Effect of mechanical vibrations on the wear behavior of AZ91 Mg alloy

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Abstract. AZ91 Mg alloy is the most promising alloy used for structural applications. The vibration induced methods are effective and economic viable in term of mechanical properties. Sliding wear tests were performed on AZ91 Mg alloy using a pin-on- disc configuration. Wear rates were measured at 5 N and 10N at a sliding velocity of 1m/s for varied frequency within the range of 5- 25Hz and a constant amplitude of 2mm. Microstructures of worn surfaces and wear debris were characterized by field emission scanning electron microscopy (FESEM). It is observed that wear resistance of vibrated AZ91 alloy at 15Hz frequency ad 2mm amplitude was superior than cast AZ91 Mg alloy. Finer grain size and equiaxed grain shape both are important parameters for better wear resistance in vibrated AZ91 Mg alloys. FESEM analysis revealed that wear is considerably affected due to frictional heat generated by the relative motion between AZ91 Mg alloy and EN31 steel surface. No single mechanism was responsible for material loss.

Keywords: AZ91Mg alloy, mechanical vibration, wear resistance, wear mechanism

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1. Introduction Magnesium and its alloys are getting attention in the field of automotive and aerospace industries due to lightest weight material among all the structural materials [1]. Grain size affect the mechanical properties like hardness, tensile strength, wear. The vibration induced methods are effective and economic viable in term of mechanical properties. There are different techniques like mechanical vibrations, electromagnetic vibrations and ultrasonic vibrations [2]. In automobile applications such as automotive brakes, piston and cylinder bores of engine, material are subjected to sliding motion. There are several factors, which influence the tribological behavior of sliding system material. These include properties of sample material along with counterface material and interaction with environment as well as experimental conditions like applied load, sliding velocity, sliding distance. Extensive researches [3], have been carried out on wear and its mechanisms. Chen and Alpas [1], investigated dry sliding wear of AZ91 alloy against AISI52100 steel counterface using a block on- ring configuration. Tests were done within a load range of 1- 350N and sliding velocity within a range of 0.1- 0.2 m/s. They observed two wear regimes; mild wear regime and severe wear regime. The mild wear regime includes oxidational and delamination whereas severe wear regime include surface damage and debris formation. They also investigated the role of contact surface temperature on the mild to severe wear transition. J.An et.al [4] studied dry sliding tests on as cast magnesium alloys $Mg_{97}Zn_1Y_2$ and AZ91 using a pin-on- disc apparatus. Tests were performed at a sliding velocity of 0.785 m/s and within a load range of 20-380N. Abrasion, oxidation, delamination, thermal softening and melting wear mechanisms were observed. Under the given conditions, for the $Mg_{97}Zn_1Y_2$ alloy the dominant wear mechanisms in the load range of 20–200N is abrasion and delamination. In the load range of 240–280 N, thermal softening is an important wear mechanism. Surface melting is the wear mechanism as the load is over 280 N. Morsy [3] performed tests within a sliding velocity range of 0.2- 1.8m/s and loads in the range of 50- 350 N against stainless steel as a counterface and found linear increment in the wear rate on increasing the sliding velocity and applied load in the mild wear region. On the other hand, in the severe wear regime, there was almost proportional rise in the wear rate with sliding velocity and load. Aung et.al [5] studied dry sliding wear behavior of AZ91 alloy at low sliding speed in the range of 0.01- 1.0m/s. Tests were done on pin-on-disc apparatus at 10N load for 1 and 10km sliding distances against JISG4303SUS440C stainless steel. Abrasive wear was dominant at low sliding speeds (<0.1m/s) whereas at high sliding speeds (>0.1m/s) frictional heat causes oxidational wear. Oxidational and delamination wear conditions were found due to protective layers of agglomerated oxidized debris and due to load bearing components along with transmitted shear strains during sliding respectively. The debris containing large flakes of delamination wear were least oxidized. Das et.al [6] studied the sliding wear of wrought AZ31 Mg alloy to delineate the micromechanisms of wear. Dry pin-on- disc tests were performed against tool steel as conterface at 673K. It was found that subsurface grains beneath the contact surface were subjected to large plastic strains and experienced dynamic recrystallization and growth. Zafari et.al [7] investigated the tribological behavior of AZ91 and AZ91 + 3RE Mg alloys. Tests were conducted at a load of 20N, sliding speeds of 0.4m/s and 1m/s and at wear temperature of 25- 250˚C. There was around 8% and 60% reduction in wear rates for AZ91 and AZ91 + 3RE alloys at 25˚C whereas at 100˚C and 0.4m/s, AZ91 showed 58% reduction.

In the light of above, study of tribological behavior has become a prime concern in the field of automotive and aerospace industries. In the present investigation, experimental work was designed to study the effect of the applied load and sliding velocity on the wear transitions. The present study emphasizes the sliding wear behavior of as-cast and vibration imposed AZ91 magnesium alloy. A wear mapping approach has been undertaken to represent the wear regimes and the main mechanism of wear in each regime.

2. Experimental methods AZ91 magnesium alloy was selected for present investigation. The alloy was prepared in the bottom pouring type casting furnace under a shielding atmosphere of argon gas as shown in Figure 1. The vibrations were imposed at constant amplitude of 2mm and varied frequency of 5, 10, 15,

20 ad 25Hz to investigate the effect on wear behavior. The chemical composition of the as-cast AZ91 magnesium alloy is given in Table 1.

Table 1. Chemical composition of AZ91 Magnesium alloy (wt %)

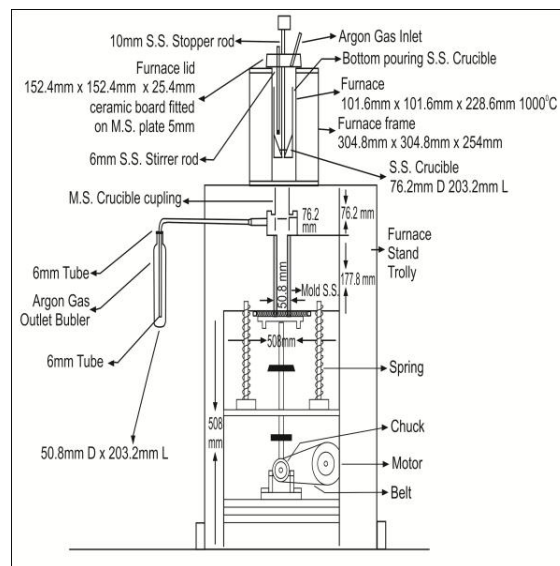| Cu	Si	Fe	Ni	Mn	Zn	Al	Mg
0.003	0.060	0.102	0.026	0.011	1.53	8.27	Bal.

Figure1. Experimental set up for mechanical vibration treatment of magnesium alloy

Wear tests were conducted on pin-on- disc apparatus. Wear test samples in the form of cylindrical pin (7mm dia and 20mm length) were machined from the cast plates. The wear test samples were wet grounded using SiC paper from 320 to 1500 grit step-by-step followed by polishing with 1.0μm and 0.5μm alumina suspension using a slow speed polishing machine. The polished surfaces were ultrasonically cleaned in acetone and dried prior to test. The narrow circular faces of the specimens were kept in contact with the slider disc. The counterface disc was made of EN31 steel (0.9-1.20% C, 0.10-0.35% Si, 0.30- 0.75% M, 0.05%S, 0.05%P, 1.0- 1.60%Cr). The diameter of the disc was 50 mm and was cleaned with acetone before each wear test. The tests were carried out at a sliding velocity of 1 m/s and applied loads at 5N and 10N for a total sliding distance of 1500m. Mass losses from the surfaces of specimens were determined as a function of sliding distance and sliding velocity at each load. The mass losses were calculated from the differences in weight of specimens measured before and after the sliding tests (after removing any loose debris) using an analytical balance having an accuracy of 0.01 mg. Volumetric wear loss was estimated by dividing the mass loss to density of the alloy. A separate specimen was used to measure the mass loss for each load. Microstructural analysis on the worn surfaces and the loose debris particles were undertaken using a field emission scanning electron microscope (FESEM).

3. Results and discussion

3.1. Cast and vibration imposed microstructure The microstructures of the as cast AZ91 Mg alloy and vibration imposed AZ91 Mg alloy at 15Hz frequency and 2mm amplitude are shown in Figure 2(a) and Figure 2(b). The as cast AZ91 alloy consists of coarse dendritic and non- uniform distribution of α-Mg primary phase, divorced eutectic β-$Mg_{17}Al_{12}$ phase and secondary precipitated β-$Mg_{17}Al_{12}$ phases. The eutectic phase precipitates in the form of network at grain boundaries. On imposing vibrations, coarse eutectic phase is refined and became discontinuous and new granular phases formed. Vibrations promote the fine dendritic structure and faster cooling of the melt [8]. Also a high heat transfer produced by vibrations inside the molten metal leads to a high solidification rate of the molten metal. The cooling rate of the molten metal without vibration is slower in comparison to vibration imposed molten metal. At 15 Hz frequency, vibration produced fine grain sizes by imparting numerous nucleation sites in the melt [9].
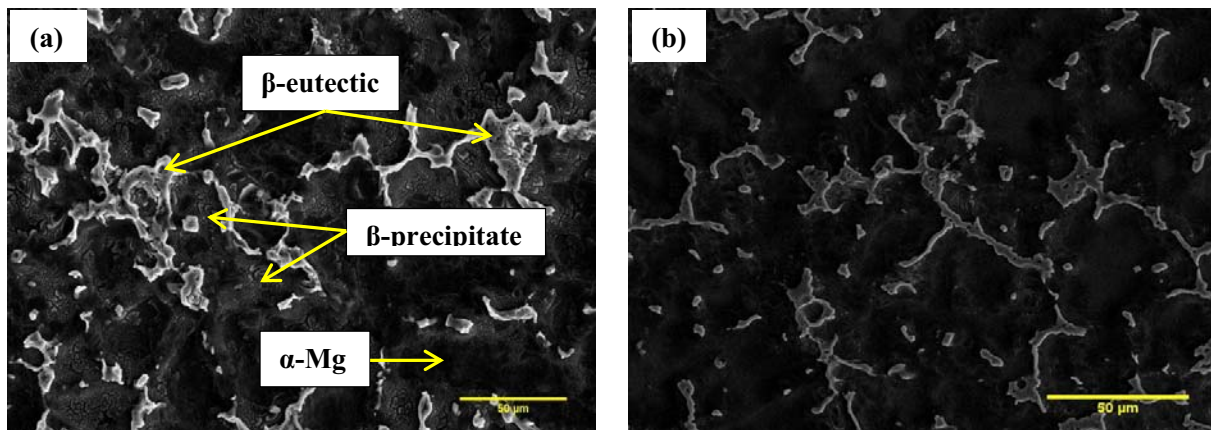

Figure 2. Scanning electron micrographs of AZ91 (a) as cast (b) 15 Hz-2mm amplitude

3.2. Mechanical properties and density Table 2 summaries the Brinell hardness, ultimate tensile strength (UTS), ductility and density of as-cast and vibration imposed at constant amplitude of 2mm and varied frequency of 5, 10, 15, 20 ad 25Hz AZ91 magnesium alloy. It was found that on imposing vibrations the mechanical properties increase up to certain frequency and then decreases on further increasing the frequency. Dislocation motion can be impeded by large grain boundary area. Therefore, fine grained material is harder and stronger than coarse grained material. The microstructure of AZ91 magnesium alloy contains α- Mg ad intermetallic compound $Mg_{17}Al_{12}$ at the grain boundaries. The improvement in the hardness of the alloy is due to the uniform distribution and features of these brittle intermetallic compounds. Hence, both cooling rate and uniformly distributed β- $Mg_{17}Al_{12}$ are responsible for the increase in hardness and tensile properties [10].

Table 2. Results of various mechanical properties at different frequencies of mechanical vibrations

Frequency of vibration (Hz)	Hardness (BHN)	Density (g/cm^3)	Ductility (% elon.)	UTS (MPa)
0	58	1.795	1.8	140
5	60	1.797	1.78	145
10	61	1.8	1.75	150

15	78	1.812	2.5	168
20	59	1.798	2.0	151
25	62	1.796	1.9	145

3.3. Friction Coefficient and Wear behavior

3.3.1. Effect of applied load on the coefficient of friction and wear rates. At lower load of 5N, the value of coefficient of friction (COF) was maximum for as cast alloy (0.5912 ± 0.0081) during sliding at 1ms^{-1} and it dropped to 0.407 ± 0.007 when the alloy was given vibration at a frequency of 5Hz. The friction gradually decreased with the increase in frequency, and reaches minimum to 0.2559 ± 0.004 at a frequency of 15Hz. This is due to the refinement and uniform distribution of the β- phase. This value of coefficient of friction once again increases on increasing the frequency of vibration up to 25Hz. This increase in the value of COF is because of the coarse and little porous structure of the alloy at higher frequencies. Similar pattern was observed for 10N load (Figure 3 a).

The specific wear rates of the AZ91 alloy are plotted against the applied loads at 5N and 10N for the tests conducted at constant sliding velocity of 1m/s in Figure 3b. At 5N load, there was a change in the slope of the wear rate curve at low frequency of 5Hz. The specific wear rate for the as cast alloy and 5 Hz frequency of vibration was 1.07 (± 0.007) x10-6mm3/Nm and 0.79 (± 0.008) x10-6mm3/Nm respectively. On further increasing the frequency, there was a decrement in wear rate and it reaches to minimum to a value of 0.51 (± 0.005) x10-6mm3/Nm when the vibration frequency was 15Hz. Again, this is happening due to the fine and uniform distribution of the β- phase and sound casting. The wear rates increased as frequency of vibration increases further to 20Hz and 25Hz, similar trend was also observed at 10N of load. The frictional force decreased between the two sliding surfaces as the actual area of contact rose towards the nominal area, on augmenting the load on the pin. This decrement in the frictional force and real surface area in contact resulted in lower wear. When sample comes in contact with rotating disc, frictional heat generates. Due to which softening of the pin surface may take place. During continuous sliding and frictional heat the sub-surface cracks may be formed preferably at the voids. These sub-surface cracks when run parallel to the sub-surface, some particles get detached from the sample and transferred to the rotating disc. These particles are present as third party between the sample and the rotating disc and become responsible for abrasion of samples. After plastic deformation, such abrasion grooves are formed as shown in Fig. 4.27 and Fig. 4.28. The results commended that wear rate of AZ91 magnesium alloy considerably get affected by frictional heat that is been generated by the relative motion between AZ91 magnesium alloy and EN31 steel surface. At both the loads specific wear rate is increasing upto 15 Hz and then decreasing on further increasing the frequency to 20 Hz and 25 Hz. According to E. Iianaganar and et.al [11] the actual area of contact to nominal area would increase on increasing the load leading increased frictional force between two sliding surfaces. The increased frictional force and real surface area in contact cause higher wear. Therefore, it could be said that on increasing the applied load, the wear resistance of the alloy with vibration at constant amplitude and varied frequency decreases. The best results were obtained at 15Hz- 2mm amplitude of vibrations at both the loads.
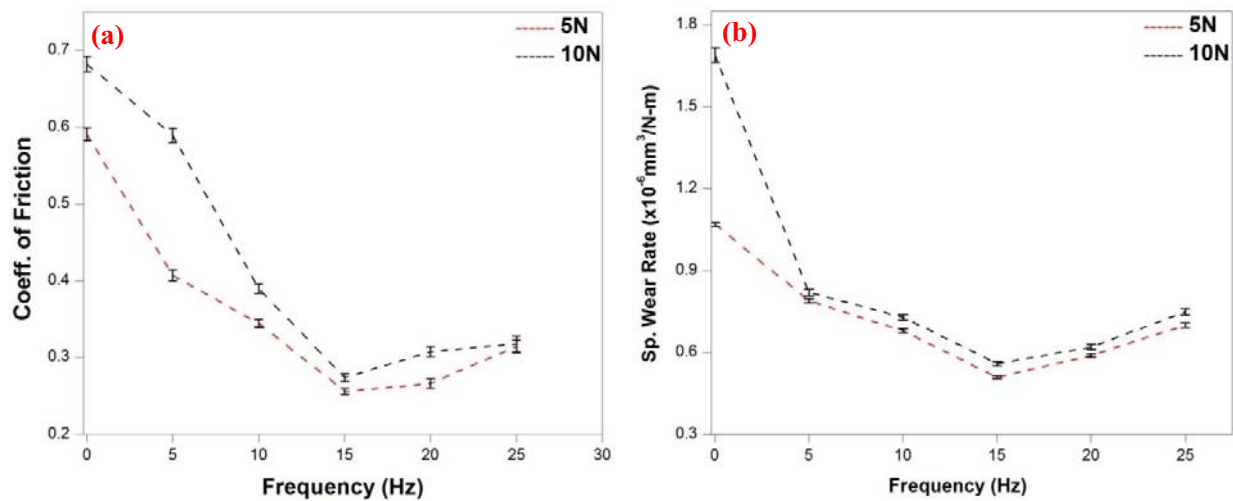
Figure 3 Effect of frequency of vibration at constant amplitude of 2mm on (a) coefficient of friction (b) Sp. wear rates of AZ91 at 5N and 10N loads

3.3.2. Examination of worn surfaces. The worn pin surfaces under scanning electron microscope examination recognized four wear mechanisms operating under various processing conditions. They are abrasion, delamination, oxidation and plastic deformation. In the following sections, the observed wear mechanisms in relation to the processing conditions are identified for better understanding of the tribological behavior of AZ91 magnesium alloy. Figure 4.1 (a-d) and Figure 4.2 (a-d) show the FESEM micrographs of worn surfaces of as-cast and vibrated (5Hz, 15Hz, 25Hz) AZ91 magnesium alloy at 5 N and 10 N loads respectively. The wear track generated on as-cast AZ91 magnesium alloy is uneven/ irregular with deep and wide abrasive grooves as shown in Figure 4.1 (a). When the as cast AZ91 alloy pin slides on EN31 steel disc, it is slightly plastically deformed and wear debris is formed [12]. Since, as-cast AZ91 pin is softer than tool steel disc, the loose worn debris embedded at the contact region of as-cast AZ91 pin. The entrapped debris particles produce further damage on both surfaces as a third-body abrasive and the debris itself undergoes delamination during the sliding. It is due to high friction caused by coarse grain size as well as inhomogeneous hardness of matrix and secondary phases. Similarly, at 10 N load worn surfaces of as-cast AZ91 magnesium alloy showed the same features and trends as observed at 5 N load (Figure 4.2 (a)). The features of abrasive grooves, embedded debris and fracture fragments are more prominent than observed at 5 N loads. It is obvious due to applied higher load, which helps to initiate high friction during wear process. Abrasive grooves, fracture fragments (delamination), oxides and embedded debris are also observed in vibration induced alloy at 5Hz (Figure 4.1 (b)). However, these features are slightly lesser than that observed in as-cast AZ91 magnesium alloy. From the Figure 4.1 (c), it can be seen that as the frequency of the vibration is increased to 15 Hz, wear track generated are smooth with mild abrasive grooves. The reason for the low friction is due to optimum surface hardness and fine grain structure which eliminate adhesion. The fine distributed second phase particles in vibrated (15Hz) AZ91 magnesium alloy could also be beneficial for high wear resistance, as it has the tendency to provide some hardness in the matrix. As the frequency of vibration is further increased to 25Hz in Figure 4.1 (d), severe plastic deformation can be seen in large number. It is in accordance to the increase the volume fraction of secondary phases after imposition of vibration at 25Hz, which provides inhomogeneous surface hardness. Similarly, at 10 N load worn surfaces of vibrated (5Hz, 15Hz, 25Hz) AZ91 magnesium alloy showed the same features and trends as observed at 5 N load (Figure 4.2 (b-d)). The features of abrasive grooves, embedded debris and fracture fragments are more prominent than observed at 5 N loads. These features are indicating the occurrence of severe metallic wear. The transition to severe wear accompanied by a significant increase in the roughness of worn surface of the samples. The severely deformed metallic layers extruded along the sliding direction [11]. It is observed that AZ91 magnesium

alloy vibrated at 15Hz at both the loads (5N and 10N) could resist adverse conditions of wear better in comparison to the other vibrated alloys under similar conditions. In case of AZ91 Mg alloy vibrated at 15Hz, the presence of fine eutectic phase strengthens the magnesium matrix. In such cases, improvement in wear resistance was due to fine grains. Therefore, it is clear that the decrease in grain size results increase in wear resistance of grain refined AZ91 alloy. So, grain size is a vital parameter for better wear resistance [13].
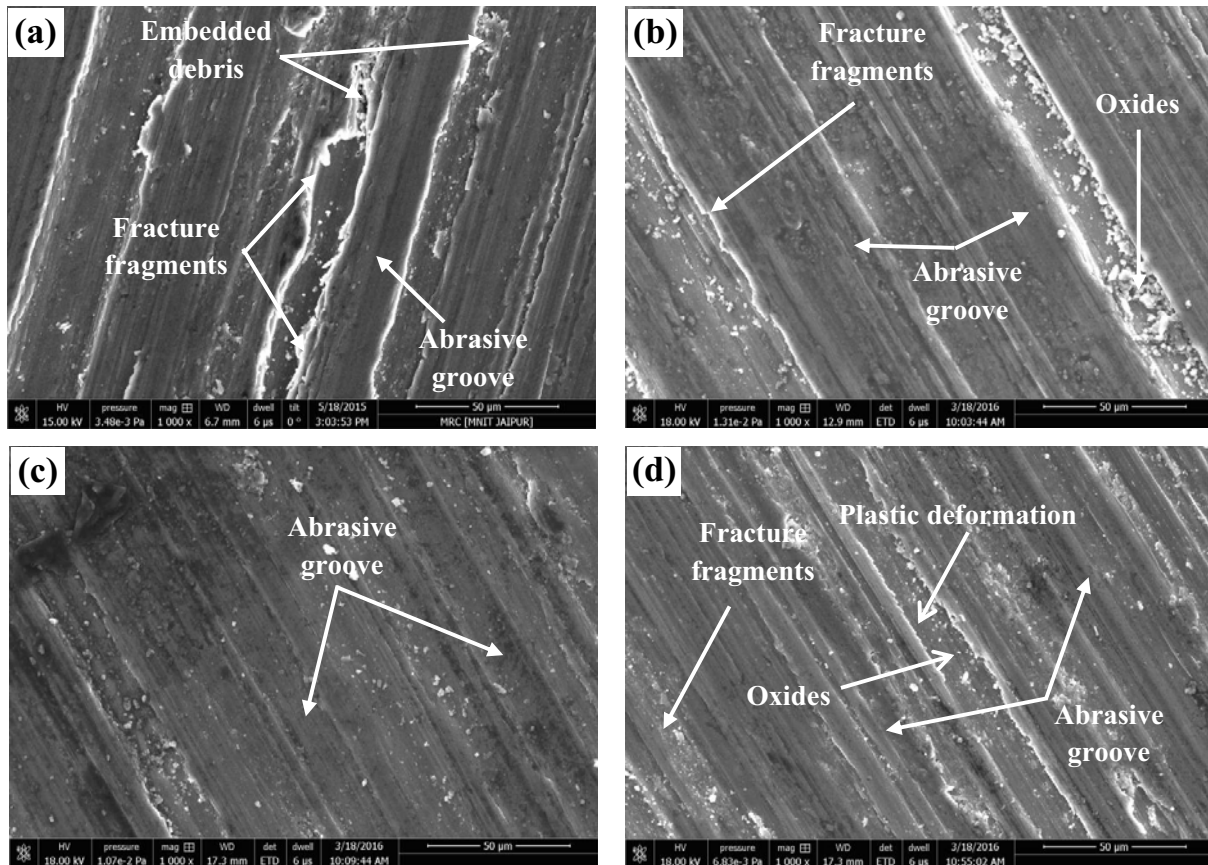

Figure 4.1 FESEM micrographs of worn surfaces of AZ91 magnesium alloy at 5 N load: (a) as-cast (b) 5Hz (c) 15Hz, (d) 25Hz.
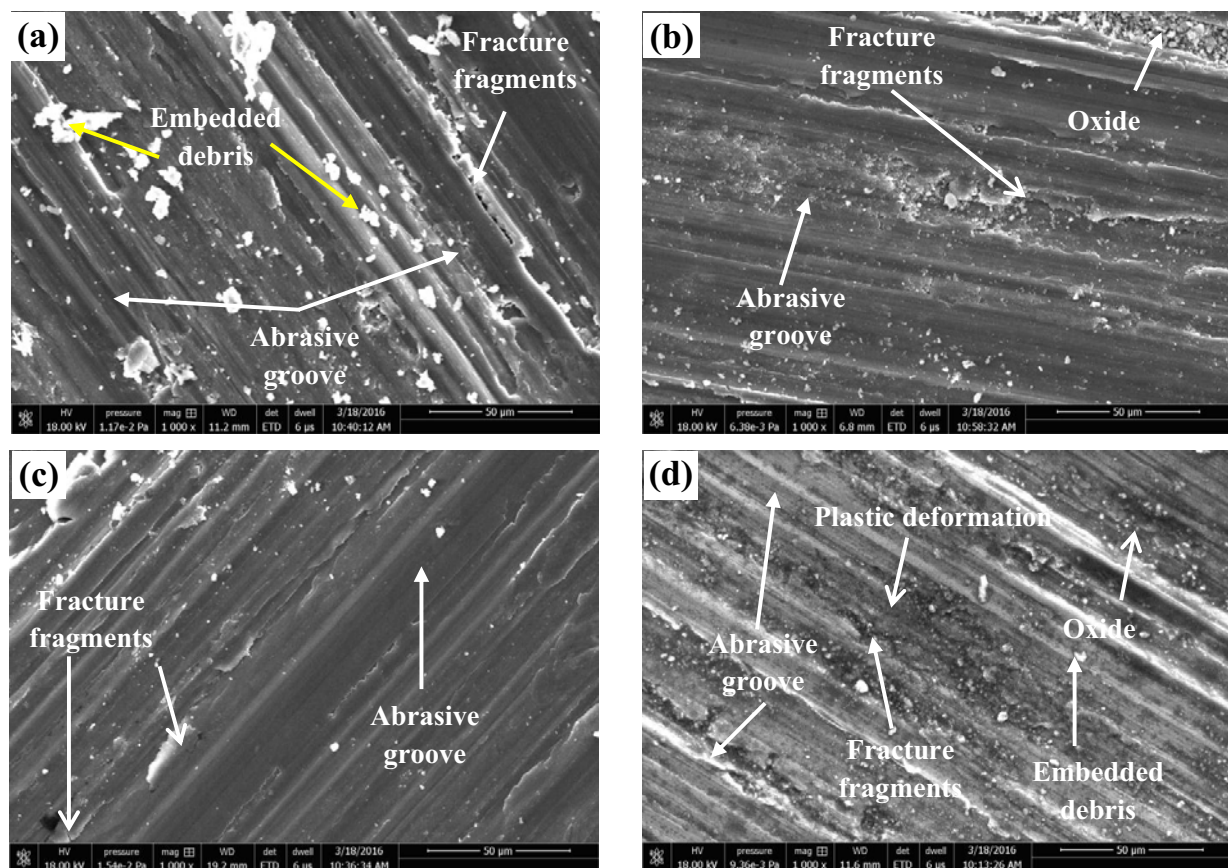
Figure 4.2. FESEM micrographs of worn surfaces of AZ91 magnesium alloy at 10 N loads: (a) as-cast (b) 5Hz (c) 15Hz (d) 25Hz.

3.4 Examination of wear debris FESEM micrographs of wear debris of as-cast and vibrated (15Hz) AZ91 magnesium alloy collected after sliding wear test at 5 N and 10 N are shown in Figure 5.1 and Figur 5.2 respectively. The as-cast AZ91 magnesium alloy at both 5 and 10 N load shows coarse debris as shown in Figure 5.1 (a) and Figure 5.2 (a). While, vibrated (15Hz) AZ91 magnesium alloy tested at 5 N and 10 N show the fine debris as shown in Figure 5.1 (b) and Figure 5.2 (b). Generally, fine debris is beneficial in term of wear resistance because fine particles in the debris reattached to form a transfer film on the surface of disc coming under sliding contact.
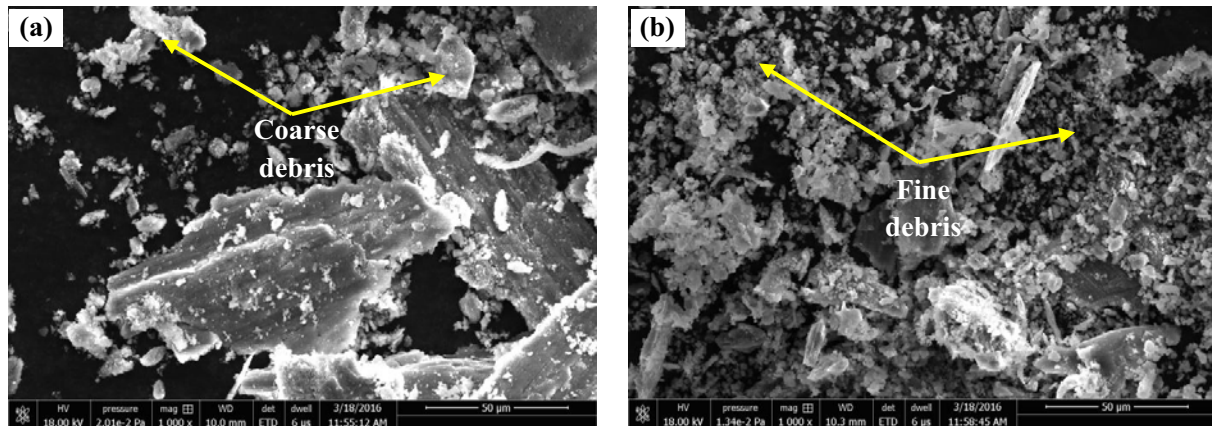
Figure 5.1. FESEM micrographs of worn debris of AZ91 magnesium alloy collected after wear test at 5 N load: (a) as-cast, (b) 15Hz.
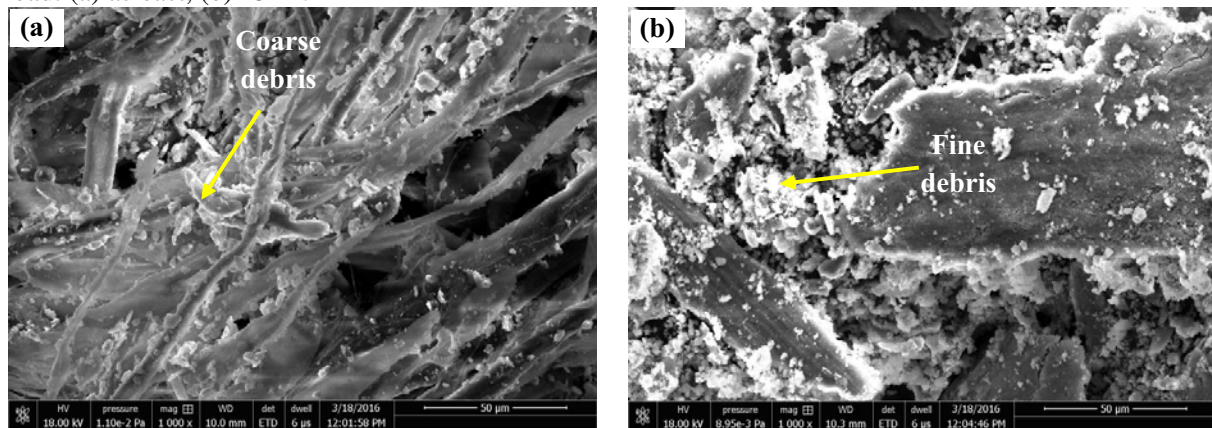

Figure 5.2. FESEM micrographs of worn debris of AZ91 magnesium alloy collected after wear test at 10N load: (a) as-cast, (b) 15Hz.

4. Conclusions

- The wear resistance of vibrated AZ91 Mg alloys increased with decrease in grain size. This was attributed to the fact that due to finer grains, grain boundary strengthening took place.
- The results commended that wear rate of AZ91 magnesium alloy considerably get affected by frictional heat that is been generated by the relative motion between AZ91 magnesium alloy and EN31 steel surface.
- It is observed that no single mechanism of wear is responsible for material loss.
- Debris generated from pin surfaces without imposing vibrations was larger in comparison to respective vibration imposed samples.
- Finer grain size and equiaxed grain shape both are important parameters for better wear resistance in AZ91 Mg alloys.

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