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Role of silicon on the tribological performance of Al-based automotive alloys and the effect of used motor oil

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ABSTRACT

A wear test in a used motor oil sliding environment was performed on Al-based automotive alloys with Silicon doped in various levels. Where a pin-on-disc wear testing equipment was used at a normal pressure of 1.53 MPa and a sliding speed of 0.51 m/s, kept constant. For comparison of the wear performance, dry and fresh motor oil sliding environments were also considered. The results showed that as silicon content was increased in the alloys, the wear rate decreased up to the eutectic composition, followed by an increase for all the environments. It was mainly for higher levels of Si-rich intermetallic Mg_2Si precipitates in the α-aluminum matrix and made the alloys' strength superior, in addition to increased wear resistance. In the post eutectic composition, primary silicon particles which are coarse and polyhedral appeared weakening the matrix. The coefficient of friction also decreased because of the higher hardness and the Si particles' employment as solid lubricants. In a dry environment, the wear rate and friction coefficient were much greater for their direct contact but lower under motor oil due to the reduced roughness caused by the sealing effects of the contact surfaces. Conversely, in oil environment, the opposite phenomenon was observed where coefficient of friction was incased with Si level to the alloy because the oil formed a thin film working as a lubricant between the contact surfaces which controlled the wear properties. Used oil demonstrates some degree of higher wear rate along with friction coefficient due to heavy and harmful chemical compounds in it. Examined by optical microscopy and SEM analysis, worn surfaces have shown that Si added alloy improved wear resistance through mild and smooth abrasive grooves filled with oxides in dry sliding conditions. In case of oil sliding environment smooth surfaces are created by the resistance of the oil film to the direct contact between the surfaces.

Keywords: automotive Al-Si alloy; wear; friction; motor oil; microstructure

1. Introduction

In the late 1950s, the use of aluminium-silicon alloys began to manufacture automobile components like cylinder blocks, cylinder heads, pistons and valve lifters etc. Aluminium having a density around of one third of steel and less dense Si addition not only improves the different properties but also reduces the weight more [1–3]. The Si addition makes the alloy of good strength, corrosion resistant, increased fluidity and free from hot shortness. Furthermore, the hard phase of Si contributes to transform the alloy into a highly wear resistant one [4, 5]. Combining with other elements, the Si particles upgrade the strength and make the alloys heat treatable. The distribution of the Si particles throughout the alloy matrix and the shapes of them affects the tribological properites of Al-Si alloys. These properties are also influenced by other alloying elements such as Fe, Cu, Mg, Ni, Zn along with a appropriate heat treatment process [6–9]. Wear is a major and common complication in automobile sector and the price of this abnormal wear is not very low. Therefore, many attempts are being taken for minimizing the adverse effect of wear by following some techniques and producing more durable material [10, 11]. Using lightweight Al-Si based automotive alloys instead of cast iron in engine components leads to increase in efficiency by saving fuel. Again engine oil is used for lubricating the moving parts of engine which reduces friction and wear. On the other hand, by removing pollutants, impurities, and additional torn parts from engine wear, it also functions as an anticorrosive, cooling, and cleaning agent [12]. Fresh motor oil has to receive various metallic particles and other compounds during operation. Among these intruded materials there are carbon, metal particles, road dust and burnt oil, and these do not separate from the oil easily [13]. The amount of these contaminants increases with running time. The used oil normally holds heavy metal content. The presence of these metals has crucially harmful effects for

Table 1. Experimental alloys chemical composition by wt%

	Si	Cu	Mg	Fe	Ni	Pb	Zn	Mn	Ti	Al
Alloy 1	0.244	2.158	0.767	0.211	0.199	0.163	0.076	0.065	0.005	Bal
Alloy 2	3.539	2.309	0.784	0.273	0.217	0.166	0.083	0.067	0.010	Bal
Alloy 3	6.149	2.113	0.754	0.301	0.264	0.163	0.111	0.073	0.012	Bal
Alloy 4	12.656	2.130	0.770	0.311	0.277	0.169	0.168	0.081	0.014	Bal
Alloy 5	17.851	2.190	0.755	0.321	0.281	0.167	0.198	0.097	0.021	Bal

not only human body but automotive parts also. Metal particles from additives such as phenols, chlorinated compounds, compounds of chlorine, zinc and phosphorus, polycyclic aromatic hydrocarbons etc are toxic and hazardous [14]. There are high percentages of zinc, lead, calcium magnesium, and barium along with lower percentages of iron, copper, sodium, aluminium, manganese, potassium, tin, nickel, silicon, boron, and molybdenum. The motor oil must be replaced continuously after a certain period for better performance of the vehicles as well as environment [15, 16].

More than a few researchers have studied the role of Si alloying elements on wear performance in the Al-based automotive alloys under different environments [17, 18]. On the other hand, incredibly limited work regarding tribological properties has been done under used engine oil. The present study reports the effect of different Si where other alloying elements remain constant into the Al-based automotive alloys on the wear behavior under used motor oil. A comparison also has been made on this property with dry sliding and fresh motor oil environment.

2. Materials and method

For studying the effect of used oil on the tribological wear properties of Al-based automotive alloy, the following five alloys were cast. The percentages of Si were varied at 0.2, 3.5, 6.1, 12.7 and 17.9 wt% while keeping 2.2 wt% Cu, 0.8 wt% Mg and 0.3 wt% Fe as constant. The chemical compositions of the developed alloys were analysed by spectrochemical methods as in Table 1.

For developing these alloys, highly pure aluminium, copper, magnesium and the Al–50%Si master alloy were melted in a graphite crucible using a natural gas-fired pit furnace. A suitable flux cover was used to avoid oxidation during melting. Casting was done at 700 ºC in a mild steel mould of 20 mm x 200 mm x 300 mm size preheated at 250 ºC. The cast alloys were kept in a muffle furnace at 450 °C for 12 hours for homogenization and for relieving internal stresses, the alloys were air cooled. Afterwards, the solution heat treatment of the alloys was carried out at 535 °C for 2 hours followed by salt water quenching for achieving a state of super saturated single phase. Samples of 14 mm length and 5 mm diameter were machined for using in a pin-on-disc wear apparatus. For reaching the peak-aged condition, the alloys were aged at 200 °C for 240 minutes [19–21]. An electric muffle furnace with a range of 900 ± 3.0 ºC was used. To get the representative hardness of a sample, Rockwell Hardness testing machine named Zwick hardness tester with 1/8th inch ball in B scale was used and an average of fifteen readings was taken. A pin-on-disc wear testing machine of ASTM Standard G99-05 was utilized to investigate the frictional and wear behavior of the Si-doped aluminium alloys [17]. The end surfaces of the pin samples were pressed against a horizontal rotating stainless steel disc during the tests. The hardness of the discs was around RC 95. The roughness of steel disc and pin surfaces was 0.40 µm and 0.11 µm respectively. A load of 30 N yielding nominal contact pressure of 1.53 MPa was used in the tests. The sliding speed was 0.51 ms^{-1} at 200 rpm with 923.2 m sliding distance on a track of 49 mm diameter. Each test was carried out in ambient condition at 22 °C and 70% humidity. Test was performed for at least nine times for each type of material. Firstly, the specimens were tested in dry sliding condition and then in fresh motor oil followed by in used motor oil environment chronologically. For both oil environments, at before the contact interface of the sample and the stainless steel counter plate, drip-type single point lubrication was maintained with a constant rate of discharge throughout the experiment. The SAE 20W-50 multigrade motor oil was used for the wear tests under engine oil environment. The motor oil of this grade contains 78 wt% base oil, 10% viscosity improvement additive and 3% detergent [22]. After a vehicle is run around 4950 km for six months, the same grade of oil was considered as the used oil. The weight loss measured (ΔW), the distance run (S.D.) and the normal load (L) applied on the surfaces of the samples were used to calculate the specific wear rates (S.W.R.). The sliding distances were determined by the track diameter and speed of rotation of the disc. For getting the coefficient of friction (µ), the load cell readings (F) were normalized by the applied normal load, L. The following equations are used for calculation the weight losses, specific wear rates and the coefficients of friction:

$$\Delta W = W_{initial} - W_{final} \qquad (1)$$

$$S.W.R. = \frac{\Delta W}{S.D. \times L} \qquad (2)$$

$$\mu = \frac{F}{L} \qquad (3)$$

Microstructural observations of the damaged surfaces were performed by using a USB digital microscope. The SEM analyses were conducted by using a JEOL scanning

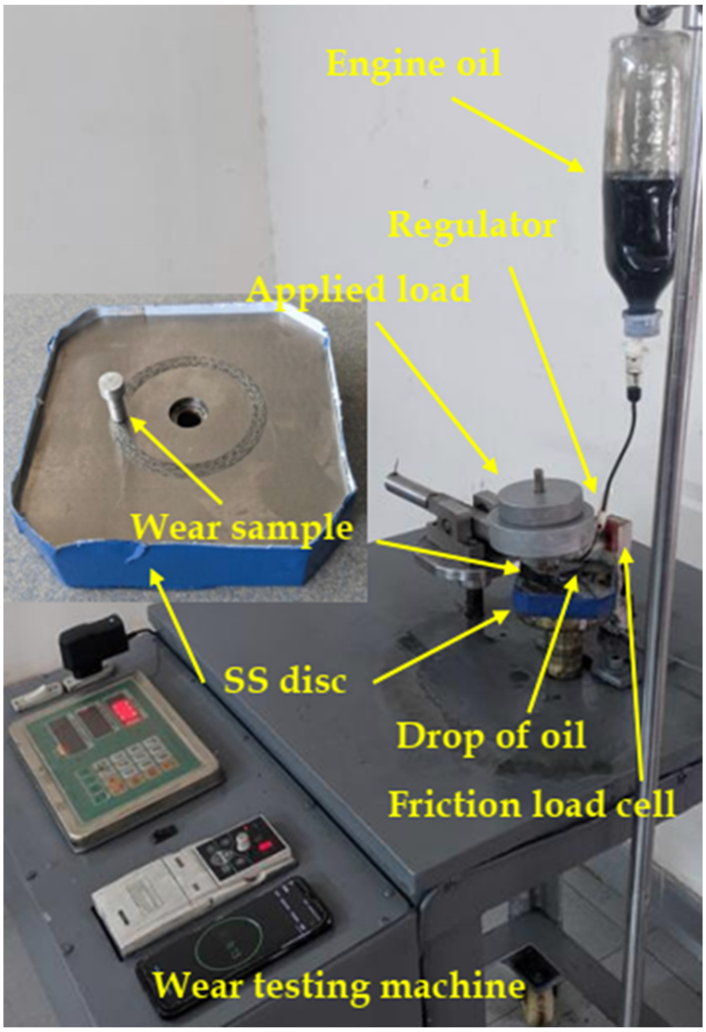

Figure 1. Photographs of wear testing machine along with the wear sample and stainless steel disc

electron microscope type of JSM-5200. The images of the experimental setup, prepared sample and counter body used are displayed in figure 1.

3. Result and discussion

3.1 Hardness

The experimental results associated with the Rockwell hardness of the aged Al-based automotive alloys are plotted in figure 2. It displays the increasing nature of hardness with the Si addition into the alloys. As discussed in the experimental section this type of alloys contain Si, Cu, Mg, Fe along with different impurities like Zn, Pb, Mn, Ni etc. So the aged samples contain different types of intermettalics but the common Al_2Cu, Al_2CuMg, Mg_2Si and Al_5FeSi phases are responsible for the higher hardness. Higher amount of Si into the alloys produces the Si-rich intermettalics in a greater amount resulting in the variation of the higher hardness [23].

3.2 Wear behavior

Figure 3 shows the effect of Si concentration on the

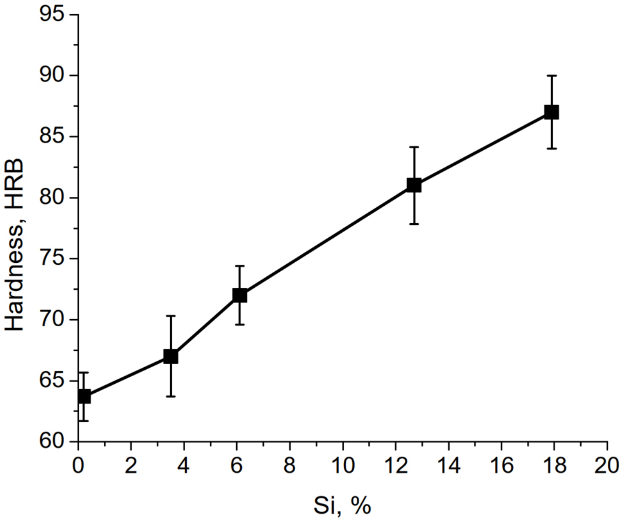

Figure 2. Variation of surface hardness with the Si concentration of Al-based automotive alloys

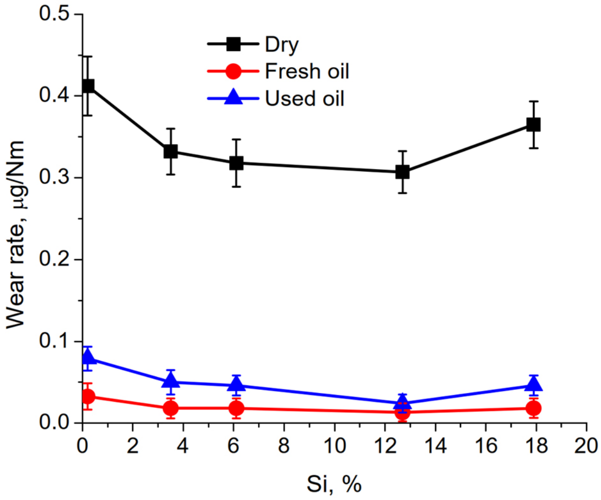

Figure 3. Variation of wear rate under dry, fresh and used motor oil environment with the Si concentration of Al-based automotive alloys.

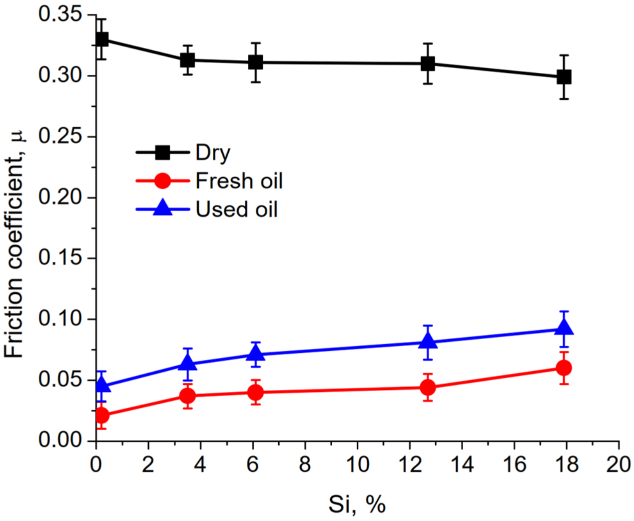

Figure 4. Variation of coefficient of friction under dry, fresh and used motor oil environment with the Si concentration of Al-based automotive alloys.

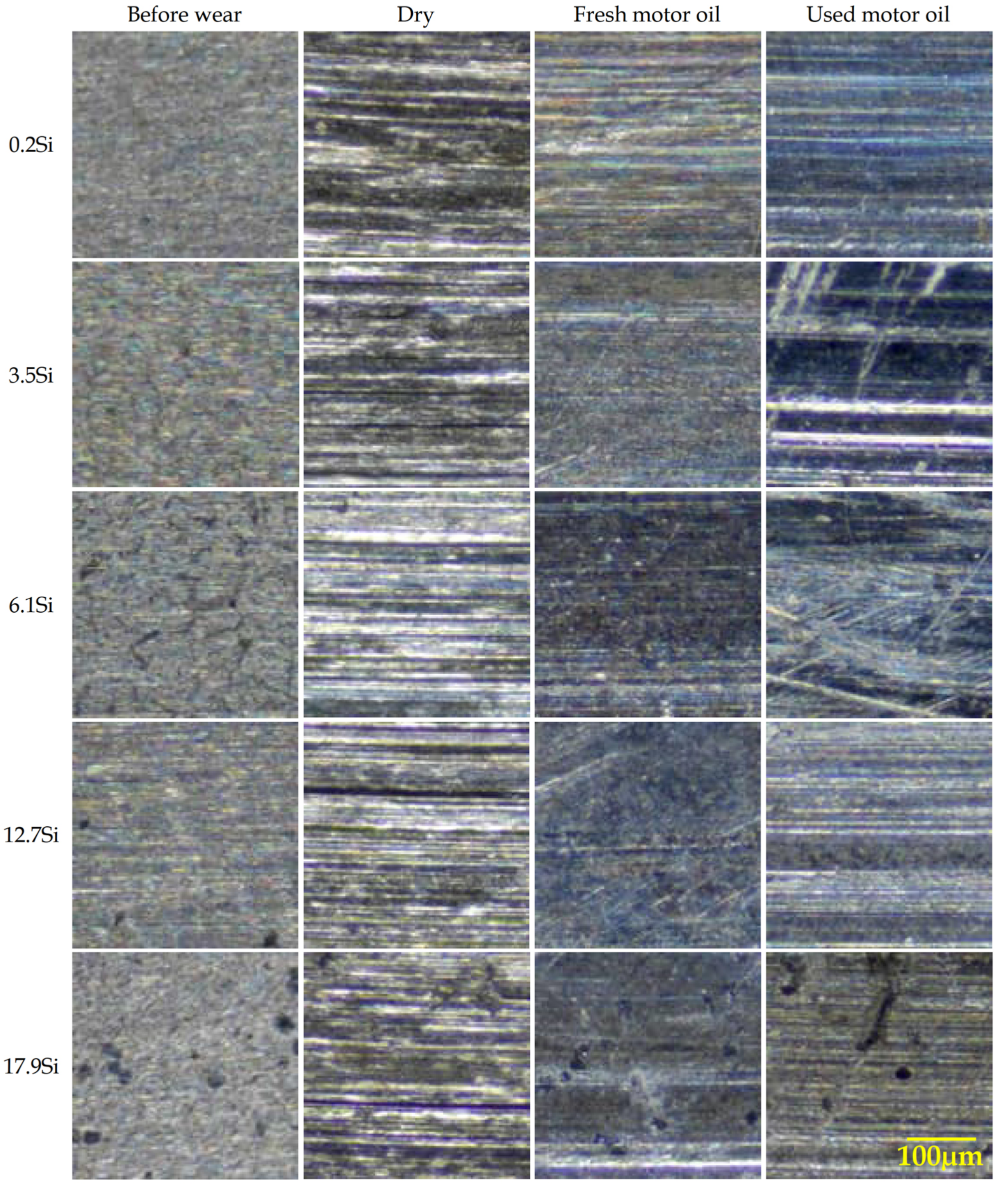

Figure 5. Optical micrographs of damaged surfaces of experimental alloys before and after wear for 923.2 m at applied pressure of 1.53 MPa and sliding velocity of 0.51 m/s under different sliding environments

wear rate of Al-based automotive alloys under different sliding environments like dry, fresh and used motor oil. The figure clearly reveals that wear rate for all the environments decreases with increase in Si content up to sudden eutectic composition of 12.7 wt% Si, after that the trend breaks. The intensity of wear rate is divergent in different environments. Due to ageing in the Al-based automotive alloys, submicroscopic precipitates of Mg_2Si and $AlCu_2$ is formed within the matrix through the presence of Cu and Mg. With the addition of Si, the primary aluminum phase which is soft and ductile and the silicon phase which is very hard and brittle are involved in eutectic reaction, offering better wear resistance of these alloys [24, 25].

In case of wear under lubrication with engine oil, it is apparent that the wear rate is remarkably reduced having the above trend which is, as the amount of Si increases the wear rate decreases. It is because of the thin film formed by the oil between the contact surfaces, which puts off the direct contact of the tribo-pair. So, the plastic and shear deformation and adhesion of the surfaces are significantly reduced, leading to reduction in the wear rate. The lubricant reduces the amount of three-body abrasion by removal of wear derivative and pollutants from the track [26–28]. In case of used oil, the wear rates are more than twice than the unused oil in similar trend with increase of Si. Used engine oils contain heavy metals and harmful chemical compounds that accumulate during exercise. These contaminants associated with additive breakdown products, burnt oil, and metal particles from engine wear, such as arsenic, lead, nickel and cadmium etc. Most of them are highly toxic in nature. Several elements are also present in used oils such as aluminium, copper, iron, magnesium, silicon and tin. These particles affect the wear

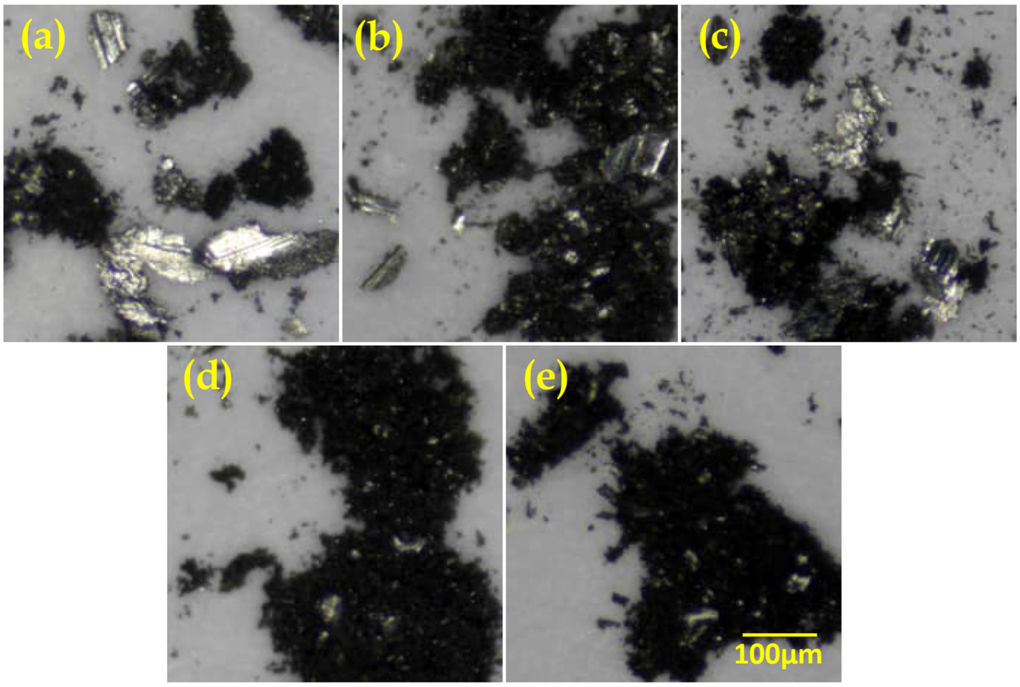

Figure 6. Optical micrographs of the wear debris under dry sliding condition (a) 0.2 wt% Si, (b) 3.5 wt% Si, (c) 6.1 wt% Si, (d) 12.7 wt% Si and (e) 17.9 wt% Si alloys

rate of the alloys. One visible thing is that wear decreases remarkably when the amount of Si increases into the alloy. That means the Si rich intermetallic has an effect to inhibit the wear rate [15]. Beyond the Si content 12.7 wt% Si, the trends of hardness and wear resistance, which are positively connected, are not followed by the hypereutectic alloy. At higher percentage of Si, there may be a primary Si particle pull-out, which may then lead to a three-body abrasive wear mechanism which results in higher wear rate through the damage of worn surface [26, 28, 29].

The variation of coefficient of friction with the percentage of Si in Al-based automotive alloys under above said environment is plotted in figure 4. The friction coefficients for all the Si added alloys under motor oil environment are much lower compared to dry sliding condition. There are direct contacts between two mating surfaces under dry sliding condition which controls the friction properties. On the other hand, an oil film is developed between the tribo-pair which reduces the roughness of the contact surfaces. Used engine oil shows the coefficient of friction some extent higher as discussed earlier, because the used oil contains different foreign constituent particles. During running the engine, the properties of the lubricating oil are affected by constant high pressure and temperature. So, the used oil loses its properties in terms of density, viscosity, corrosive properties, total acid number, cloud point, flash point etc. [30, 31]. The values of the friction coefficients under dry sliding condition decline with the concentration of Si into the alloys. It may be attributed that the Si particles are broken down into small fragments acting as a solid lubricant at between the surfaces. These fragmented particles bear most of the load under continuous sliding, making the friction coefficient lower for higher Si added alloys. The differing occurrence as increasing trend of friction coefficient is observed under both the oil sliding conditions. In this condition, the friction is controlled by the lubricating film and the Si particles get functionless in terms of frictional properties.

3.3 Optical micrographs

Figure 5 depicts the optical micrographs of the surfaces of the aluminium alloys with different percentages of Si before and after wear of 923.2 m sliding distance at applied pressure of 1.53 MPa and sliding velocity of 0.51 m/s under different environments. Highly polished surfaces of the alloys before wear show the smooth surface with no plastic deformation. Only scratches are observed due to polishing. Without etchant, this type of surface does not provide enough information like other typical microstructures. The typical microstructures of Al-Si automotive alloys consist the α-Al phase with different intermetallic particles distributed in intragranular and grain boundaries and with the eutectic phases are increased with the addition of Si. In the present case, microstructures display some different lighter and darker tones only which depend on the amount of various elements present into the alloys. However, the dark spots became more prominent for higher Si added alloy because of Si-rich intermettalics and the primary Si particles gathered into the Al matrix as seen in case of 17.9 wt% Si added alloys. [32].

It is observed from the figures of dry condition that narrow grooves and craters are developed on the damaged surfaces due to thermal softening of the alloy material. The thermal softening of alloys is initiated due to excessive

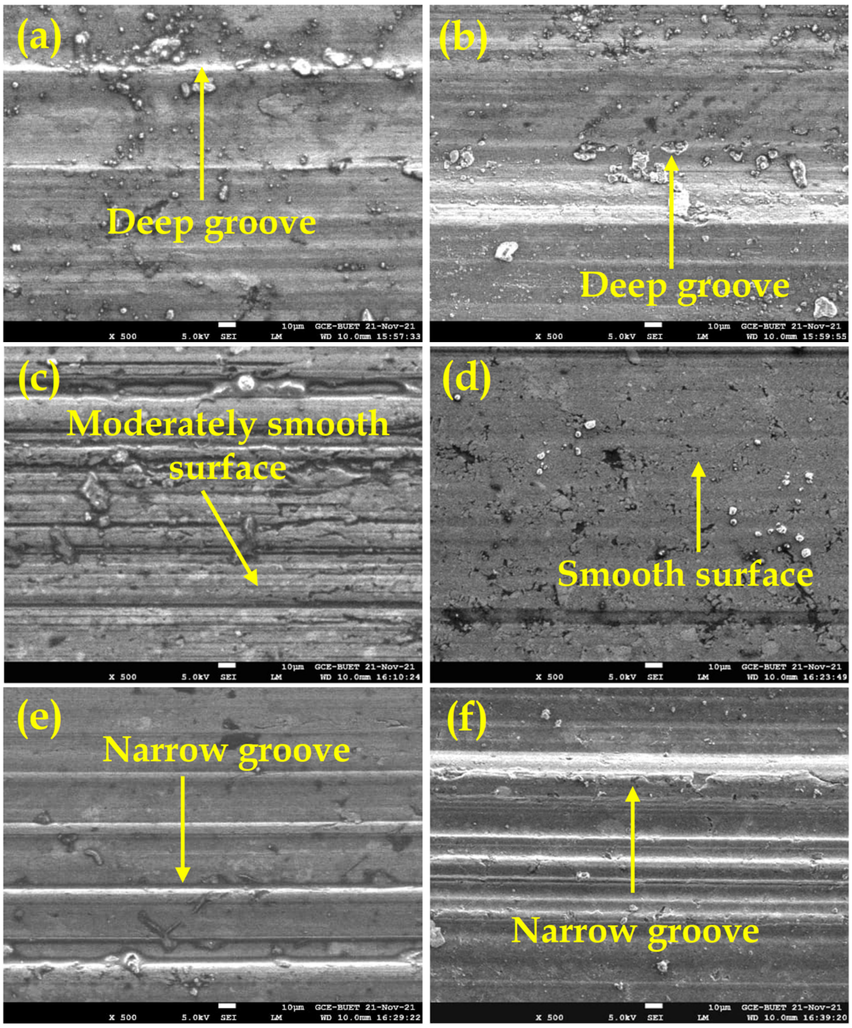

Figure 7. SEM images of the worn surfaces of the experimental alloys under dry (a) 0.2 wt% Si, (b) 12.7 wt% Si, fresh oil (c) 0.2 wt% Si, (d) 12.7 wt% Si and used oil (e) 0.2 wt% Si, (f) 12.7 wt% Si sliding environment for 923.2 m at applied pressure of 1.53 MPa and sliding velocity of 0.51 m/s

pressure and temperature and is time dependent. So it occurs more effectively if dry sliding is continued for prolonged period [33–35]. It is also noted that the wear marks on the worn surfaces decrease as the Si amount increases because of Si-rich phase specially Mg_2Si, to precipitate into the grain and increase the strength. Higher amount of this precipitates result in higher level of strength so reduction of wear marks. Hypereutectic alloy beyond 12.7 wt% Si, the shallow deep ploughing and grooves with high degree of delamination are visible. The higher level of primary Si into the matrix encourages the damage of worn surface through a three-body abrasive wear mechanism. When tested under fresh oil sliding environment, slight plastic deformation and micro-scuffing on the worn surface of the alloys are observed. There is also the presence of a smooth, complete, and dense tribo-film, which helped to lower the friction coefficient and wear rate of the specimen. However, under used oil condition, the shape of the wear groove is not regular in terms of width and depth which indicates that the lower quality could have influenced the discontinuous tribo-film. The figure also exhibits that the worn surfaces of higher Si added alloy specimens are relatively smooth because of accordingly hard and fine inermetallics are there [36].

The optical micrographs in Fig. 6 display the wear debris created from wear test of the experimental alloys under dry sliding condition. The wear debris of the alloys are granular and mixtures with some chips are created from the stainless-steel disc. The sizes and shapes of the wear debris along with stainless steel chips are dissimilar for the different alloys. The sizes and shapes of the stainless particles are relatively lower according to the Si contents in the alloys. Higher Si means the higher amount of fine precipitates into the alloys along with the refinement of grain structures. This affects the sizes of the counter body particles, as the grinding wheel produces the fine particles with fine grit of grinding wheel [37, 38]. From the figure it is clearly observed the highest size of chips is obtained by the 0.2 wt% Si alloy and lowest by the 17.9 wt% Si alloy.

3.4 Scanning Electron Microscopy

SEM microphotographs of the 0.2 wt% Si and 12.7 wt% Si added automotive alloys after wear for 923.2 m under dry, fresh and used motor oil environment are presented in figure 7 where the applied pressure of 1.53 MPa and the sliding velocity of 0.51 m/s were used. It clearly suggests for dry sliding condition abrasive wear in base alloy revealing the scratches are most prominent with random crevices and deep marks spread throughout (Figure 7a). However, the addition of 12.7 wt% Si to the automotive alloy has resulted in improved wear resistance, which can be seen through small cracks with grooves and dislodging of material clearly indicating combination of mild abrasive grooves and smooth abrasive grooves filled with oxides. Higher level of different Si-rich intermetallics, as particles of higher strength resists the removal of material from the surface (Figure 7b). On the worn surface shown under fresh engine oil environment, the continuous and uniform lubricating films can largely restrict the plowing effect and preserve the materials from serious abrasion. As a result, smooth surfaces are reflected (Figures 7c and d). It is well known that the used engine oil contains different harmful metal particles highly toxic in nature, which have influenced the tribo-film. It also oscillates the friction force, as a result, wear groove is not so smooth and uniform (Figures 7e and f). The higher Si added alloys under oil environment display the better smooth surfaces because of the fine precipitates into the alloy especially Mg2Si particles resist the wear from different harmful environments [24, 39].

4. Conclusion

A comparison of the influence of fresh and used motor oil on the tribological behavior was studied and based on the experiments and characterization, the following conclusions may be drawn:

Higher Si added alloys achieved the higher hardness due to formation of different Si-rich intermetallics resulting in improvement of the wear properties of the Al-based automotive alloys. Beyond the eutectic composition of Si, the higher amount of primacy Si formed into the alloy weakens the matrix strength, thus increasing the wear rate.

The wear rate is higher for dry sliding condition but lower for motor oil environment, since oil film put off the direct contact of the tribo-pair. In case of used oil the wear rate increases some extend as the quality of the oil deteriorated by foreign harmful particles.

The coefficient of friction in dry environment is much greater because there are direct contacts and under motor oil environment this friction is reduced by the sealing effect, which reduces the roughness of the contact surfaces. Some variation is observed due to higher density and foreign particle into the used oil.

The coefficient of friction decreases with the Si addition in dry sliding condition as Si particles are deformed into small fragments and act as a solid lubricant at the boundary. Under engine oil condition the thin film along with the wear particles control the friction behavior where the Si particles lose their effectiveness.

Worn surfaces in dry sliding condition are found higher abrasive wear and plastic deformation due to thermal softening of the material during wear. Under oil sliding condition, a smooth surface is observed which acts as a lubrication film and stay away from direct contact on the moveable surfaces. Harmful foreign particles into the used oil play unenthusiastic role on the surface. Higher Si added alloys contain the superior intermetallics due to ageing which is responsible for such smooth worn surfaces.

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