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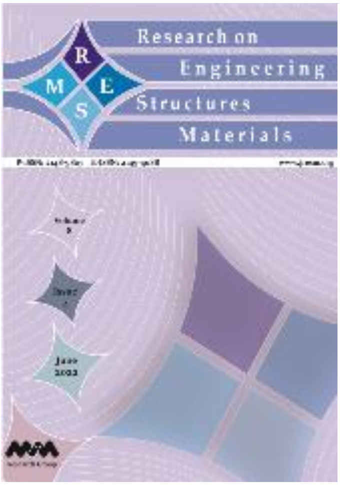

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Research Article

Wear studies on Al-Si automotive alloy under dry, fresh and used engine oil sliding environments

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Abstract

A comparative study has been made on the wear behavior of eutectic Al-Si automotive alloy under a dry, fresh and used engine oil sliding environment. The wear tests have been conducted using a standard pin-on-disc apparatus. The results show that with silicon content, the wear loss decreases up to the eutectic composition, mainly for an increase in strength through Si-rich intermetallics. Therefore the lower wear rate along with the coefficient of friction is observed under dry sliding environment. Under the engine oil environment, the lubricating film controls the wear, so the results are the lowest wear rate and coefficient of friction. Used oil shows both wear rate and friction coefficient to some extent higher due to the presence of heavy and harmful chemical compounds. Wear test surfaces are examined by optical and SEM analysis and found that higher abrasive wear and plastic deformation on the worn surfaces are created in dry sliding condition as well as lower Si added alloy. On the worn surface under engine oil lubricating condition, smooth surface morphology is observed as form a lubrication film and thumbs down any direct contact on the moveable surfaces. Higher Si-added alloys contain superior fine intermetallics due to ageing, which is responsible for such smooth worn surfaces.

1. Introduction

Aluminum alloys are widely used in transportation and other industries because they offer different useful properties like improved wear and corrosion resistance, good castability and a better combination of mechanical properties [1-3]. Among the various cast aluminum alloys known, Al-Si alloys have been well considered for these applications, mainly in automobile industries, e.g. cylinder heads, engine blocks, pistons, bearings etc. When Si is alloyed as the major elemental, it belongs to the 4xxx series of aluminum alloys. This series of alloys can be hypo-eutectic, eutectic, or hyper-eutectic, depending on the concentration of Si in it. The Al-Si alloy with 12.6 wt% Si is eutectic. The alloy is hypo-eutectic and hyper-eutectic if the concentration of Si is lower and higher than the eutectic composition, respectively [4, 5]. It has been previously studied and found that a certain amount of Si in automotive alloys enhances the strength to meet the required demand. Therefore, hypoeutectic Al-Si alloys can be used in light applications, and eutectic alloys have moderate automotive applications. On the other hand, hyper-eutectic alloys are used for heavy structures [6]. Al-Si alloys are also used in the aviation industry. Saracyakupoglu et al [7, 8] conducted wear-based fractographic investigations on aviation-grade parts. In these studies, it was shown that Al-Si alloy-based aviation-grade parts are commonly used while there are fatigue possibilities depending on the

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working conditions of the aircraft. It is well established that Al-Si alloys are the most important alloys in terms of wear properties and improve with the concentration of Si in the alloys [9]. Wear is one of the most commonly encountered problems in industries, necessitating the replacement of mechanical components that are required but unserviceable. Although the consequences of wear are rarely catastrophic, it significantly reduces operating efficiency and brings about increased power losses [10]. For enhancement of the strength, other alloying elements such as Fe, Ni, Cu, Mg etc. are added to Al-Si alloys [11]. However, in most cases, Cu and Mg have been considered alloying elements for the reason that the strength of the alloys accelerates through heat treatment. Eutectic or near eutectic Al-Si alloys form needle or plate-like silicon particles [12-14]. On the other hand, hyper-eutectic alloys form silicon particles as large cuboids, which control the strength and fracture behavior of the alloys [15-17]. Alloying elements play a vital role in the structure of these alloys. It includes type of bonding, atomic or molecular arrangements, microstructure etc. [18-20].

The lubrication method is normally employed to reduce the wear and friction for two or more moving surfaces. Engine oil as a lubricant helps to reduce wear by creating a lubricating film between two moving mating parts, therefore, decreasing the contact between them. Due to the prolonged use of engine oil, it loses lots of its quality, as dust, combustion byproducts, blow-by gases or worn or corroded particles get mixed with it. Among the foreign materials, there are carbon, metal particles, road dust and burnt oil, and these do not separate from the oil easily [21]. So the quality of used oil has a significant role in the performance and long life of an engine. That is why the engine oil must be changed on regular basis [22, 23].

Nevertheless, there is no sufficient report regarding the influence of Si on friction and wear behavior of Al-Si alloy automotive alloys under fresh and used engine oil conditions. The primary purpose of this study is to analyze the wear performance of the automotive Al-Si alloys for different concentrations of Si under a dry sliding environment while keeping the percentages of other prime elements fixed. As there is lubricating motor oil flowing between the machine parts in engines, wear study under engine oil environment is of great interest. Again, as many particles are intruded into the engine oil after prolonged use, properties of oil like viscosity, thermal stability, oxygen stability etc. are changed, which may have a substantial effect on the wear behavior of automotive alloys. Hence, an additional investigation has been made for the best performed Al-Si alloy on the wear behavior in fresh engine oil and in the same graded oil collected from a vehicle after running for around 5000 km.

2. Materials and Methods

The intention was to add different levels of Si into the automotive alloys while keeping the other alloying elements such as Cu, Mg and Fe constant. The chemical composition analyzed by spectrochemical methods after melting is shown in the following Table 1.

Table 1. Chemical composition by wt% of the experimental alloys

	Si	Cu	Mg	Fe	Ni	Al
Alloy 1	0.244	2.158	0.767	0.211	0.199	Balance
Alloy 2	3.539	2.309	0.784	0.273	0.217	Balance
Alloy 3	6.149	2.113	0.754	0.301	0.264	Balance
Alloy 4	12.656	2.130	0.770	0.311	0.277	Balance
Alloy 5	17.851	2.190	0.755	0.321	0.281	Balance

For developing these alloys, aluminum (Al99.750), copper (Cu99.997), magnesium (Mg99.80) and the master alloy of Al–50%Si alloys 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 °C in a mild steel mould of 20 mm x 200 mm x 300 mm size, which was preheated at 250 °C. The cast alloys were homogenized at 450 °C for 12 hours, and the samples were solutionized at 535 °C for 2 hours, followed by salt water quenching using an electric muffle furnace. The sample of 14 mm in length and 5 mm in diameter were machined from the experimental alloys for wear study. The samples were aged at 200 °C for 240 minutes to attend the peak aged condition [24, 25]. Alloy densities were considered from the chemical composition. The hardness of the aged samples was measured using a Rockwell Hardness testing machine where a 1/8th inch ball in the B scale was used. Tensile testing was carried out according to ASTM specification at room temperature in an Instron testing machine at the strain rate of 10^{-3} s^{-1}.

The frictional and wear behavior of the aluminum alloys were investigated in a pin-on-disc type wear apparatus by the following ASTM standard G99-05 [26]. The 309s stainless steel disc was used as the counter surface material having hardness and roughness around HRB 95 and 40 μm, respectively. A load of 20 N was used for all the samples in the dry sliding condition, where the calculated contact pressure was active at 1.02 MPa. Moreover, the load was incremented from 5 to 50 N in other experiments. During the test, the disc was rotated at 200 rpm on a track of 49 mm diameter at the sliding speed of 0.51 ms^{-1} with variable sliding distances ranging from 154 m to 2770 m. All the tests were carried out in ambient conditions at 22 °C and 70% humidity. At least five tests were completed for every material. The specimens were first subjected to dry sliding conditions and then chronologically to the fresh engine oil and used engine oil. For both the oil environments, drip-type single-point lubrication at the contact interface of the sample and the stainless steel counter plate was maintained with a constant rate of discharge throughout the experiment. The multigrade motor oil 20W-50 was considered for wear test under a lubricant environment. This type of engine oil contains 78 wt% base oil, 10% viscosity improvement additive and 3% detergent [27].

The engine oil of the same grade was collected from an automobile after 6 months of running 4950 km and was considered as used oil. The wear rate was calculated from the measured weight loss (ΔW), the distance run during the test ($S.D.$), and the normal load (L) applied to the samples [10]. The sliding distances were calculated from the track diameter and speed of rotation of the disc. The reading from the load cell (F) was normalized by the applied normal load, L, to determine the coefficient of friction (μ). The mathematical relations to obtain the weight loss, specific wear rate ($S.W.R.$) and the coefficient of friction are expressed by the following equations:

$$\Delta W = W_{initial} - W_{final} \tag{1}$$

$$S.W.R. = \frac{\Delta W}{S.D. \times L} \tag{2}$$

$$\mu = \frac{F}{L} \tag{3}$$

Microstructural observation of the worn specimen surfaces and wear debris from the test were done by using USB digital microscope. The SEM analyses were conducted by using a JEOL scanning electron microscope type of JSM-5200. Some photographs of the prepared sample, counter disc and the experimental setup are shown in Fig. 1.

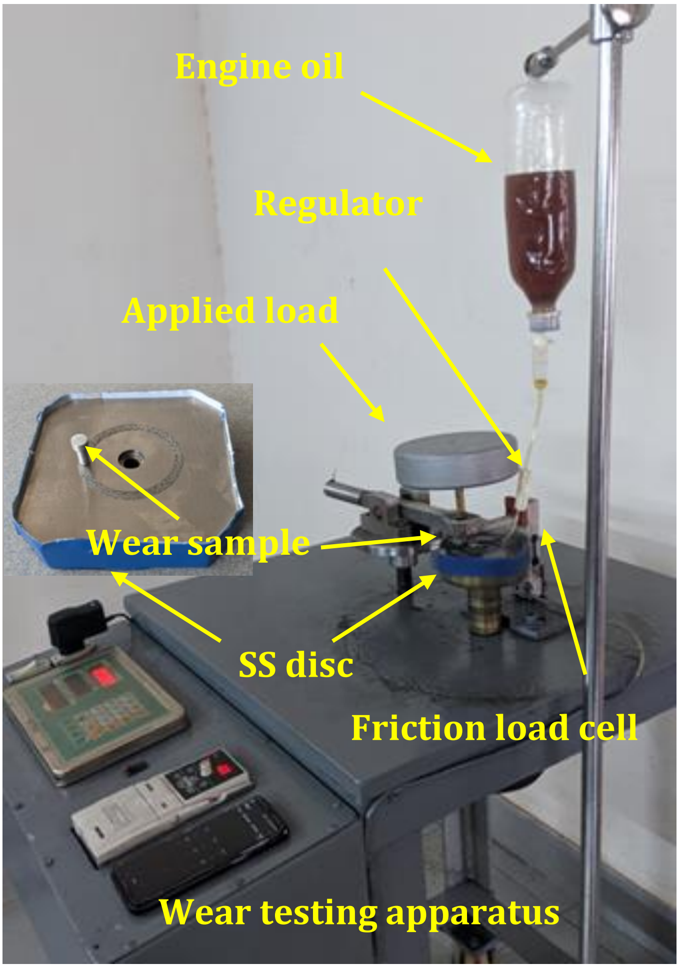

Fig. 1 Photographs of wear testing machine setup with wear sample and friction disc

3. Results and Discussion

3.1. Physical and Mechanical Properties

Figs. 2 to 5 show the different physical and mechanical properties such as density, hardness, tensile strength and elongation of different Si-added automotive alloys, respectively. From the chart, it is observed that density decreases with the addition of Si (Fig. 2). It is known that the density of Si is 2.329 gm/cm^3, which is lower than that of Al, 2.7 gm/cm^3. The percentages of the other elements in the alloys are more or less constant except Si and Al [28]. So, the higher levels of Si make the alloy lighter.

Similarly, the figure associated with the Rockwell hardness displays the opposite nature of density (Fig. 3), where the hardness of the aged alloys increases with the concentration of Si percentages into the alloys. The aged samples contain different types of intermetallics but Al_2Cu, Al_2CuMg, Mg_2Si and Al_5FeSi phases are common which are responsible for the higher hardness. Higher amount of Si into the alloys produces higher amount of Si-rich intermetallics, resulting in higher hardness [24, 29].

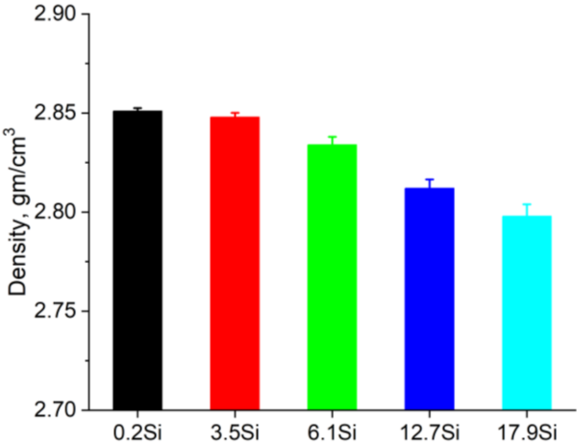

Fig. 2 Variation of density of the experimental alloys

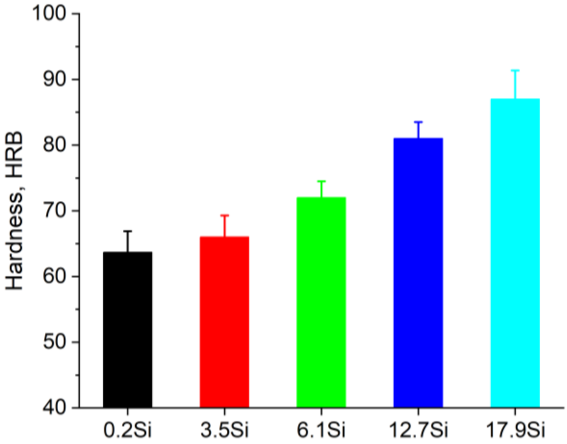

Fig. 3 Variation of hardness of the experimental alloys

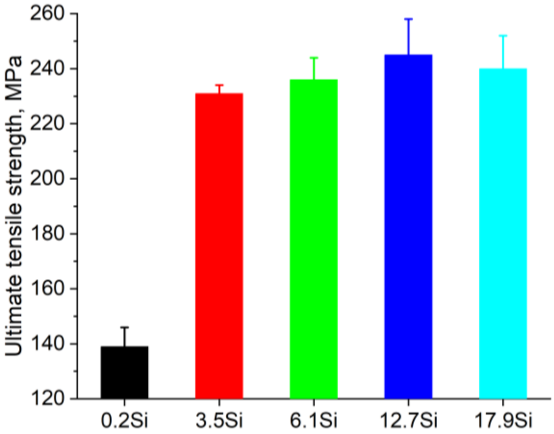

Fig. 4 Variation of ultimate tensile strength of the experimental alloys

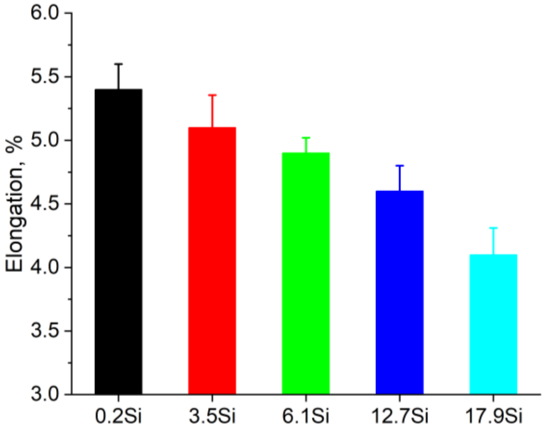

Fig. 5 Variation of % elongation of the experimental alloys

It is seen from Fig. 4 that Si addition into the aged alloys increases the tensile strength up to the eutectic composition of the alloys. During ageing, it forms the intermetallic hardening phase Mg_2Si, in addition to Al_2Cu, which precipitates in the α-aluminum matrix and increases the tensile strength. Higher levels of Mg_2Si precipitates in higher Si added alloys make strength of the alloy superior [30]. However, when the primary silicon appears as coarse polyhedral particles, the strength properties decrease with increasing silicon content [31].

The figure of percentages elongation confirmed that Si has an impact showing the reduction of this property (Fig. 5). The rate of ductility minimizing with the Si content is easily understandable. Higher Si means the density of fine precipitates are maximum into the alloy, which makes the alloys brittle resulting in lower elongation [32]. Another cause of lower elongation is, higher amount of Si stays slackly into the alloy's matrix [20, 33].

3.2. Wear Behavior

The weight losses, as a function of sliding distance for all the alloys at a constant pressure of 20 N or 1.02 MPa and velocity of 0.51 m/s under dry sliding conditions is shown in Fig. 6. The weight loss of the alloys increases with sliding distance, but higher Si added alloys show lower weight loss compared to the other lower Si added alloys. But the hyper-eutectic 17.9Si added alloy shows some deviation. During wear test, with increasing the sliding distance, the duration of contact between the rotating disc and sample surface also increased, resulting in further weight loss. Present results on the general wear loss behavior of aluminum alloys agree to some extent with the previous study [10]. These types of alloys consist of different particles like Al, Si, Cu, Mg, and Fe elements. Due to solution treatment and ageing, it forms different intermetallics into the Al matrix. It should be stated that especially formation of the Mg_2Si phase improved the friction and wear properties of the alloys. Higher Si addition means a higher level of Mg_2Si phase is formed, which inhibits weight loss. The obtained results are supported by the hardness values in Fig. 3. It is revealed that the Al-Si alloy with Si content beyond the eutectic composition 12.7Si has the primary Si particles. During the test, increased amount of Si may have a tendency to pull out, which could eventually result in a three-body abrasive wear process [34-36]. It means that, the fractured primary Si particles promote worn surface damage and act as third-body abrasives [37]. So the conventional casting and heat treatment of this type of the eutectic Al-Si automotive alloy offers the best wear properties, and beyond eutectic composition there is deterioration of wear property.

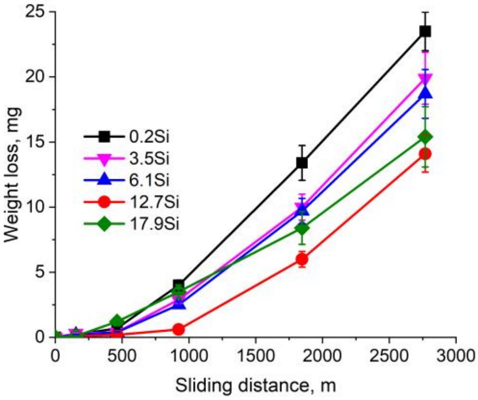

Fig. 6 Variation of the weight loss with sliding distance in dry sliding environment

The influence of sliding distance on the wear rate of 0.2Si and 12.7Si added automotive alloys under dry, fresh and used engine oil sliding environment is shown in Figs. 7 to 9 respectively. Figure 7 clearly reveals that under the dry sliding condition, as distance increases, wear rate increases in both alloys. The increase in wear rate can be attributed to frictional heat and softening of materials as prolonged intimate contact between the two mating surfaces [38]. The thermal softening of alloys is initiated due to excessive pressure and temperature and is time-dependent. So it occurs more effectively if dry sliding is continued for a prolonged period [39-41]. However, the automotive alloy with higher Si addition has shown relatively better wear resistance when compared to 0.2Si alloy. Probably, the addition of Si has resulted in microstructural modifications which contribute to an increase in hardness and strength of the base alloy, thereby reducing the surface damage and thereby increasing wear resistance. Furthermore, during wear tests, the generation of an intermediate oxide layer between mating surfaces is also one of the probable reasons for increased wear resistance. The additional amount of Si forms Mg_2Si phases with the Mg particles present in the alloys. When the alloy surface gets into contact with air, Mg_2Si further forms MgO and SiO_2 layers [42, 43]. In addition, the fine and uniformly distributed Si phase usually enhances passivation on edges during friction and can reduce the stress concentration, thereby increasing the strength between the Si and the matrix and improving the wear resistance [36].

The wear rate of the alloys drastically decreases under engine oil sliding environment. Under dry sliding condition, there are direct contacts between two mating surfaces which dominate the properties, as a result, higher loss of materials. When the materials go under engine oil environment, the material removed through the wear to a certain extent take over on the lubricating film [44]. In case of wear under fresh and used engine oil sliding environment, the graphs show the opposite phenomenon where wear rate decreases with the sliding distance (Figs. 8 and 9). It is because engine oil slows down the heat generation moreover preventing the softening of contact materials. In both environments, the higher 12.7Si alloy shows better wear performance since its higher strength. In the case of wear in used oil, both alloys show an inferior property in terms of wear rate. The used engine oil contains several metal particles, combustion by-products and gases, worn particles, so loses its quality. Foreign particles are highly toxic along with the corrosive products, which affects the wear rate of the alloys resulting in higher wear rate [21]. Early obsession noted that 12.7Si added alloy shows relatively lower wear rate as Si-rich intermetallics inhibit the wear in such environment [10].

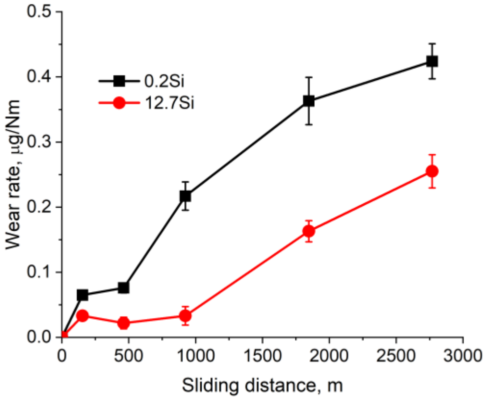

Fig. 7 Variation of wear rate with sliding distance in dry sliding environment

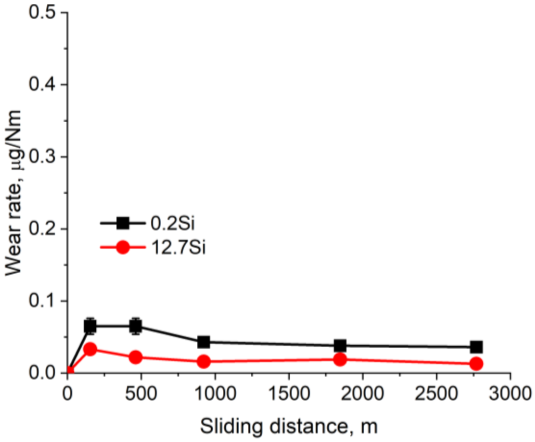

Fig. 8 Variation of wear rate with sliding distance in fresh oil sliding environment

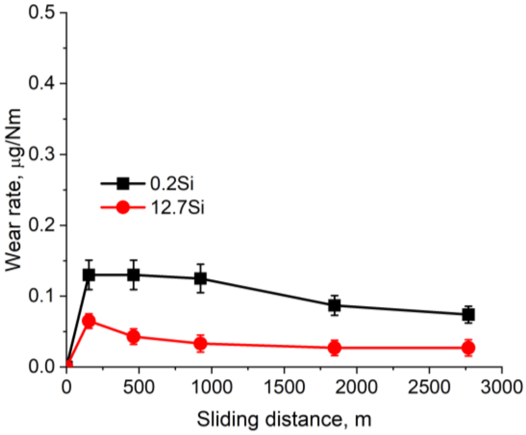

Fig. 9 Variation of wear rate with sliding distance in used oil sliding environment

Influences on the frictional force at different sliding distances for the 0.2Si and 12.7Si automotive alloys under the above-said sliding environments are represented in Figs. 10

to 12. It clearly reflects that the frictional coefficient of both alloys fluctuates at the lower sliding distances at a constant pressure of 1.02 MPa and at a constant sliding speed of 0.51 m/s. As initially, the surfaces in contact are comparatively rougher, the coefficient of friction is not steady in the beginning. However, the frictional coefficient is relatively lower for 12.7Si added alloy than that of 0.2Si alloy. A decrease in frictional force can be attributed to better hardness and strength, as the low plastic deformation of the alloy at real contact areas may lead to a lack of friction coefficient [45]. It is also due to the creation of an intermediate oxide-rich layer between mating surfaces which acts as a solid lubricant [46]. At the initial stage, the friction coefficient of the sample increases to a peak value, followed by a gradual steady-state value. The increased coefficient of friction is attributed to a localized adhering of the worn debris to the Al surface, as reported in previous investigations [37].

The coefficient of friction for both alloys in the engine oil environment is much lower than under dry conditions. It is because an oil film is developed between the tribo-pair, which reduces the roughness of the contact surfaces. In the used engine oil environment, there is some additional friction coefficient as some foreign particles are there. Foreign particles like worn-out metal, carbon, road dust etc. hinder relative motion. It also rapidly attains a steady state while establishing the lubricating mechanism. In the case of wear under engine oil environment, the scenario of the coefficient of friction is changed, where 12.7Si added alloy attains the higher coefficient of friction. In this condition, the friction is controlled by the lubricating film leading to the lower value of 0.2Si alloy. Under these circumstances, the Si particles lose their role of frictional properties. The film produced by the used oil makes the higher coefficient of friction [44, 47].

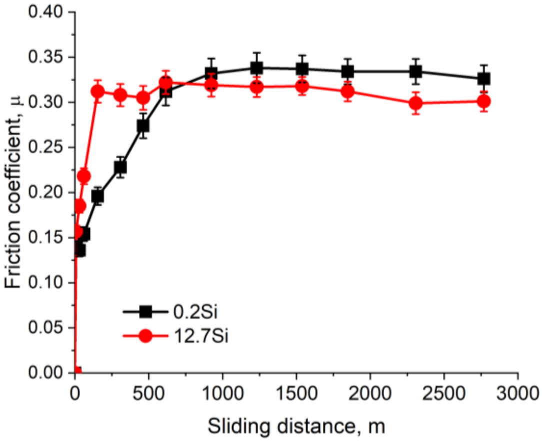

Fig. 10 Variation of coefficient of friction with sliding distance in dry sliding environment

Fig. 13 shows the deviation in the coefficient of friction for both alloys during dry sliding under different loads. Such a reduction in friction coefficient may be associated with the development of oxide layers. The increase in temperature between the disc and pin surfaces due to increasing load acts as the driving force for oxidation increase. Apart from Si particles are deformed into tiny fragments and act as a solid lubricant at the interface. These deformed particles carry the majority of the applied load under incessant sliding, so there is an inferior coefficient of friction [48].

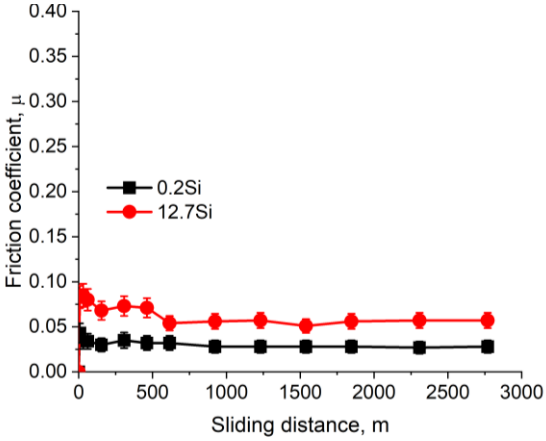

Fig. 11 Variation of coefficient of friction with sliding distance in fresh engine oil sliding environment

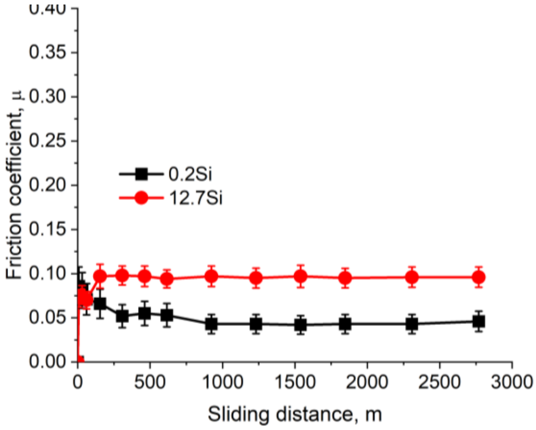

Fig. 12 Variation of coefficient of friction with sliding distance in used engine oil sliding environment

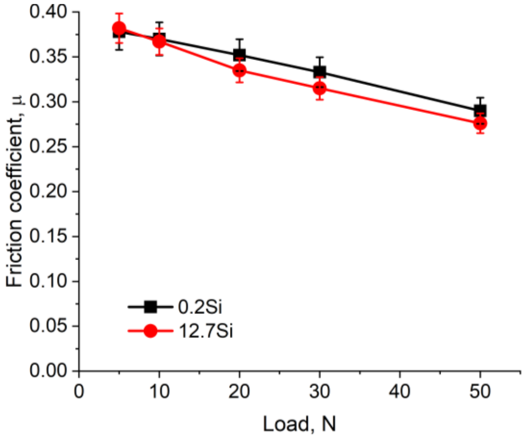

Fig. 13 Variation of friction coefficient with applied load in the dry sliding environment

Again, under the engine oil environment, opposite scenario is observed as the increasing trend of coefficient of friction with a normal load. These related graphs are shown in Figs. 14 and 15. This phenomenon occurred because the increased amount of worn-out particles from the counter body are mixed with the engine oil continuously, changing the oil film between the tribo-pair, in case of alloys with higher Si content. The harder surface of the alloys with higher Si wears away material from the counter surface. As a result, there is a continuous increase in the coefficient of friction with the load. This tendency goes up as the used oil already contains a number of heavy particles and additional components from engine wear. It is already discussed earlier regarding the quality of used engine oil.

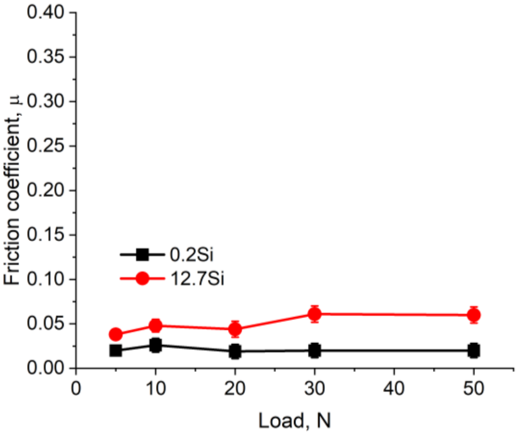

Fig. 14 Variation of friction coefficient with applied load in fresh engine oil sliding environment

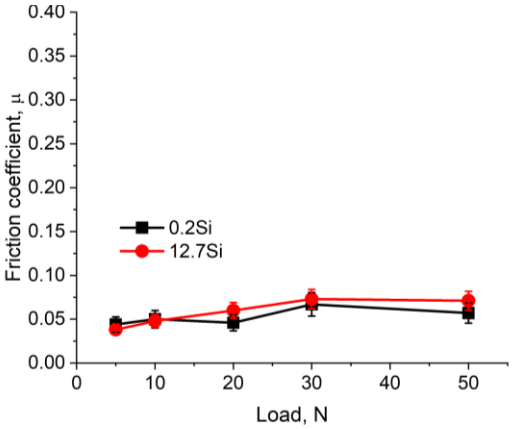

Fig. 15 Variation of friction coefficient with applied load in used engine oil sliding environment

3.3. Optical microscopy

The optical images presented in Fig. 16 are of the worn surfaces of 0.2Si, and 12.7Si added automotive alloys before and after wear for 2770 m at applied pressure of 1.02 MPa and sliding velocity of 0.51 m/s under dry, fresh and used engine oil sliding condition.

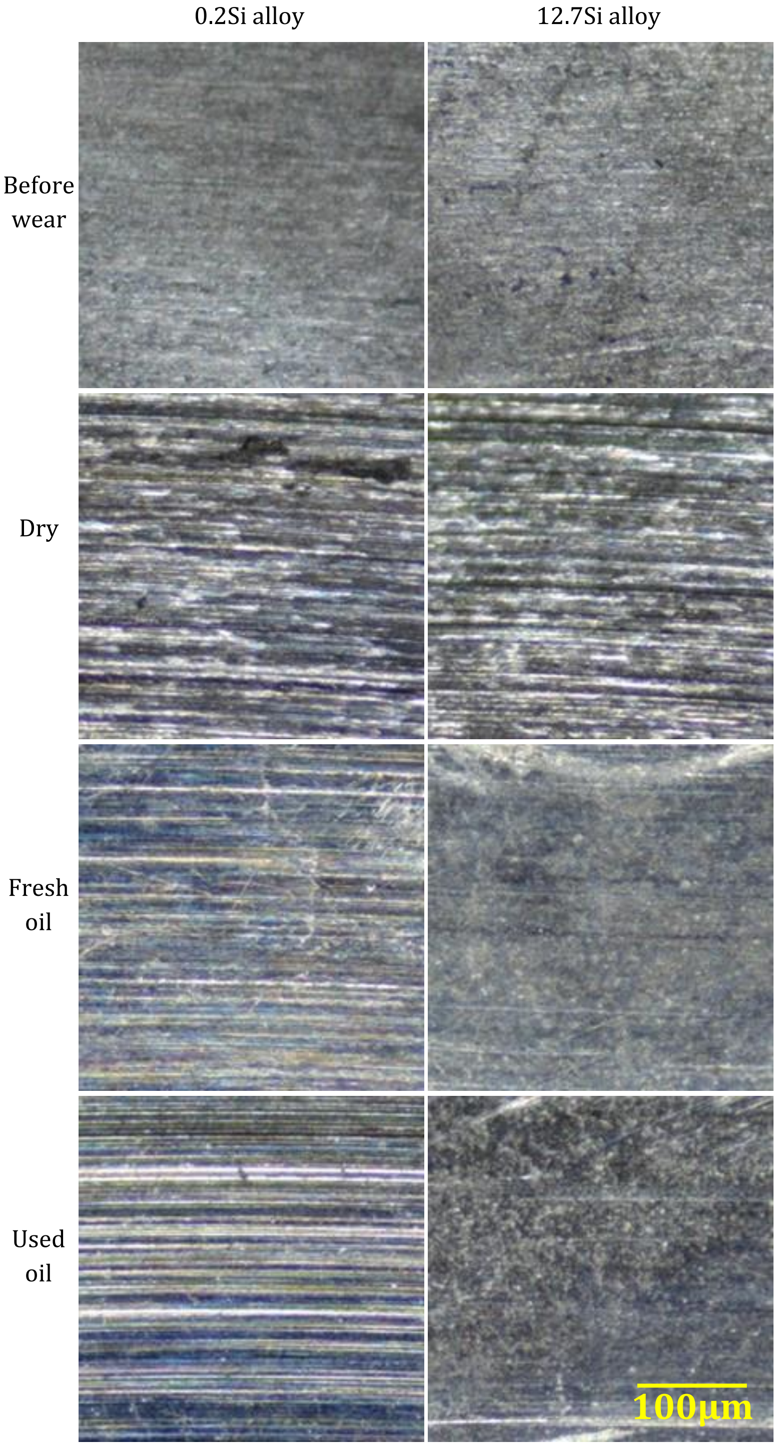

Fig. 16 Optical micrograph of polished surfaces of experimental alloys before and after wear in dry, fresh and used engine oil sliding environment for 2770 m at applied pressure of 1.02 MPa

Before wear, both the alloys display smooth and no evidence of plastically deformation surfaces. Without etching, the polished microstructure does not offer available information. However, this type of alloy consists of Al-rich dendritic matrix, α-Al phase, and a eutectic mixture in the interdendritic region. Therefore polished surfaces display some different tones since various levels of alloying elements are present in the alloys. The tone turns lighter and darker depending on the number of elements present in the alloys. However, the dark spots became more prominent on the surface of the 12.7Si added alloy because of the increasing percentage of Si in the Al matrix [49].

In dry sliding condition, the worn surfaces clearly show grooves running parallel to the sliding direction, the localized flow of surface material followed by delaminating of material and surface cracks. From the figure, it can also be observed that the wear marks in the worn surfaces of higher Si-added alloy were lower as the higher Si-rich phase increased the strength of this alloy. In the fresh oil sliding environment, the worn surfaces of both the alloys display a smooth surface, but the smoothness of 12.7Si alloys is higher than that of 0.2Si alloy. It is because the oil inhibits the thermal softening as well as the direct contact between two moving surfaces of the material, causing minimum removal of metal. The higher Si added alloy contains different fine precipitates and so higher smooth surfaces. As discussed earlier, the used engine oil contains different harmful particles and so produces higher wear marks on the surfaces. The alloy of 12.7Si displays a smoother surface than that of 0.2Si alloy because of Si-rich intermetallics prevent wear [50].

Figure 17 shows the optical micrographs of the dust particles created from the friction of 0.2Si and 12.7Si automotive alloys under dry conditions. The dust particles of the 0.2Si alloy, which are granular and not adherent to other particles, are mixed with some chips originating from the stainless-steel disc (Fig. 17a). Whereas Fig. 17b shows different nature, the wear particles of the 12.7Si added alloy are fused together in an almost flat continuous amount of material. Higher Si means a higher number of fine precipitates into the alloys along with the refined grain structures. This affects the size of the counter body particle as the fine grinding wheel produces the fine particles during grinding. One observation is the counter body particles are seen higher with respect to increasing Si contents alloys as higher hardness [51].

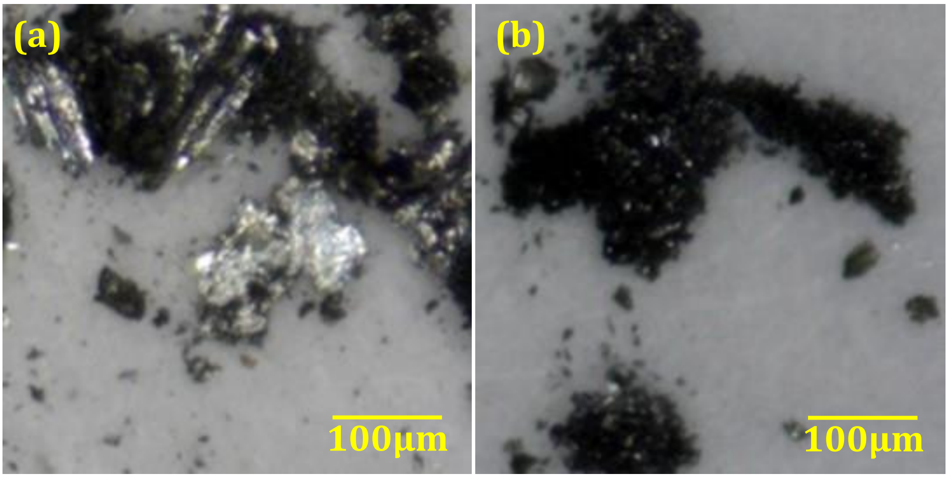

Fig. 17 Optical micrograph of dust of dry sliding condition (a) 0.2Si and (b) 12.7Si

3.4. Scanning electron microscopy

SEM microphotographs of 0.2Si and 12.7Si automotive alloys after wear test under different conditions at a distance of 2770 m are presented in Fig. 18. It is clearly suggesting abrasive wear in 0.2Si alloy revealing grooves due to abrading action by the hard particles, which got entrapped (Fig. 18a). For the 12.7Si added alloy under same wear environment the microphotograph revealed small cracks with grooves and dislodging of material clearly indicating combination of abrasive and delaminative wear (Fig. 18b). Further, SEM microphotographs of 12.7Si addition have revealed a reduced wear rate than that of 0.2Si alloy. The addition of Si has reduced the depth of abrasive grooves due to higher hardness and an increased intermediate layer of oxide. The alloys under engine oil sliding conditions have smooth surfaces as the oil produces a thin layer

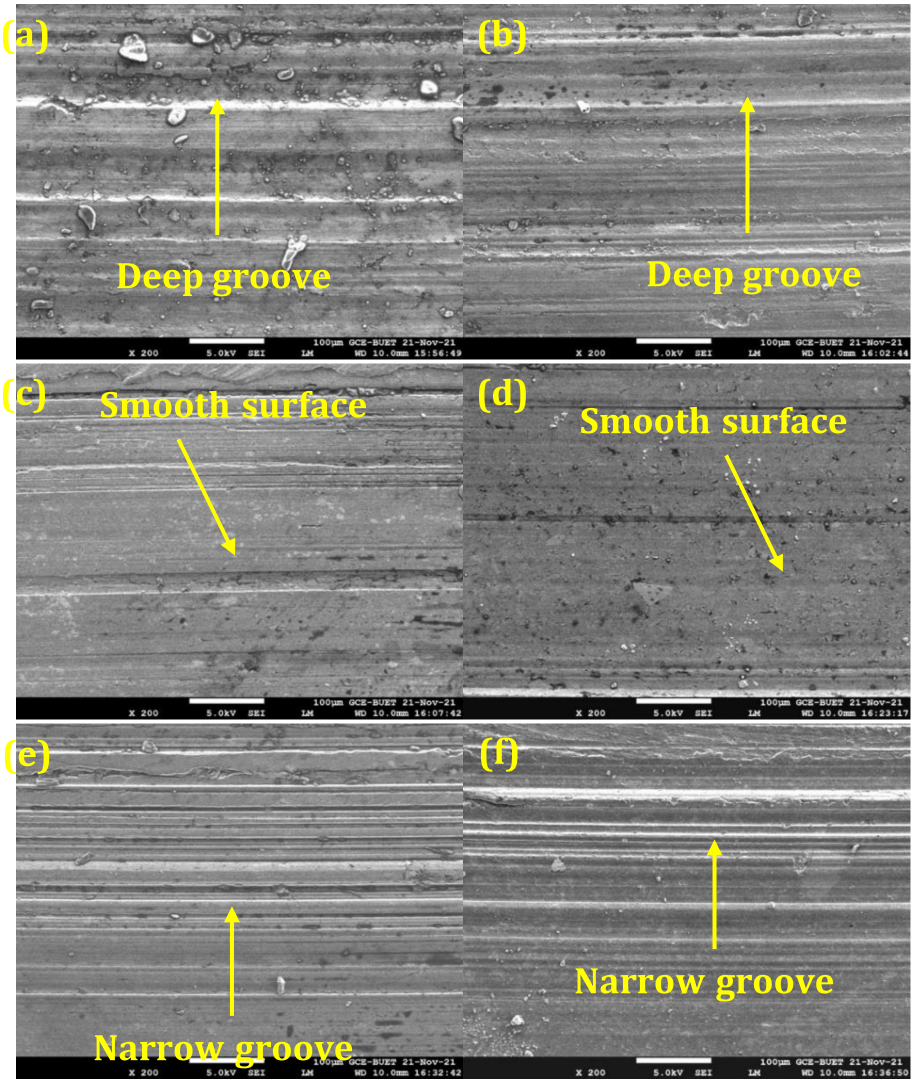

Fig. 18 SEM images of the worn surfaces of the experimental alloys in the dry condition a) 0.2Si, b) 12.7Si, in fresh oil c) 0.2Si, d) 12.7Si and used oil e) 0.2Si, d) 12.7Si after wear for 2770 m at applied pressure of 1.02 MPa

which reduces the direct contact between two movable surfaces (Fig. 18c and d). Wear is created through the engine oil under lower temperatures. While going through the used engine oil environment, both the alloys have resulted in severe wear in terms of deep grooves, as evident in Fig. 18e and 18f. SEM microphotographs of 12.7Si added alloy have revealed decreased wear rate at both conditions when compared to the lower 0.2Si added alloy. The addition of Si has reduced the depth of abrasive grooves due to higher hardness and an increased intermediate layer of oxide [22, 24].

4. Conclusions

This study investigated the influence of Si on tribological properties of the Al-based automotive alloy and made a comparison of the influence of fresh and used engine oil along with the dry sliding condition. From the study following conclusions can be drawn.

- Higher Si-added alloys achieved higher hardness due to the formation of different rigid Si-rich intermetallics through the ageing treatment. As a result, it improves the wear properties of the Al-based automotive alloys but beyond the eutectic composition forms the higher rate of primacy Si into the alloy, which weakens the matrix strength.
- The wear rate increases with sliding distance at dry sliding conditions due to thermal softening of the material but under an engine oil environment wear rate decreases as it holds back the heat generation to prevent the softening of contact materials. Heavy and harmful chemical particles in used oil increase the wear rate to some extent.
- Friction coefficient is too higher under dry sliding condition for their direct contact but lowers under engine oil environment due to the formation of thin film between the contact surfaces, which reduce the roughness. Used oil exhibits some degree of higher friction coefficient for its damaged quality.
- At dry sliding conditions, the lower coefficient of friction is observed for higher Si added alloy for its higher hardness and worked as a solid lubricant. On the other hand, under the engine oil environment, the opposite phenomenon is shown where there is a higher coefficient of friction for higher Si added alloy because the oil forms a thin lubricating film between the contact surfaces, which controls the wear properties.
- Worn surfaces in dry sliding conditions are found with higher abrasive wear and plastic deformation due to thermal softening of the material during wear. Under oil sliding condition, a smooth surface is observed as the oil forms the lubrication film and thumbs down direct contact on the moveable surfaces. Different types of harmful foreign particles in the used oil play an unenthusiastic role on the surface. Higher Si added alloy contains superior intermetallics due to ageing since responsible for such smooth worn surfaces.

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