation of matrix, supporting and load bearing. Apart from these, an increase in fine reinforcement content reduces the fraction of the matrix area in contact with the steel counterface. This results in the decrease in the adhesion of aluminum with the mating surface decreasing the temperature rise due to frictional heat.

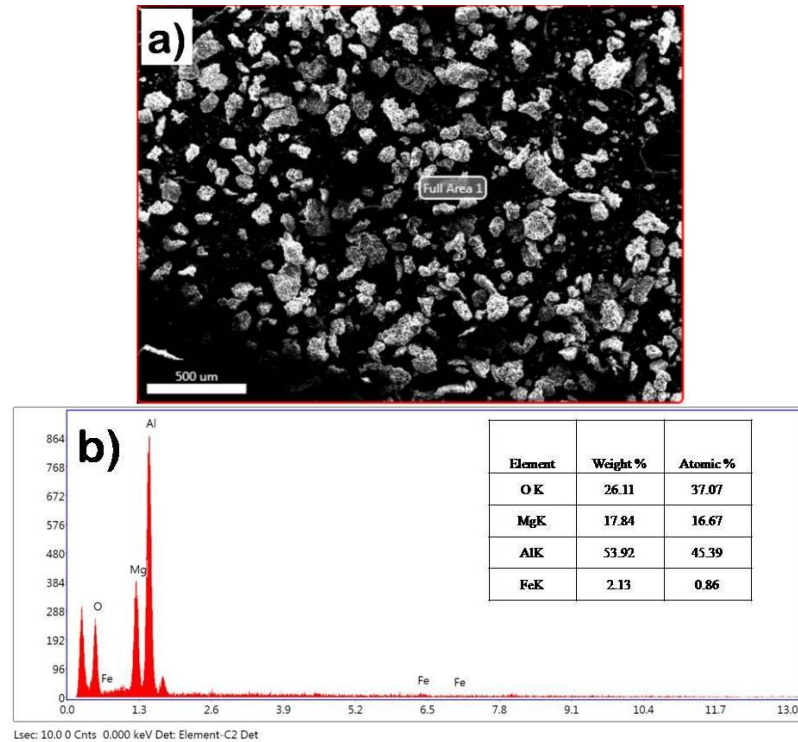


Fig.7.4.SEM of the worn surface of full area at inner zone of A356%-10%Mg FG composite at 40 N load (a) type of debris formed and (b) corresponding EDS analysis.

Surface roughness of the worn specimens has been quantified by determining the average vertical deviations from the perfectly smooth surface (R_a) using a stylus profilometer. The values of R_a with increasing sliding distances for worn surfaces of the specimens from inner zones of FG composites are shown in Fig.7.5. From the figure it is evident that, as the sliding distance increases, initially up to 2400m the R_a values are more or less steady beyond that a sharp increase is observed. The surface of A356-7.5Mg is much smoother compared to that of A356-2.5Mg FG composite (Fig.7.6). The surface

roughness follows a trend similar to that found for wear rates and inverse relationship between surface roughness and hardness is established.

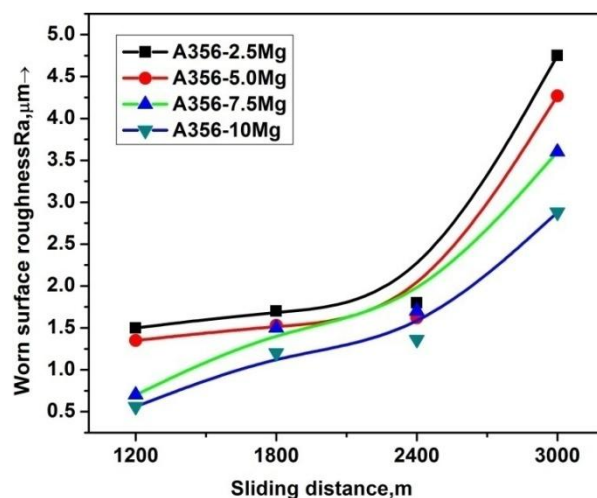


Fig.7.5. Effect of sliding distances on the worn surface roughness (Ra) of inner zone of FG composites.

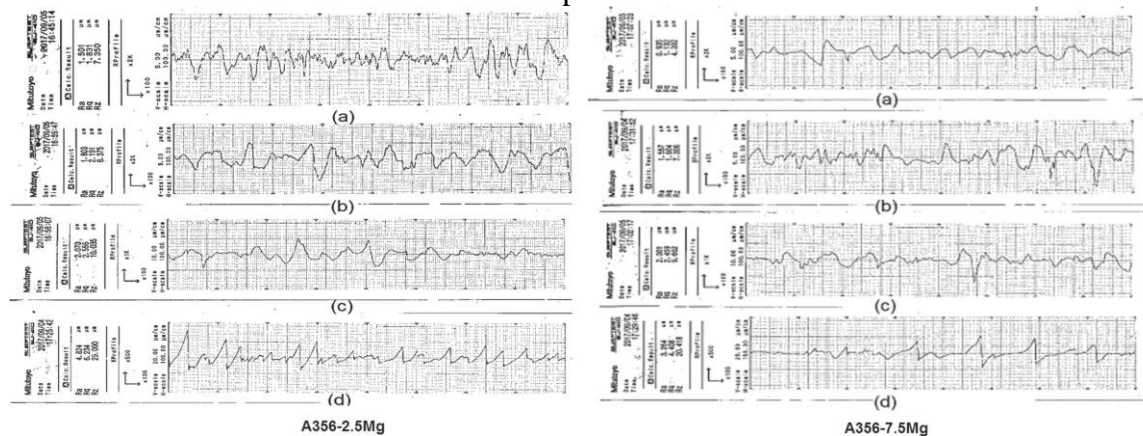


Fig.7.6. Worn surface profile of FG composites at a fixed normal load of 40 N with varying sliding distances; (a) 1200 m, (b) 1800 m, (c) 2400 m and (d) 3000 m.

7.2.2. Effect of applied load

The effect of varying applied normal loads on the wear rates of A356 matrix alloy and the inner zones of two FG composites are shown in Fig.7.7 (a). It is evident from the figure that, the wear rate increases initially with higher normal load for all centrifugally cast A356 alloy as well as FG composites. With low loads wear rate increases linearly up to about 10 N of normal load then a steady state of mild wear regime is reached and

beyond about 30 N loads, transitions from mild to severe wear causes a sudden increase in wear rates. Certainly, it is evident that the wear resistance of A356 alloy is lower than those of inner zones of Al-Mg₂Si composites. The lower wear rates of FG composites can be attributed to the high population of reinforcement phase of Mg₂Si.

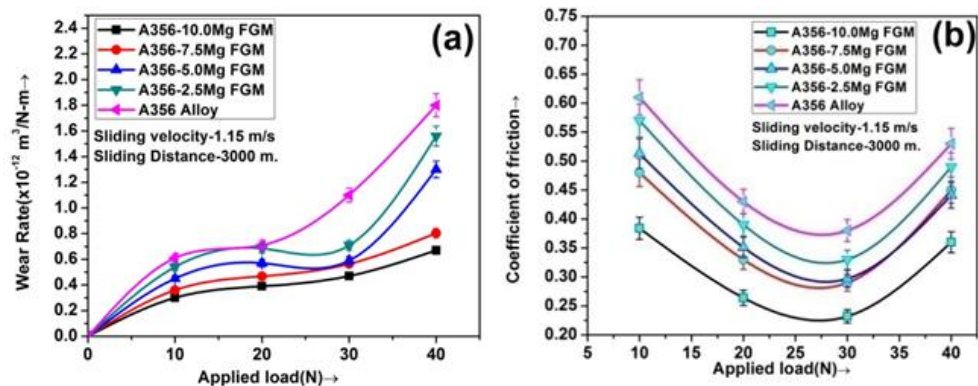


Fig.7.7.Effect of applied normal load on; (a) wear rate and (b) Co-efficient of friction of inner zones of FG composites and A356 matrix alloy.

At comparatively low normal loads hard asperities on the steel disc or hard particles in between the pin and the disc cause ploughing or cutting of softer aluminium alloy or composites. This results in removal of small fragments of material causing an abrasive type of wear. The deeper grooves are formed by higher degree of penetration by hard counterface asperities. The wear mechanism in the steady state condition is predominantly oxidation as well as formation of mechanically mixed layer (MML) on to the worn surface.

It is known that Fe from the counter disk material forms a covering along with the mechanically mixed layer and acts as a lubricant to reduce the wear rate. The oxide films as well as the MML account for the low wear rates in the mild wear regime. The inner zones of FG composites show better wear resistance because of their better load bearing

capacity and ability to maintain a stable oxide film prohibiting metal-to-metal contact [128-130].

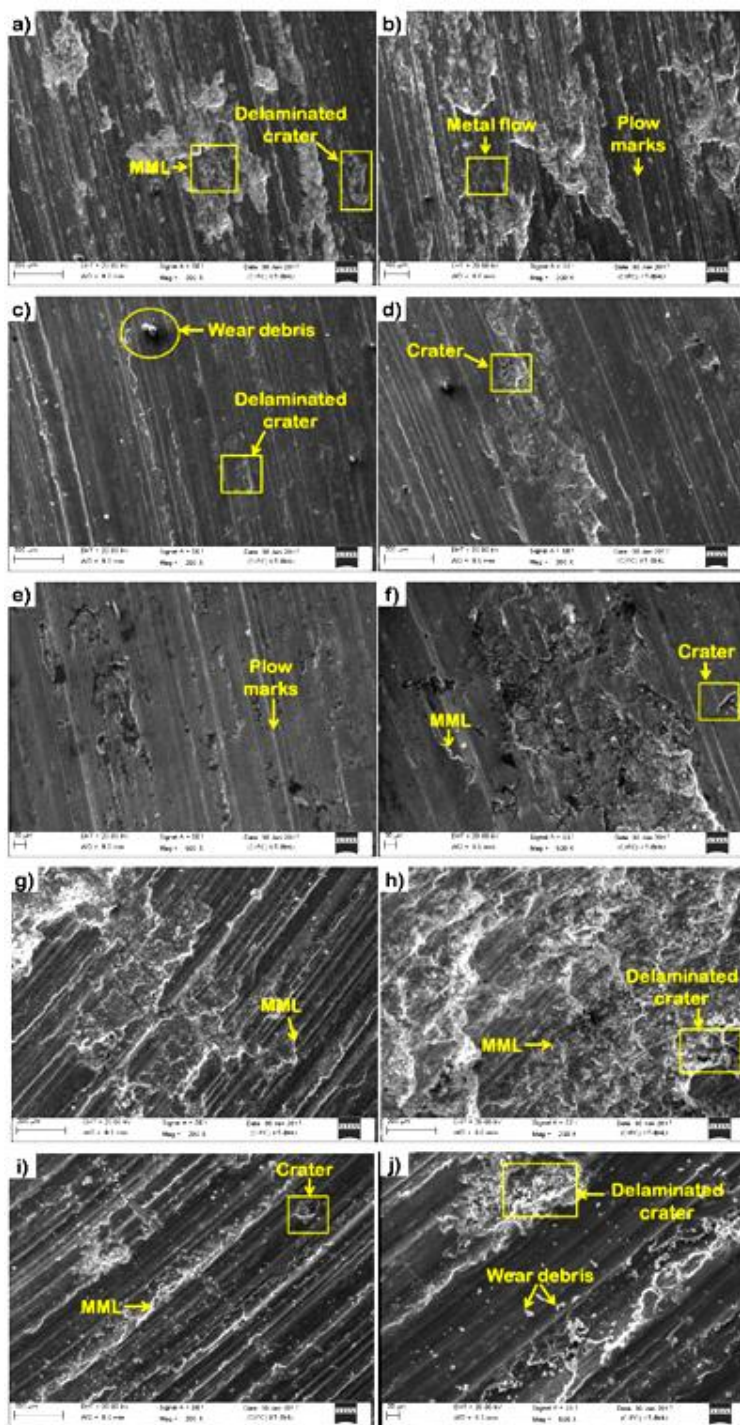


Fig.7.8. SEM images of the worn surfaces; (a) and (b) are of A356 matrix alloy; (c) and (d) are of A356-2.5%Mg FG composite; (e) and (f) are of A356-5%Mg FG composite; (g) and (h) are of A356-7.5%Mg FG composite; (i) and (j) are of A356-10%Mg FG composite with normal load of 20 N and 40 N respectively.

As the applied normal load increases, the plastic deformation starts appearing on the worn surfaces, subsequently severe delamination, as shown in the SEM micrographs (Fig.7.8). Sufficient plastic deformation during sliding wear in a microstructure containing hard second-phase particle causes crack nucleation preferentially at these hard second phase particles. The optical micrographs beneath the wearing surface show clear evidence of severe plastic deformation and the material flows beyond the edge of the specimen to coil up (Fig.7.9(i) &(ii)). Void formation was basically due to the plastic flow of the matrix surrounding these hard particles. The aluminum grains are elongated and Mg₂Si particles are aligned along the direction of sliding. High interfacial shear stresses developed due to friction between pin and disc, are perhaps responsible for plastic flow of subsurface aluminum matrix and directional alignment of Mg₂Si particles. Moreover, the brittle eutectic Mg₂Si near the worn surface is fragmented into small particles in course of sliding and provides the favorable sites for crack nucleation.

Similar subsurface features were observed by Siddhalingeswar et al. with in situ Al-4.5Cu-5TiB₂ composite [131]. A few cracks and voids started at these fragmented Mg₂Si particles and perhaps propagate toward the surface of the composite, resulting in delamination. Separation or flaking of severely deformed matrix grains just beneath the surface is observed.

These features are apparent from the micrographs of the transverse sections of subsurface layers along the sliding direction (Fig.7.10). The work-hardening due to plastic deformation are apparent from the plot (Fig.7.11) of matrix microhardness with depth beneath the worn out surface of the FG composites [131].

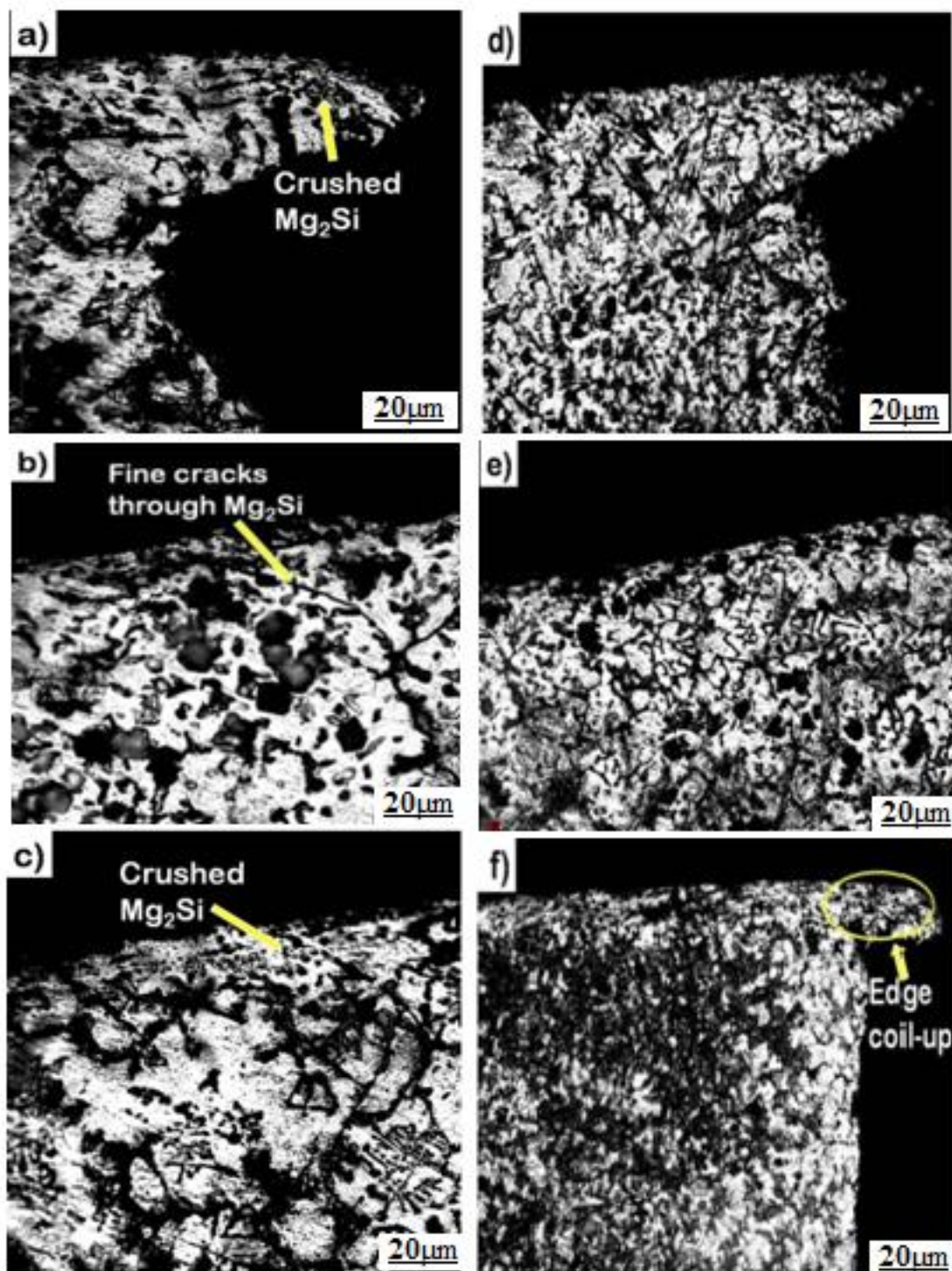


Fig.7.9. Optical micrographs of the worn out (3000 m sliding distance at normal load 40 N) subsurface transverse section along the sliding directions; (a)–(c) are of A356%-2.5%Mg and (d)–(f) are of A356%-7.5%Mg Fg composites respectively.

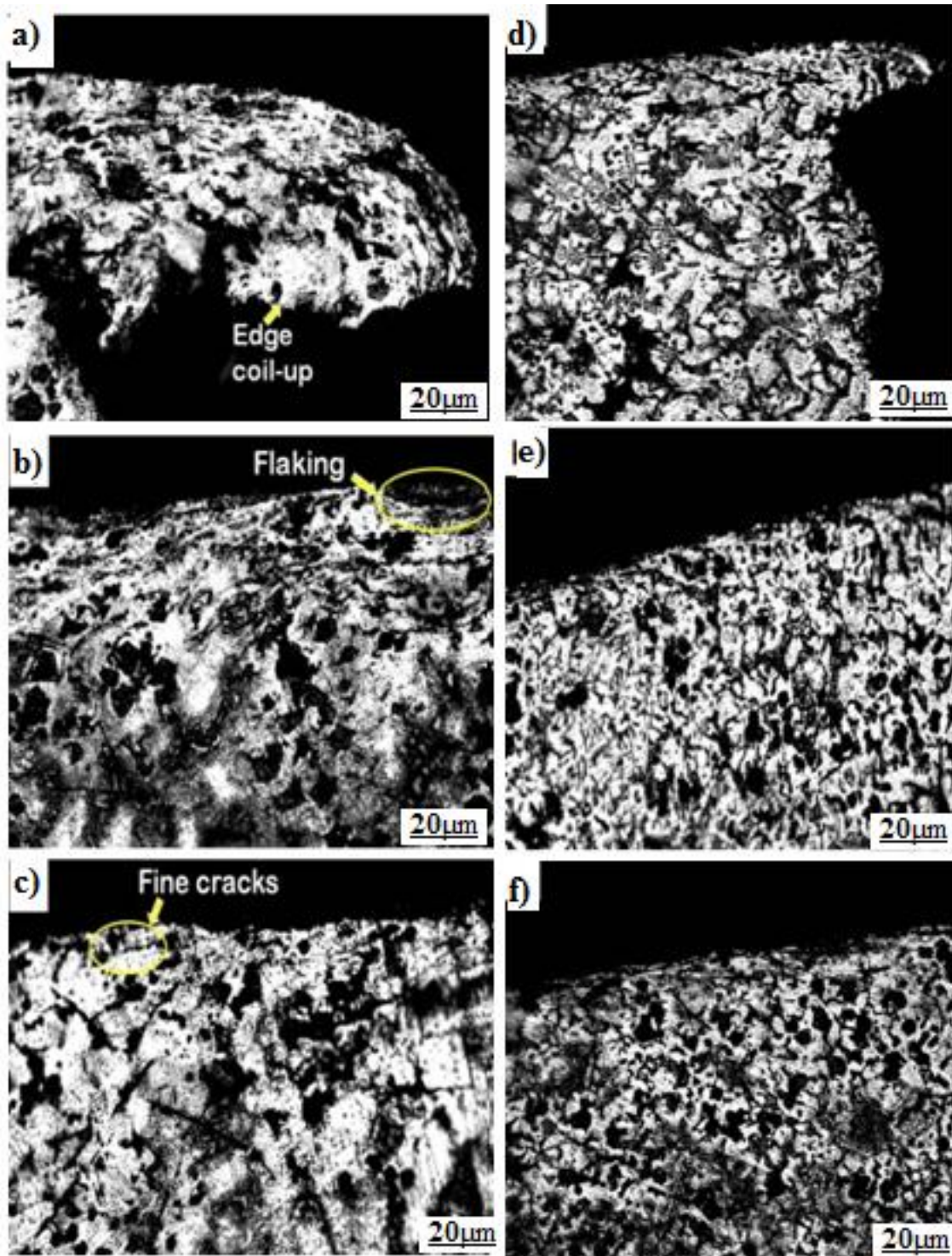


Fig.7.10. Optical micrographs of the worn out (3000 m sliding distance at normal load 40 N) subsurface transverse section along the sliding directions; (a)–(c) are of A356%-5%Mg and (d)–(f) are of A356%-10%Mg FG-composites respectively.

The increased wear rate in the severe wear regime beyond a normal load of approximately 30 N in the matrix alloy and A356%-2.5%Mg FG composites is perhaps due to the increase in mating area between the two surfaces with increase in load. This leads to generation of high amount of frictional heat between the mating surfaces. High frictional heating results in softening of the pin surface and wear rate increases as hard asperities of steel disc penetrate more into soft pin surface. The increased normal load may also lead to increase in tendency to form subsurface micro cracks as well as deformation and fracture of asperities. However, in case of higher %Mg composite the mild wear region still persists up to a load of 40 N perhaps due to better load bearing capacity by the higher volume percentage of Mg₂Si reinforcement.

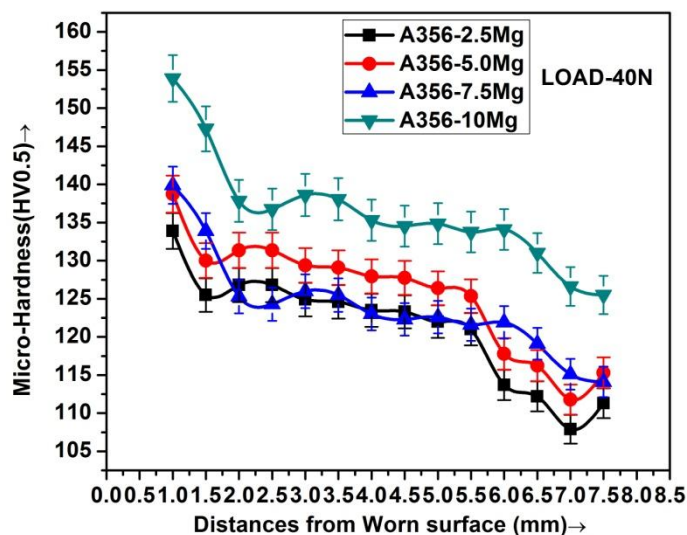


Fig.7.11. Matrix micro-hardness versus depth beneath the worn surface of the FG composites at 40 N normal load

The effect of increasing normal load on the co-efficient of friction of the matrix alloy and the inner zones FG-composites at constant sliding distance (3000m) and sliding velocity (1.15ms^{-1}) are shown in Fig.7.7(b). Initially, the COF values decrease with increasing normal load up to about 30 N in the matrix alloy as well as in the FG composites. Further increase in the applied normal load causes to raise the COF values in

all the materials tested. This trend can be explained as due to formation of mechanical mixed layer on the mating surface the COF values decrease initially as the MML are generating a smooth surface. But in the severe wear regime above 30 N normal load, the MML is disrupted and hard debris is formed in between the pin and the counterface resulting in the rise in COF values.

7.2.3. Effect of volume% Mg₂Si on dry sliding wear behavior

The effect of volume% of Mg₂Si particles on the specific wear rate (at 40 N normal load and sliding velocity of 1.15ms⁻¹) and co-efficient of friction of the different zones of FG composites are shown in Fig.7.12(a) and (b) respectively. It is evident from the figure that the specific wear rates of both the composites are decreasing with increasing segregation of Mg₂Si particles from inner to outer zones.

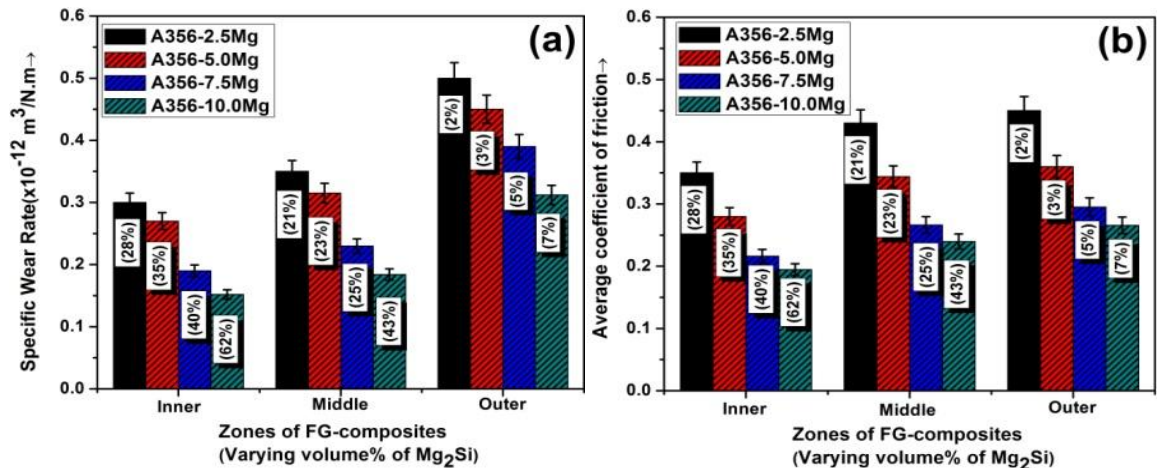


Fig.7.12 Effect of volume% Mg₂Si on (a) specific wear rate and (b) average COF at different zones of FG composites at fixed normal load of 40 N, sliding velocity of 1.15 m s⁻¹ and sliding distance of 3000 m

The effect can be attributed to several factors contributing to the ultimate wear behavior. Primarily, due to increase in bulk hardness with increase in volume% of Mg₂Si as a consequence of α-Al grain refinement, good matrix-reinforcement interfacial bonding

and increase in dislocation density [132]. Higher grain boundary per unit area of Al matrix due to grain refinement enables to bear higher load and so increased wear resistance [133].

Moreover, direct metal-to metal contact between matrix and counterface are reduced by the presence of Mg_2Si particles, thus, Mg_2Si particles act as a load bearing phase and the matrix is protected during sliding process. Increase in volume% of Mg_2Si particles causes higher dislocation density around the Mg_2Si particles during solidification hence, strength and hardness of composites improve which results in lowering of specific wear rate [134]. Apart from these, an increase in volume percentage of Mg_2Si in MML restricts the further removal of material from the surface.

From Fig.5.21(b), it is clearly observed that the coefficient of friction decreases with increasing the volume% Mg_2Si particles both in A356-2.5Mg and A356-7.5Mg FG composites. Due to the same reason inner zone has the lowest COF values in a particular composite. This is perhaps due to the pretty high normal load of 40 N, the degree of delamination increases which leads to the increase in the amount of wear debris. The debris are sticking back on the matrix by applied load which results in the reduction in the effective contact area and the number of junctions. Consequently, less energy is required to shear during sliding. Over and above, the 40 N normal load causes to rise the contact surface temperature during sliding producing protective oxidation MML. This will lead to reduction in the friction and COF value decreases.

7.3. High temperature wear behavior of Al-Mg₂Si in-situ functionally graded composite

The cylinder liners are subjected to a scuffing type of wear by the continuous movement of piston against it at a considerably elevated temperature of around 150°C to 200°C. Hence, high temperature linear reciprocating wear characteristics were evaluated for the inner surface of some T6 treated Al-Mg₂Si composites with varying %Mg.

7.3.1. Effect of Mg contents on wear mass loss

The mass loss incurred on different inner zone samples under a load of 200N at frequency of 25Hz and stroke length of 5mm for 40 minutes of test duration at 200°C are shown in Fig.7.13. The samples selected were with varying Mg content Al-Mg₂Si composites in solution treated and ageing conditions. From the figure it is evident that, the wear loss decreases up to Mg percentage of 7.5 wt.% and then increases little bit for the sample with 10 wt.% Mg sample. The effect of hardness are not reflected in the final wear behavior as the Al-10%Mg composite is having maximum hardness among these samples. The size of the primary blocky Mg₂Si (Fig.7.14) perhaps play an important role for the mass loss as finer particles develop lesser stress concentration at the matrix /particle interface and it increases with particle size. The cracks are initiated during wear at these interfaces [135,136]. Another cause responsible for inferior wear resistance of this composite is the porosity. The A356-10%Mg has highest extent of porosity because extended freezing range with high Mg content. However, at room temperature the wear performance of A356- 10%Mg was best. The severity of reciprocating stress in combination with softened matrix probably results in dislodge of very coarse Mg₂Si particles which leads further a three-body abrasive wear.

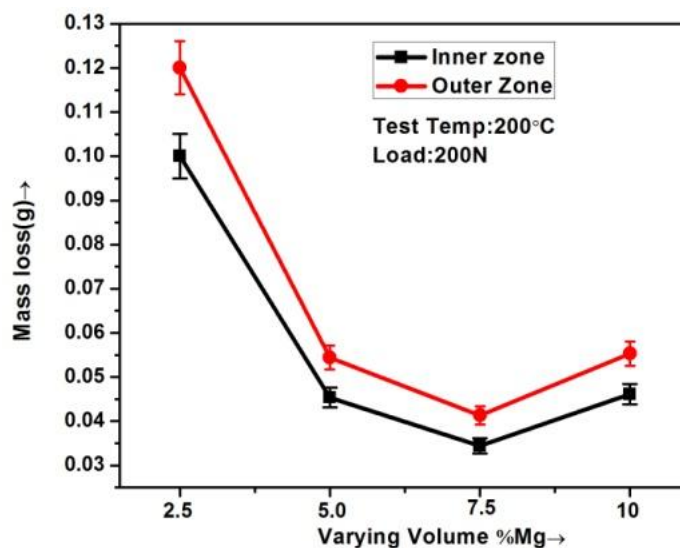


Fig.7.13. Variation of mass loss with different %Mg in Fg composites.

7.3.2. Evaluation of co-efficient of friction

The nature of the co-efficient of friction with increase in Mg –content in FG composites is complex as depicted in Figs.7.15 to 7.17. The COF increases as %Mg is increased from 2.5% to 5%. This is perhaps due to increase in volume% of reinforcing particles. With further increase in Mg% to 7.5%, the COF is found to be reduced. This is probably due to the strong oxide layer developed on the wear surface from the frictional heating as a result of ball asperities and reinforcement interaction. This heating is higher than that developed in composite with 5%Mg as the junction points are more in composite with 7.5% Mg.

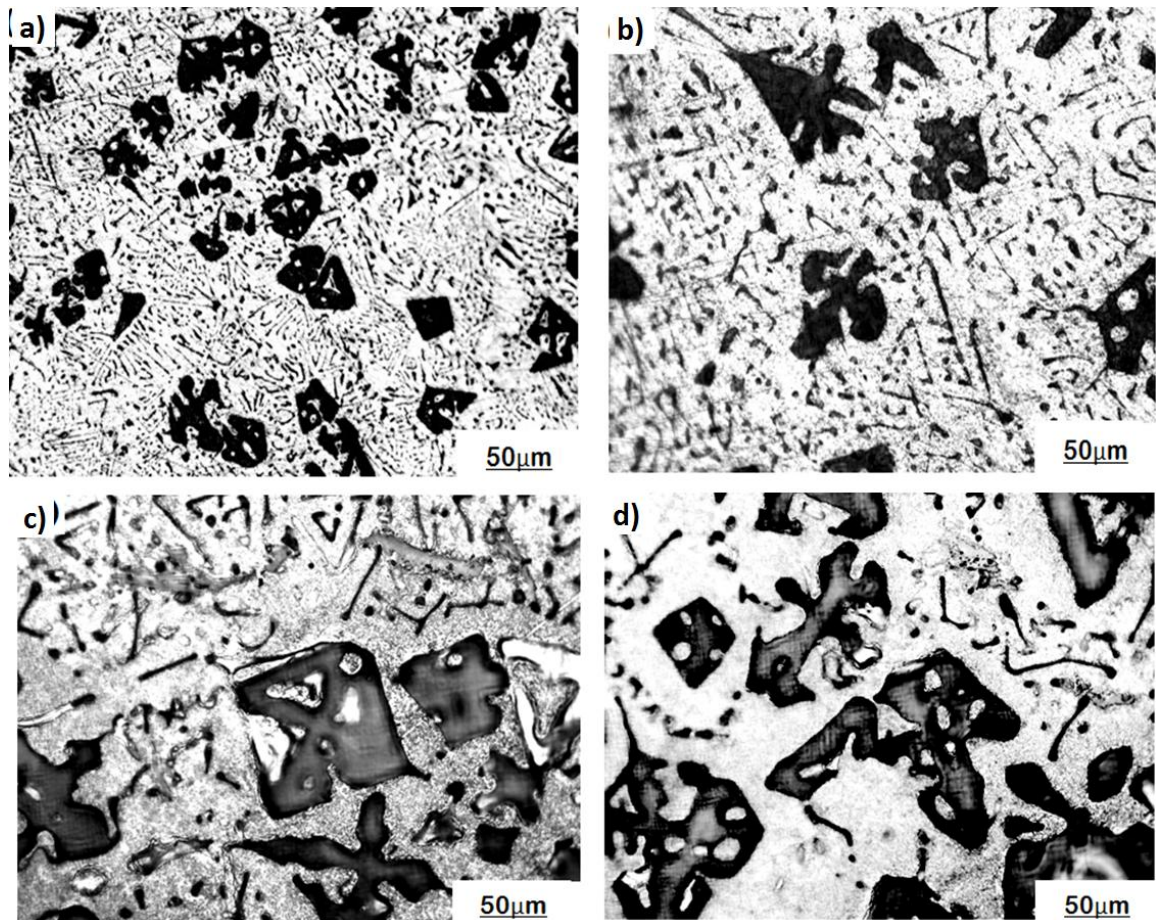


Fig.7.14 Morphology of primary Mg_2Si in T6 treated samples; a) with 2.5wt.% Mg, b) with 5.0 wt.% Mg, c) with 7.5 wt.% Mg and d) with 10 wt.% Mg.

The high test temperature is also accelerating the oxidation of the wearing surface. Some of the dislodged Mg_2Si particles from the Al matrix embedded again in the softened matrix by the compressive load. This can lead to the reduction in the contact area and number of junctions and resulting in the decrease in COF values. However, further increase in Mg% to 10% leads to coarsening of the primary Mg_2Si particles. These can not withstand the shearing action by the asperities and are dislodged from the softened matrix. Adherence between ball and the block increases with a net result of increase in COF value.

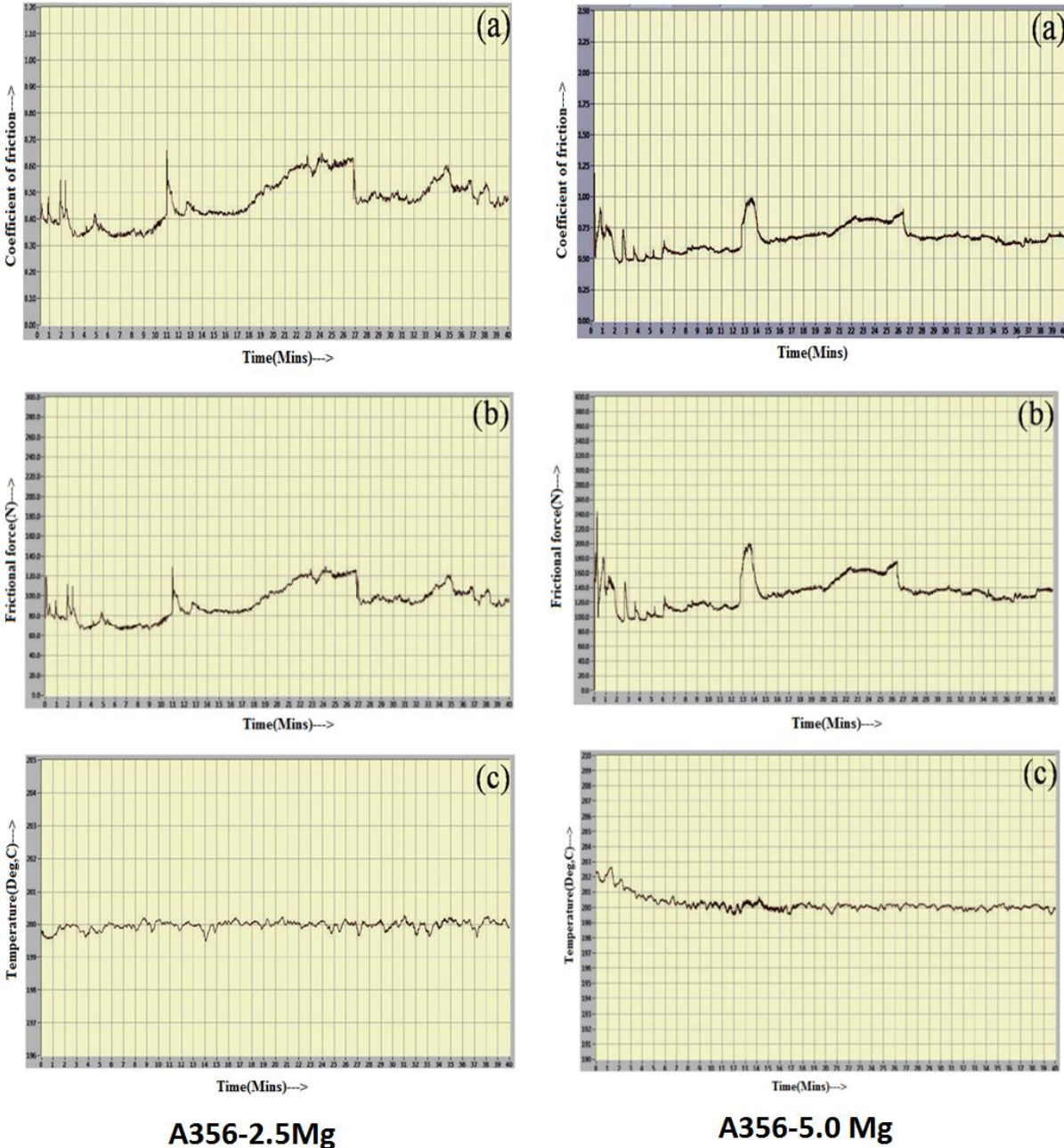


Fig.7.15. Co-efficient of friction, Frictional force (N) and Temperature °C vs. time profiles of inner zones of T6 treated A356-2.5%Mg and A356-5.0%Mg composites

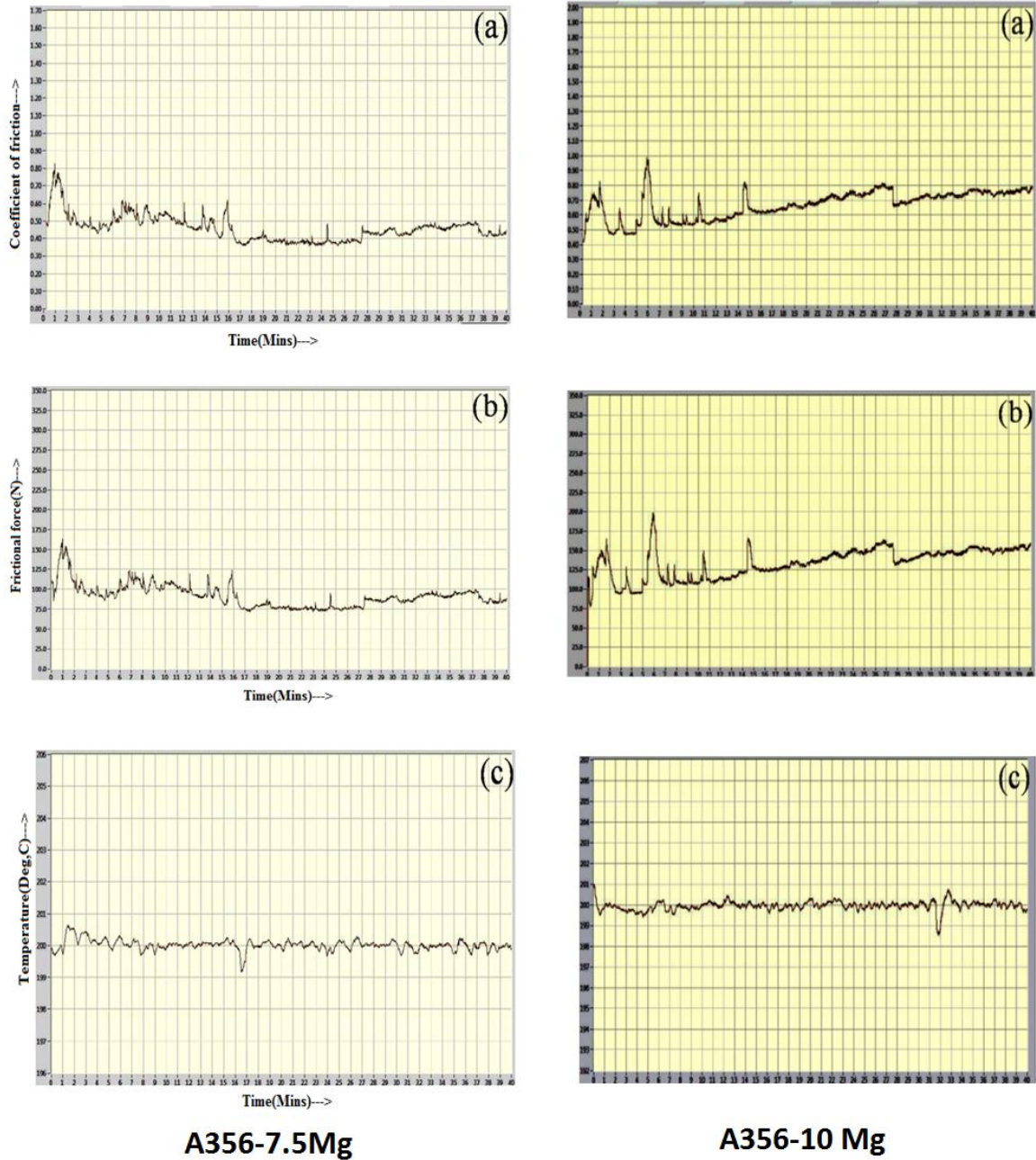


Fig.7.16. Co-efficient of friction, Frictional force (N) and Temperature $^{\circ}\text{C}$ vs. time profiles of inner zones of T6 treated A356-7.5%Mg and A356-10%Mg composites.

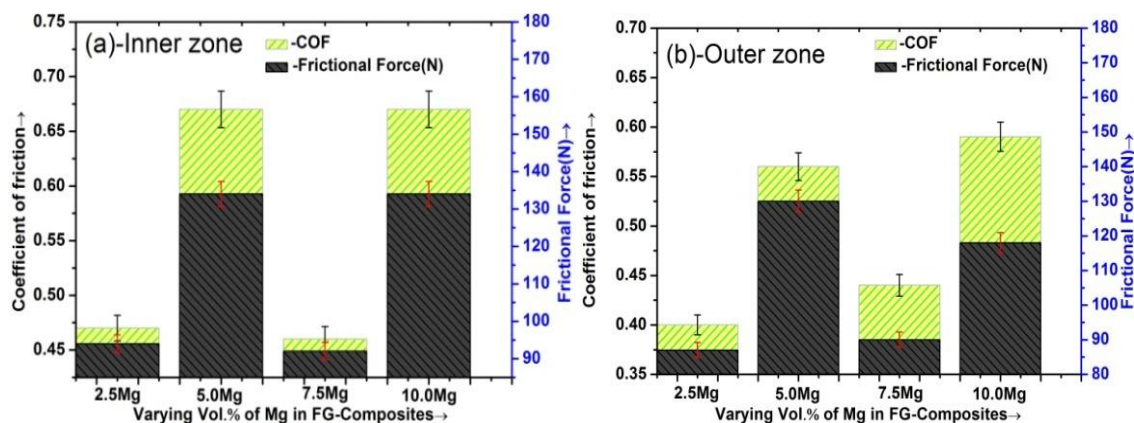


Fig.7.17. COF and Frictional force (N) vs. wt.% Mg in the composites at (a) inner zones, (b) Outer zones.

7.3.3. Characterization of worn surfaces

Figs.7.18 to Fig.7.21 show the worn surface SEM Images of T6 treated A356 with 2.5Mg, 5.0Mg, 7.5 Mg and 10 Mg at inner zones respectively. A softened flow pattern of wear scars in wavy form due to high temperature wear are evident in all the composite samples. In T6 condition both primary Mg_2Si and eutectic Si contents have crucial role to combat wear. In composite with 2.5%Mg due to lesser volume percent of reinforcing particles the hard asperities on the steel ball or hard particles in between the test piece and the ball cause ploughing or cutting of softer aluminium alloy or composites. This results in removal of small fragments of material causing an abrasive type of wear. The deeper grooves are formed by higher degree of penetration by hard counterface asperities.

Increase in wear test temperature has been reported [137] to soften the contact surface during sliding. Beside this, thermal deformation at a critical temperature is activated above a critical temperature depending on the matrix and the reinforcement. A transition from mild to severe mode of wear happened to be active at a critical temperature of $0.4T_m$. With application of

load plastic deformation starts appearing on the worn surface and severe Delamination as shown from the SEM micrographs (Fig.7.18). Sufficient plastic deformation of a matrix containing hard second –phase particles causes crack nucleation preferentially at these hard second phase particles.

The clear evidence of severe plastic deformation and the material flows can be observed by the sub-surface micrographs (Figs.7.23 to 7.25). High interfacial shear stresses developed due to friction between ball and test surface, are perhaps responsible for plastic flow of subsurface aluminum matrix and directional alignment of Mg_2Si particles. Moreover, the brittle primary as well as eutectic Mg_2Si near the worn surface is fragmented into small particles in course of sliding and provides the favourable sites for crack nucleation.

Direct metal-to metal contact between matrix and counterface ball are reduced by the presence of Mg_2Si particles that is the effective contact area is reduced, thus, Mg_2Si particles act as a load bearing phase and the matrix is protected during reciprocating wear. Increase in volume% of Mg_2Si particles causes higher dislocation density around the Mg_2Si particles during solidification hence, strength and hardness of composites improve which results in lowering of specific wear rate. Consequently, the mass loss are decreased in 5%Mg composites and further in 7.5% Mg composites. Beside these, at elevated test temperature as well as due to frictional heat oxide layer of mechanically mixed layers are formed (Fig.7.22). The worn ball surface images are shown in Fig.7.26 and the corresponding EDS analysis are shown in Fig.7.27. Therefore, an increase in volume percentage of Mg_2Si in MML restricts the further removal of material from the surface. The presence of plate or flake –like debris are due to delamination wear at high temperature.

In case of 10%Mg composite, the flow of material in wavy form is most prominent. This is due to the softening of matrix surface at high test temperature due to higher effective contact area. This higher effective contact area results due dislodge of coarser primary Mg_2Si particles from the matrix. The cracks initiated in the matrix/particle interface are evident in the transverse sub-surface micrograph.

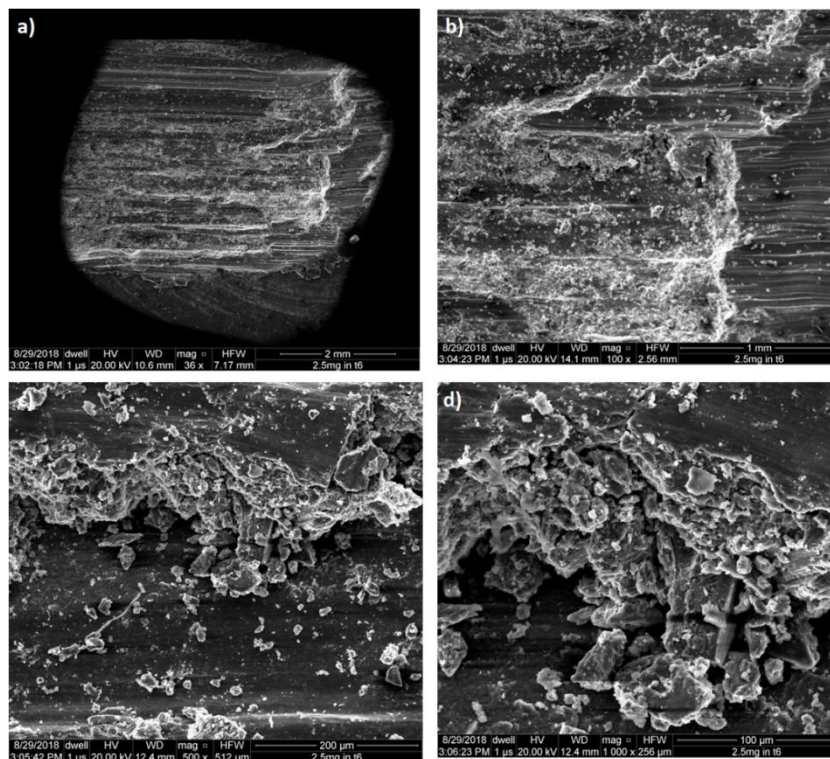


Fig. 7.18. Worn surface SEM Images of inner zone of T6 treated A356+2.5Mg FG-composite at different magnifications.

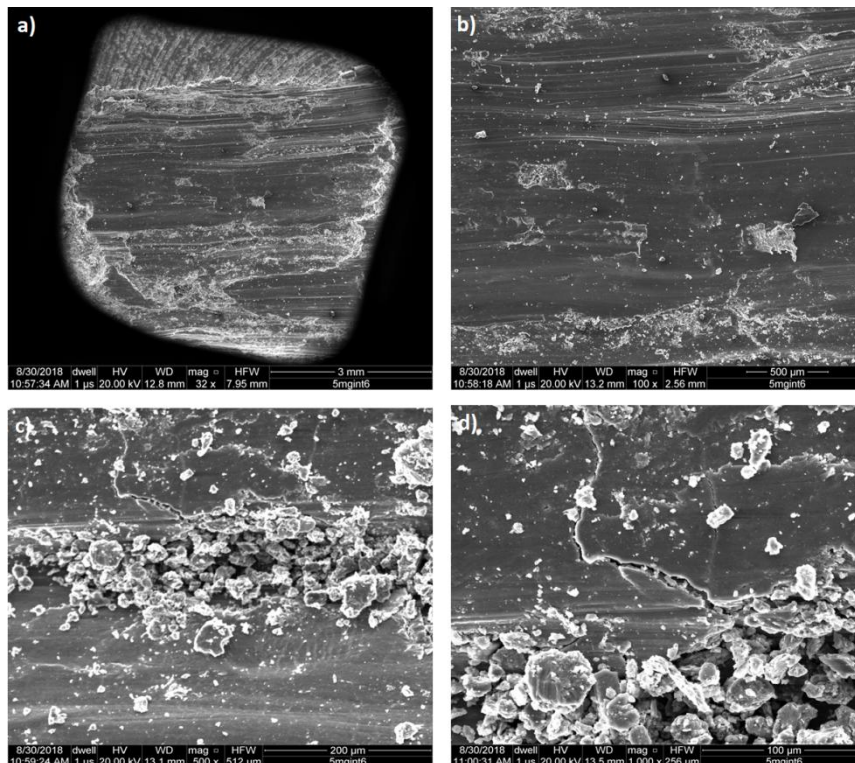


Fig.7.19. Worn surface SEM Images of inner zone of T6 treated A356+5Mg FG composite at different magnifications.

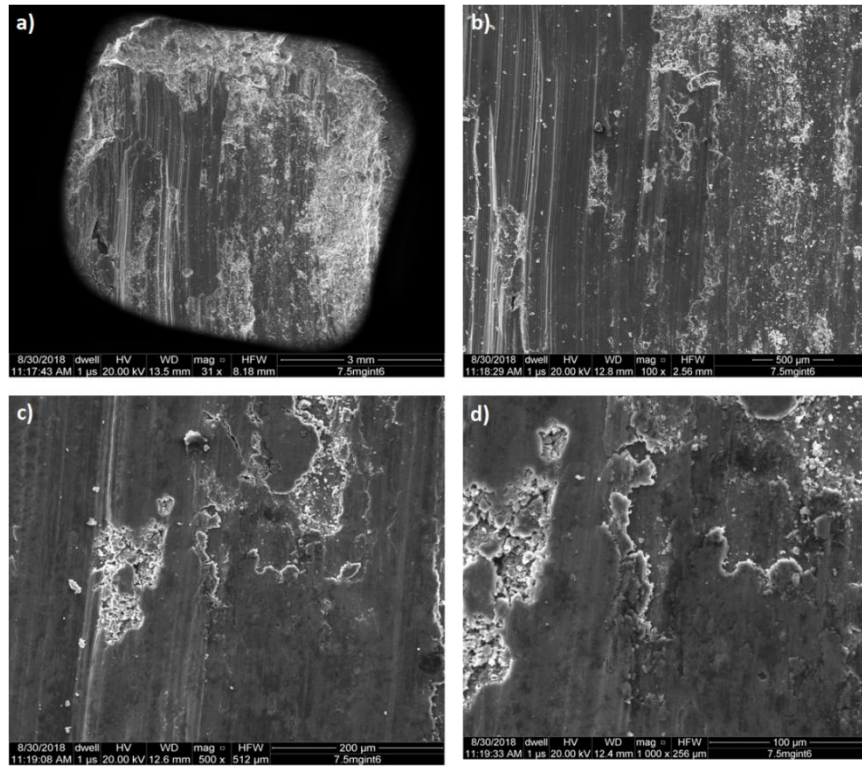


Fig.7.20. Worn surface SEM Images of inner zone of T6 treated A356+7.5Mg FG composite at different magnifications.

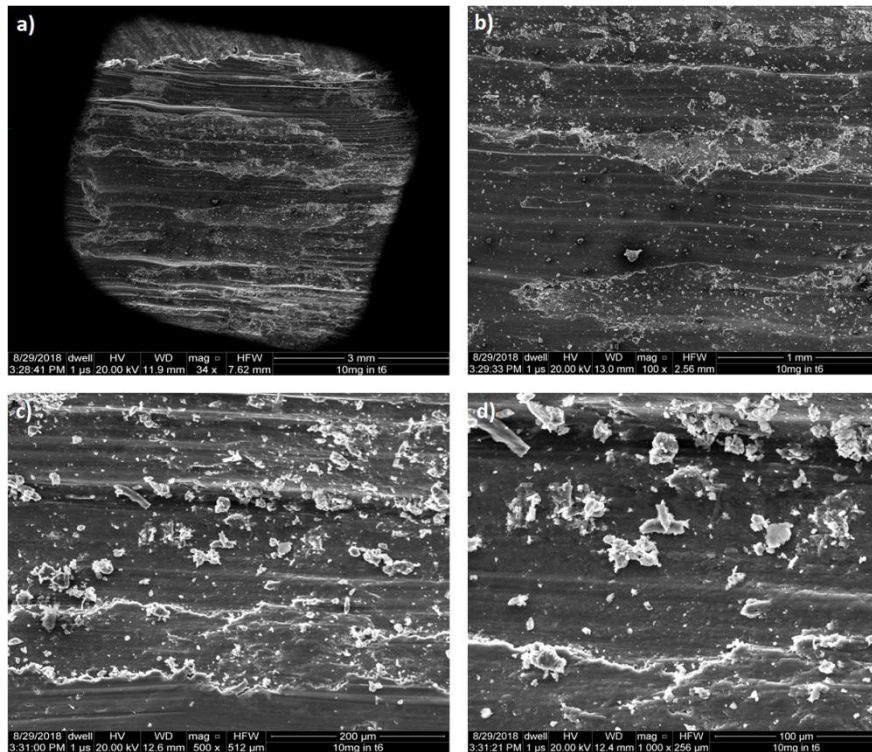


Fig.7.21. Worn surface SEM Images of inner zone of T6 treated A356+10Mg FG composite at different magnifications.

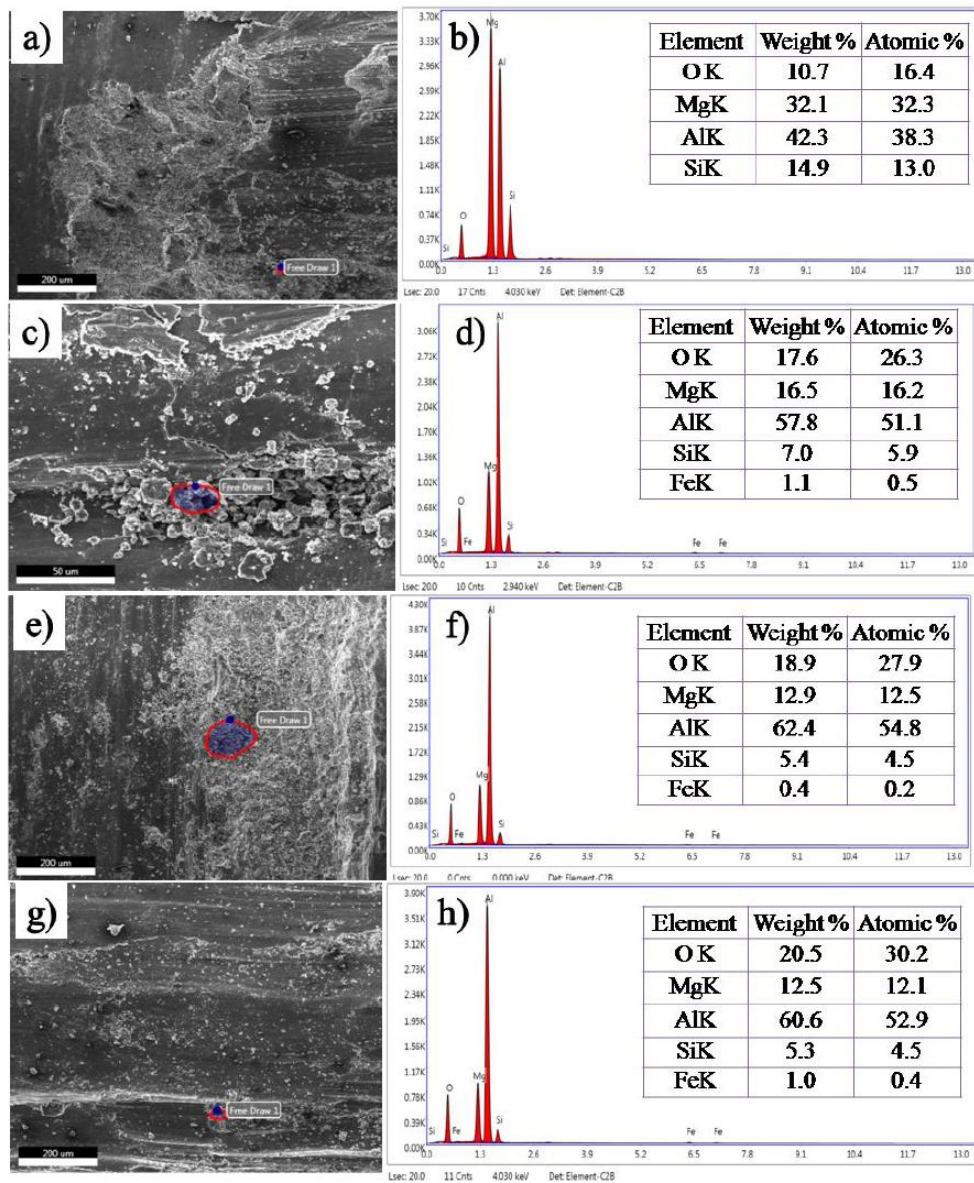


Fig.7.22. EDS analysis of wear debris: (a) and (b) are of A356-2.5Mg; (c) and (d) are of A356-5.0Mg; (e) and (f) are of A356-7.5Mg; and (g) and (h) are of A356-10Mg FG composites at inner zone in T6 condition.

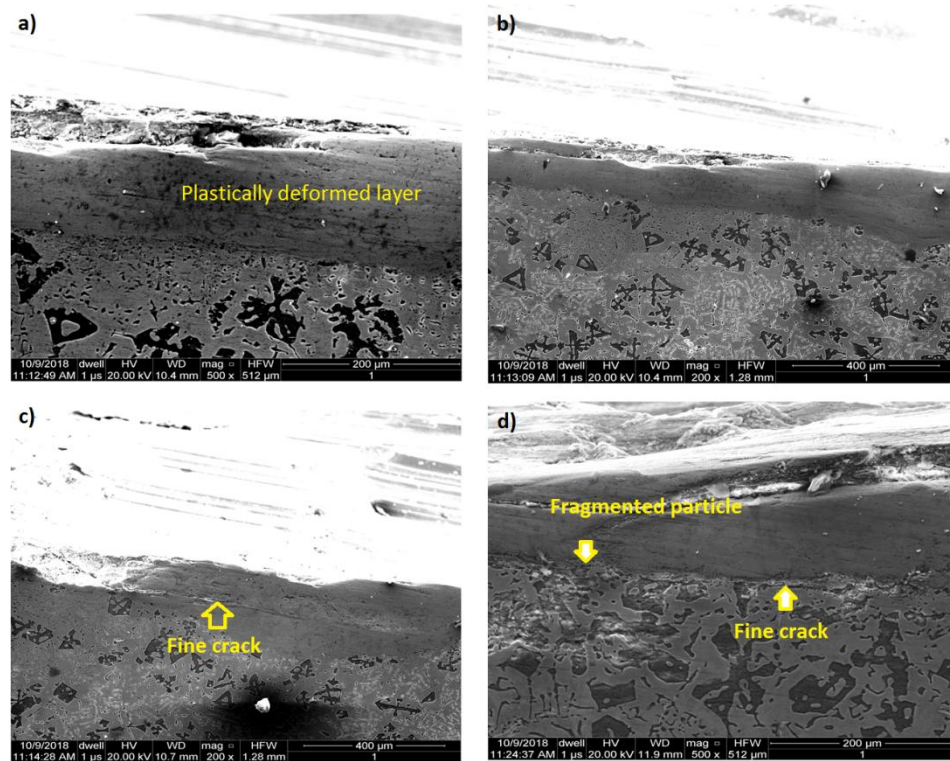


Fig.7.23. Subsurface SEM image of the worn out section of A356-2.5% Mg FGM after T6 heat treatment at inner layer.

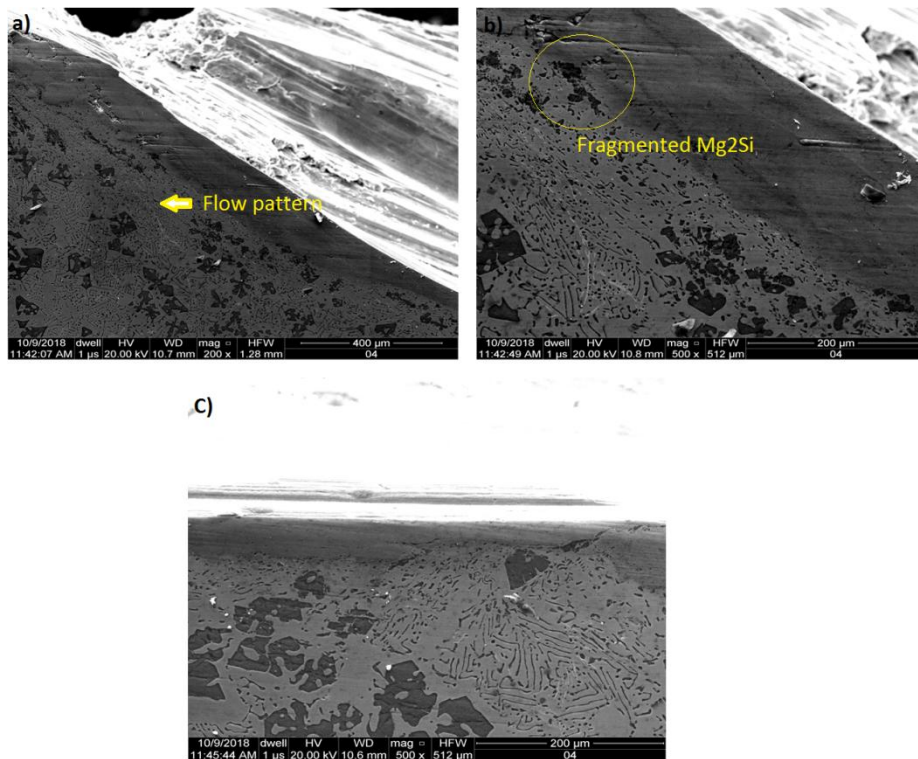


Fig.7.24. Subsurface SEM image of the worn out section of A356-5% Mg FGM after T6 heat treatment at inner layer.

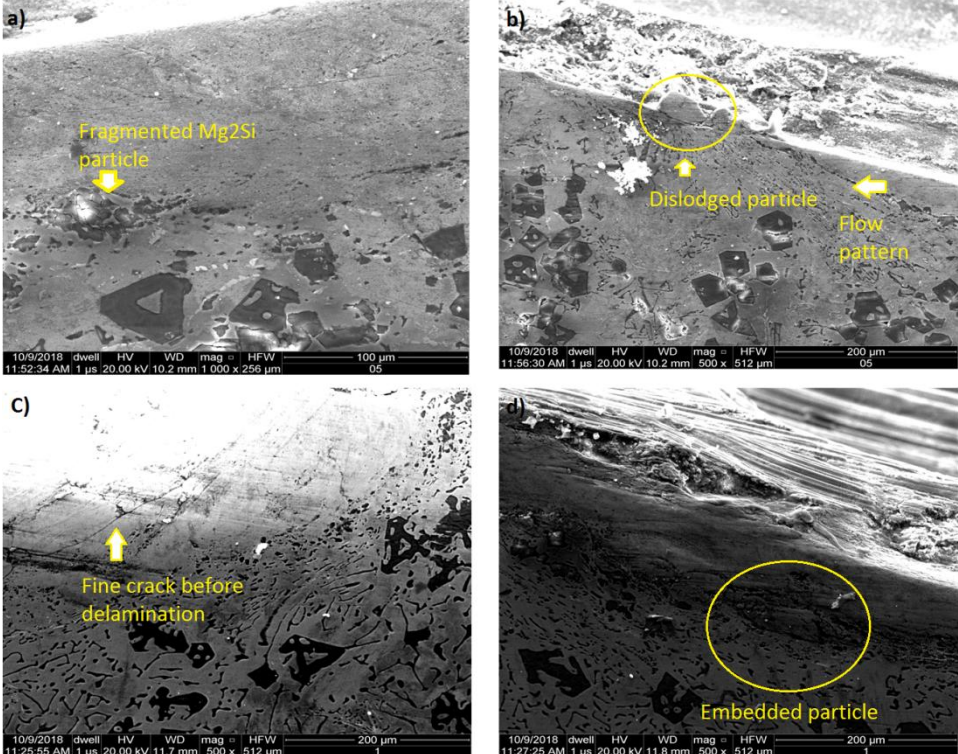


Fig.7.25. Subsurface SEM image of the worn out section of a) and b) A356-7.5% Mg FGM and c) and d) A356-10% Mg FGM after T6 heat treatment at inner layer.

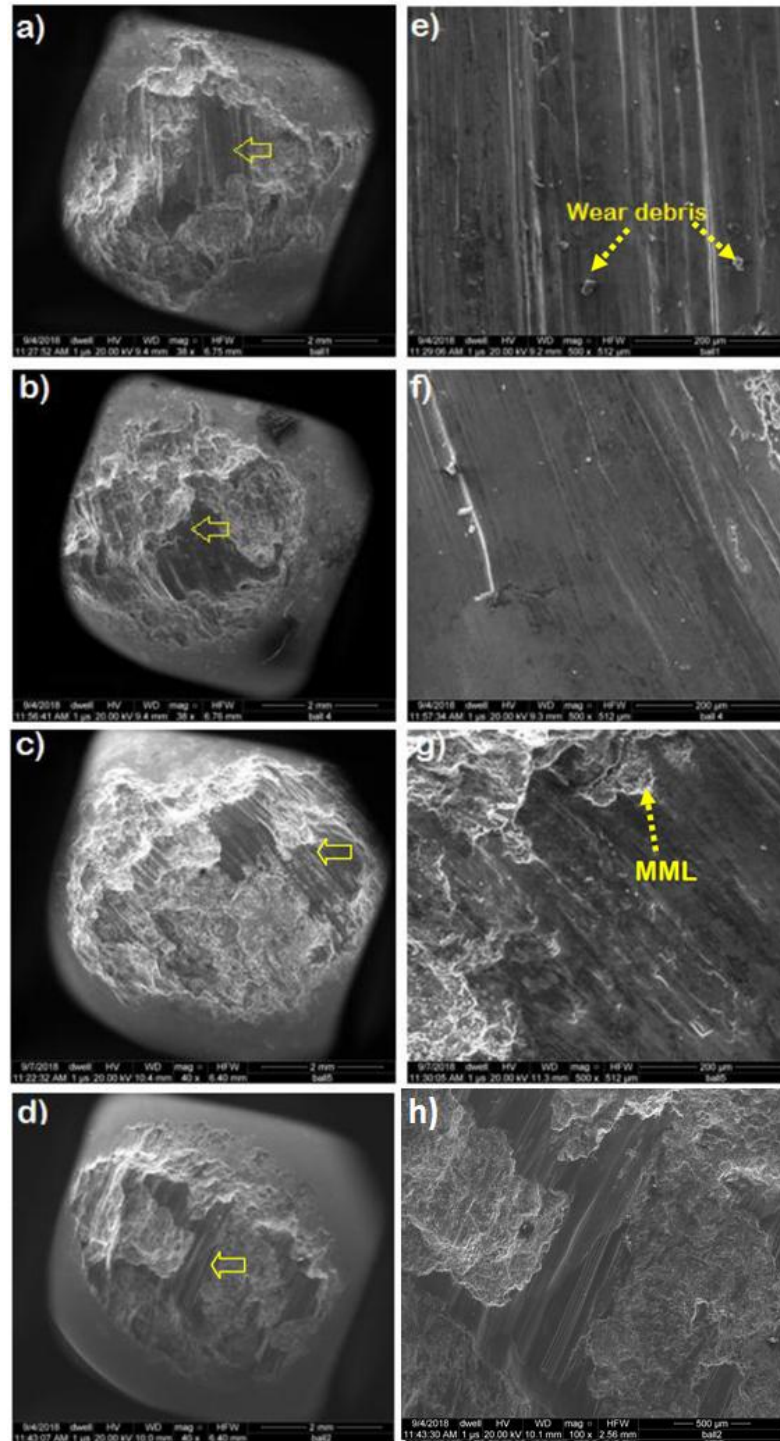


Fig.7.26. SEM images of worn surfaces of a) steel ball used as counterface for plates of A356-2.5Mg, (b) steel ball used as counterface for plates of A356-5.0Mg, (c) steel ball used as counterface for plates of A356-7.5Mg and (d) steel ball used as counterface for plates of A356-10Mg FG-composites. e), f), g) and h) are at higher magnifications of a), b), c) and d) respectively.

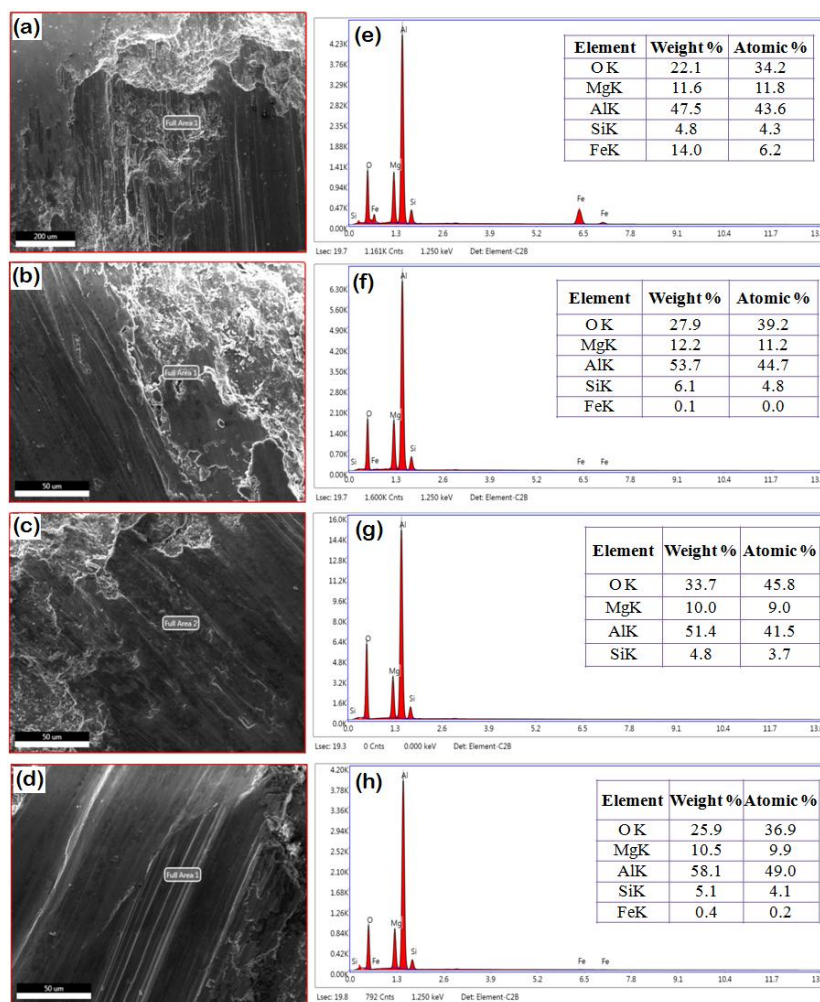


Fig.7.27. SEM EDS analysis of worn ball surfaces for (a)A356-2.5Mg,(b) A356-5.0Mg, (c) A356-7.5Mg and (d)A356-10Mg FGMs and (e),(f),(g) and (h) are the corresponding elemental distribution at inner zone under T6 condition.

7.4 Chapter Summary

The effect of magnesium content on the room temperature dry sliding wear behaviour and high temperature linear reciprocating wear of centrifugally cast functionally graded A356-Mg₂Si in situ composites have been characterized in the present chapter. Based on the experimental findings following conclusions may be drawn:

- (a) The composites show better wear resistance due to their better load bearing capacity and capacity to maintain a protective stable oxide film along with mechanically mixed layer, protecting against metal-to-metal contact.
- (b) A mild wear regime is observed below about a normal load of 30 N beyond this the wear is in severe regime. This perhaps due to the disruption of oxide film with mechanically mixed layer by a process of delamination. Subsurface microstructures confirm the delamination wear by specific microstructural features.
- (c) The mass loss at high temperature at high temperature reciprocating wear decreases with increase in %Mg from 2.5% to 7.5% and rises little bit with 10%Mg. This is perhaps due to coarser primary Mg₂Si particles and higher % porosity present in 10%Mg composite.
- (d) The COF values show a complex nature. It increases with increase in Mg-content from 2.5% to 5%, then decreases with 7.5% and finally again increases with 10%Mg. The initial increase is due to higher volume% of Mg₂Si in 5%Mg composite than in 2.5%Mg composite which causes more asperities and reinforcement interaction. Further increase in Mg₂Si content in 7.5%Mg composite generates large amount of frictional heat which produces oxidized MML layer. This layer reduced the COF value. Shearing of coarse Mg₂Si particles from the

softened matrix of 10%Mg composite causes adherence of ball and block which leads to increase in COF value.

- (e) So far as the high temperature wear resistance and COF is concerned, 7.5%Mg shows best combination of wear characteristics.