International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:8, No:8, 2014

Wear Behavior of Commercial Aluminium Engine Block and Piston under Dry Sliding Condition

M. S. Kaiser, Swagata Dutta

***Abstract*—**In the present work, the effect of load and sliding distance on the performance tribology of commercially used aluminium-silicon engine block and piston was evaluated at ambient conditions with humidity of 80% under dry sliding conditions using a pin-on-disc with two different loads of 5N and 20N yielding applied pressure of 0.30MPa and 1.4MPa, respectively, at sliding velocity of $0.29ms^{-1}$ and with varying sliding distance ranging from 260m-4200m. Factors and conditions that had significant effect were identified. The results showed that the load and the sliding distance affect the wear rate of the alloys and the wear rate increased with increasing load for both the alloys. Wear rate also increases almost linearly at low loads and increase to a maximum then attain a plateau with increasing sliding distance. For both applied loads the piston alloy showed the better performance due to higher Ni and Mg content. The worn surface and wear debris was characterized by optical microscope, SEM and EDX analyzer. The worn surface was characterized by surface with shallow grooves at loads while the groove width and depth increased as the loads increases. Oxidative wear was found to be the predominant mechanisms in the dry sliding of Al-Si alloys at low loads.

***Keywords*—**Wear, friction, gravimetric analysis, aluminium-silicon alloys, SEM, EDX.

I. Introduction

ALUMINIUM-SILICON alloys have been used in tribo components involving sliding movements with a contacting counter-body [1]-[3]. The response of these components greatly depends on their material-related parameters, e.g., the nature shape, size, content, and mode of distribution of given micro-constituents. Also, service/test conditions influencing the wear characteristics of materials include load, speed, temperature, environment, counter-body roughness, and configuration of the sliding pair, relative to a constant design aspect [4]. It has been observed that even a minor alteration in any of the parameters can change the sliding wear behavior significantly. Thus, it is essential to characterize the material for their mechanical properties and sliding wear behavior in as many situations as possible. This would enable us to develop a better understanding about the response.

Aluminium-silicon based alloys are well-known casting alloys with high wear resistance, low thermal expansion coefficient, good corrosion resistance and improved mechanical properties in a wide range of temperature. These properties lead to the application of Al-Si alloys in automotive industry, especially for cylinder blocks, cylinder heads, pistons and valve lifter [5]-[7]. Wear is another major failure of engine block material. This process is attributed to a couple of factors. Firstly, the presence of hard particles and chemicals in cooling and lubrication fluid results in abrasive and corrosive wear. Secondly, erosive wear is also significant from the impact of hot air and gases. Third, friction between the block wall and piston ring can produce adhesion even in oil lubrication. Finally, fatigue also contributes to the wear of engine block. Various types of aluminum alloys are continually being developed to improve their wear resistance. Among these alloys, aluminum-silicon (Al-Si) alloys have been found to be beneficial in many industrial applications and considered to be appropriate substitutes for cast iron components. The addition of silicon in aluminum alloys improves their wear, casting, machining and corrosion characteristics [8], [9].

The aim of the present investigation is to observe the structure and dry sliding wear behaviour of the commercially used aluminium–silicon block and piston so that specific recommendation can be put forward towards the tribological use of this alloy for local automobile spare parts manufacturers.

II. Material and Methods

The materials used in the current study were commercial aluminum-silicon engine block and piston. The alloys were analyzed both by wet chemical and spectrochemical methods. The chemical compositions of the alloys are given in Table I. The sample of 12 mm length and 5 mm diameter were machined from the cast bar for wear study by following ASTM Standard G99-05. The end surface (5 mm dia) of the pin samples were polished using emery papers 1, 0, 2/0. Afterwards, the samples were polished in a fine grade wheel polisher. Later, the end surface was cleaned in running water. Finally, the samples were dried in acetone. Cast iron discs were used as the counter-body material. The hardness of the cast iron discs was around RC 50. One of the surfaces of the disc was grinded by surface grinding machine and cleaned with cotton. The frictional and wear behaviors of the aluminium alloys were investigated in a pin-on disc type wear apparatus by following ASTM Standard G99-05. During the wear tests, the end surface of the pin samples were pressed against horizontal rotating cast iron disc. Two different loads of 5 N and 20 N were used throughout the test, which yielded nominal contact pressures of 0.30 MPa and 1.4 MPa. The tests

M. S. Kaiser is working as a Deputy Director in the Directorate of Advisory, Extension and Research Services, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, phone: 0088-02-9663129; fax: 0088-02-9665622; (e-mail: mskaiser@iat.buet.ac.bd).

Swagata. Dutta is with the Institute of Appropriate Technology, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh (e-mail: swagata_dutta@iat.buet.ac.bd).

International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:8, No:8, 2014

were conducted at the sliding speed of 0.29 ms $^{-1}$ with varying sliding distances ranging from 260 m – 4200m. All the tests were carried out in ambient air (humidity 80%) under dry sliding condition (without lubrication). The wear debris produced during the wear tests were collected for stereomicroscopic investigation. After completion of wear tests, samples were cleaned with acetone. At least four tests were done for each type of material. Wear rates were calculated from average values of weight-loss measurements. Wear rate was estimated by measuring the mass loss (ΔW) after each test. Cares have been given after each test to avoid entrapment of wear debris. It is calculated that ΔW to sliding distance (S.D) using:

$$W.R = \Delta W/S.D \qquad (1)$$

Microstructural observation of the worn specimens were done carefully by using OPTIKA Microscope with a CCD camera (Model: OPTIKA) attached to PC at different magnifications and some selected photomicrographs were taken. The SEM investigation and EDX analysis were conducted by using a JEOL scanning electron microscope with an energy dispersive X-ray analyzer (Model: Link AN - 10000) attached.

TABLE I
CHEMICAL COMPOSITION OF AL-SI ENGINE BLOCK AND PISTON (WT %)

Alloy	Si	Mg	Cu	Ni	Fe	Zn	Mn	Al
Block	10.783	0.238	2.281	0.083	0.795	0.760	0.256	Bal
Piston	9.764	0.492	2.446	0.278	0.400	0.104	0.495	Bal

III. RESULTS AND DISCUSSION

A. Wear Test

Figs. 1 and 2 elucidate the variation of weight loss with the variation of sliding speed for both engine block and piston alloy at applied pressure of 0.30MPa (Normal Load 5N) and 1.4MPa (Normal Load 20N) respectively. Moreover, Figs. 3 and 4 depict the variation of wear rate with the variation of sliding speed for both engine block and piston alloy at applied pressure of 0.30MPa (Normal Load 5N) and 1.4MPa (Normal Load 20N) respectively. Other parameters, such as sliding velocity (0.29 ms^{-1}), surface roughness (2 µm), and humidity (80%) are identical for these four figures. It can be seen from Fig. 1 that, at lower applied pressure (0.30MPa) the weight loss at all sliding distances vary insignificantly for both block and piston. As the sliding distance increase the weight loss increases for both the alloys. At relatively higher applied pressure (1.4MPa) both the alloys show higher weight loss as compared to weight loss at low load and at all sliding distances (Fig. 2). However, for higher applied pressure, differences in weight loss values for block and piston are evident. The block showed higher weight loss at relatively low and high ends of sliding distance.

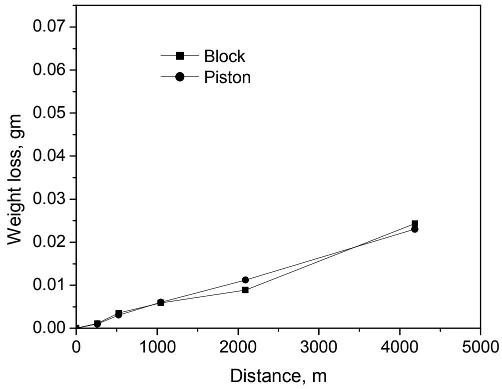

Fig. 1 Variation of weight loss (gm) with the variation of sliding distance (m) at applied pressure of 0.30MPa (Load 5N) and sliding velocity 0.29 ms^{-1}

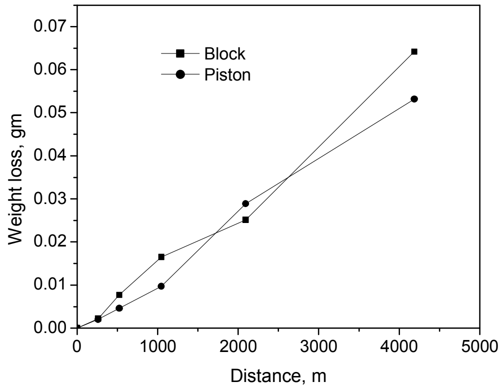

Fig. 2 Variation of weight loss (gm) with the variation of sliding distance (m) at applied pressure of 1.4 MPa (Load 20N) and sliding velocity 0.29 ms^{-1}

Figs. 3 and 4 present the wear rate vs. sliding distance plot for both block and piston. At lower applied pressure, it can be observed that wear rate increased at a steep rate initially for both block and piston and after a certain point onwards attained a constant value (Fig. 3). In the case of higher applied pressure, the nature of the curves are quite similar to that of the lower applied load, only difference is in the value of wear rate increased quite significantly for both the alloys (Fig. 4) with block showing higher values than piston at lower and higher realm of the investigated sliding distance range. The competition of frictional heat softening and strain hardening determined the down -and-up trend. Figs. 3 and 4 clearly indicate that the wear rates of both the alloy increased with increasing the load from 5N to 20N. The wear rate for engine block increased from $6x6^{-10}$ gm/m (5N) to $1.6x10^{-5}$ (20N) at sliding distance of 1000 m. For all sliding distances, the wear rate for both the alloys increased one order of magnitude with increasing load from 5N to 20N. For both applied pressures the piston alloy showed lower wear rate as compared to that of block alloy. The result is due to the presence of higher percent of Ni and Mg in piston alloy as seen from the chemical analysis (Table I). Ni forms an intermetallic Al_3Ni which

International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:8, No:8, 2014

increases as Ni content increases. This intermettalic increases the strength of the piston alloy leading to lower wear rate. More over Mg addition is beneficial to enhance the abrasion resistance of the alloy due to uniformly distribution of hard particles and reduction of friction coefficient [10]. The sliding movement occurs in very small areas at the peaks and over time. The ruptures or breaks at the peaks increase the contact area and results in rise in temperature. The increase in the load causes rise in friction.

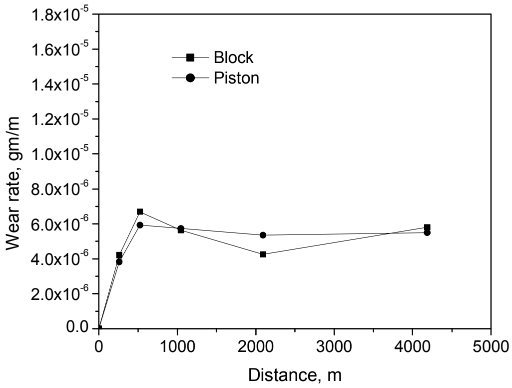

Fig. 3 Variation of wear rate (gm/m) with the variation of sliding distance (m) at applied pressure of 0.30 MPa (Load 5N) and sliding velocity 0.29 ms^{-1}

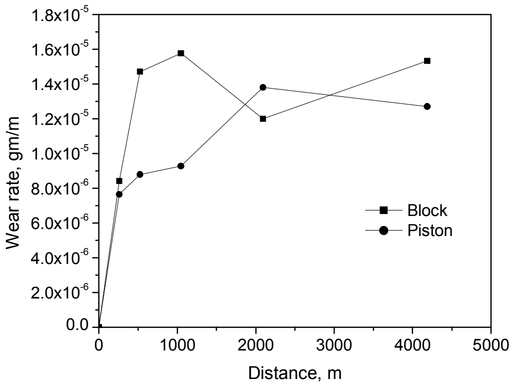

Fig. 4 Variation of wear rate (gm/m) with the variation of sliding distance (m) at applied pressure of 1.4 MPa (Load 20N) and sliding velocity 0.29 ms^{-1}

Aluminium–silicon casting alloy readily oxidizes in air in the initial duration of rubbing. An increase in the load leads to increased wear and loss of the metal. The initial rubbing duration breaks the surface layers, which cleans and smoothes the surfaces and increases the strength of the connections and contact between the surfaces. The friction force due to the tillage effect between the surfaces increases the temperature between them. This effect results in adhesion and increases the deformation at the surface layers, leading to further loss of the metal.

B. Optical Microscopic Observation

In this study of dry sliding wear of two Al-Si alloys against a cast iron counter-body, the wear was described as a mixed mode of elastic-plastic contact where Archard's law was obeyed. The applied pressure range investigated was 0.30 MPa and 1.4 MPa. This range of applied pressure was previously found to exhibit mild wear (MW) in these alloys [11]. In Fig. 5 are presented the worn surfaces for both block and piston alloys at different loads and sliding distances. Firstly, it can be observed that for a given alloy and for a given load, as the sliding distance increase the wear marks becomes more visible and deep. In some portions of the investigated worn surface there are evidence of crater formation. It can also be seen that for a given alloy and at a given sliding distance, as the load is increased the wear marks also becomes more deep and prominent. Increasing the load from 5N to 20N also increases the fraction of flaky wear debris. At low loads and at all sliding distances, the wear marks in the worn surfaces of block and piston alloy are similar in nature whereas at higher applied loads the wear marks in the worn surfaces of block are more deep and intense than that of the piston alloy leading to their higher material loss and corresponding high wear rate. The wear mechanisms in the dry sliding of Al-Si alloys can be classified as oxidative wear. Oxidative wear occurred at low applied loads. In this wear process an aluminium oxide layer (l0-80 pm) formed on both the wearing Al-Si surface and the counter-face [11]. Wear occurred firstly by oxidation of the asperities and then secondly by fracture and compaction of the oxidized wear debris into this film. The wear rate was low, due to the amount of metal removed being confined to the thickness of this oxide formation. Some localized deformation of the substrate and fracture of the Si particles was observed. Oxidative wear was considered to be generally independent of the Si content or Si particle size. Under conditions of mild wear a tribolayer was formed on the surface of Al-Si alloys. This layer was found to consist of an ultrafine mixture of aluminium, silicon and α-iron. The formation of this surface resulted from the transfer of material from both the Al-Si alloy pin material and the steel counter-face. It was also found that the observed iron-rich layer, formed on the Al-Si surface due to mutual material transfer between the sliding surfaces, was composed of an ultrafine mixture of Al, Si and α-Fe (<1 μm). Furthermore, it was argued that as wear continued, the deposition reached a stage where these transferred layers could not adhere and became detached [11].

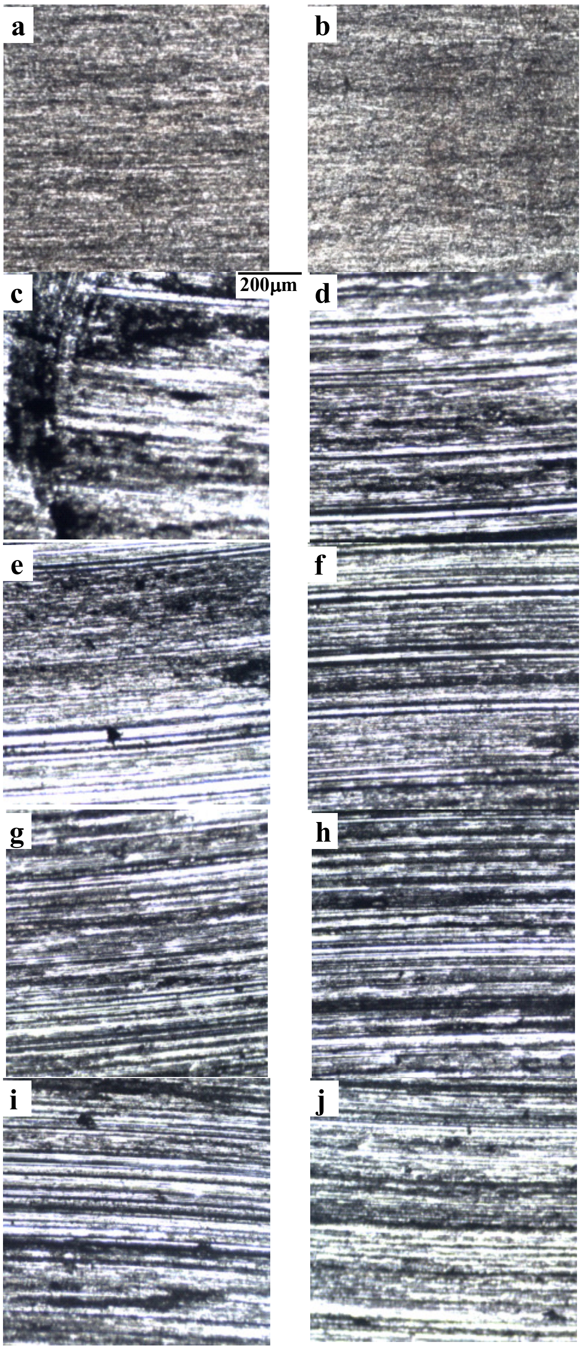

Fig. 5 Optical micrograph of worn surfaces before wear (a) block, (b) piston, after wear at applied pressure of 0.30MPa for 15 min (c) block, (d) piston, for 4 hours (e) block, (f) piston, at applied pressure of 1.40MPa for 15 min (g) block, (h) piston and for 4 hours (i) block (j) piston

Fig. 6 shows the typical wear debris collected from the wear test. At low loads the wear debris was equiaxed, laminar and consisted of a small iron content. An increase in the applied normal load formed wear debris of various shapes and sizes. The debris size ranged from a few microns, to a few millimeters. Visually, the debris produced at 20 N appeared in the form of a dark, brown powder. The micrograph (Fig. 6) shows the debris produced at a load of 20 N was mainly composed of very fine, equiaxed particles but also contained plate-like and ribbon-shaped iron particles in smaller amounts. The fine and large debris particles were a mixture of Al, Si, Fe, and oxygen. The ribbon-shaped particles had an appearance similar to machined chips, and were mainly composed of Fe indicating that they were cut from the steel counter-face.

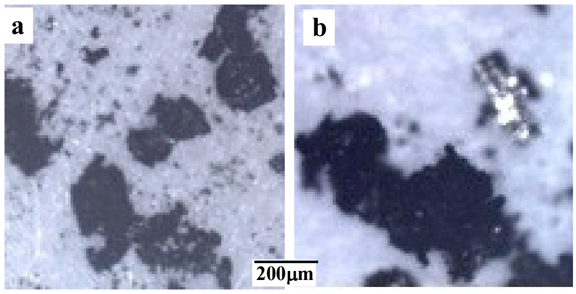

Fig. 6 Wear debris collected from wear test at 1.4 MPa (20N) applied pressure and sliding distance of 4200m for (a) Block, (b) Piston

C. SEM and EDX Observation

The SEM micrographs of as-received Al-Si block and piston are shown in Figs. 7 (a) and (b) respectively.

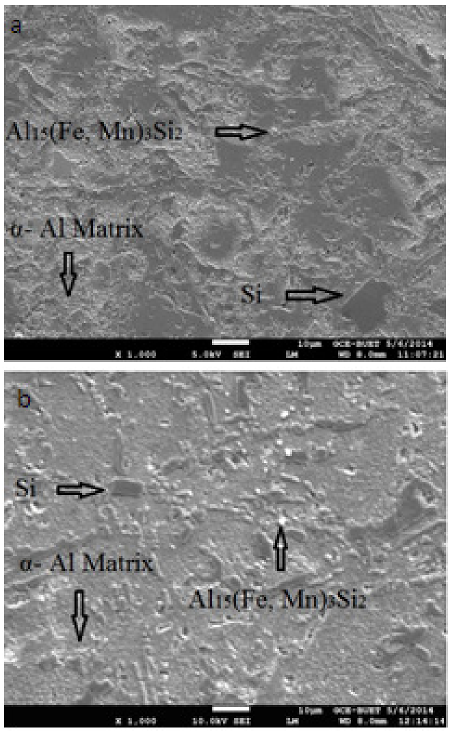

Fig. 7 SEM micrographs of as-received Al-Si (a) block and (b) piston

The microstructure consisted of mainly primary Al dendrite, eutectic Si, $Al_{15}(Fe, Mn)_3Si_2$, Mg_2Si and a few number of Fe-rich intermetallic phases on α-Al matrix in the inter-dendritic region. It can be seen that the eutectic Si phase is flake-like and acicular morphologies. Two type of $NiAl_3$ phase are the plate-like and needlelike morphologies [7].

The SEM micrographs of the worn surfaces of Al-Si block and piston are shown in Figs. 8 and 9. The corresponding EDX profile analysis of the block alloy for the selected area of the SEM is shown in Figs. 8 (b) and (c). The weight percentage of elements found by EDX analysis in these areas were 37.67% O, 51.03% Al, 5.60% Si, 0.75% Mn, 3.74% Fe and 0.76% Cu, 0.44% Zn and, 22.23% O, .04% Mg, 58.01% Al, 15.49% Si, 2.27% Fe, 0.72% Ni, 0.80% Cu, 0.42% Zn respectively.

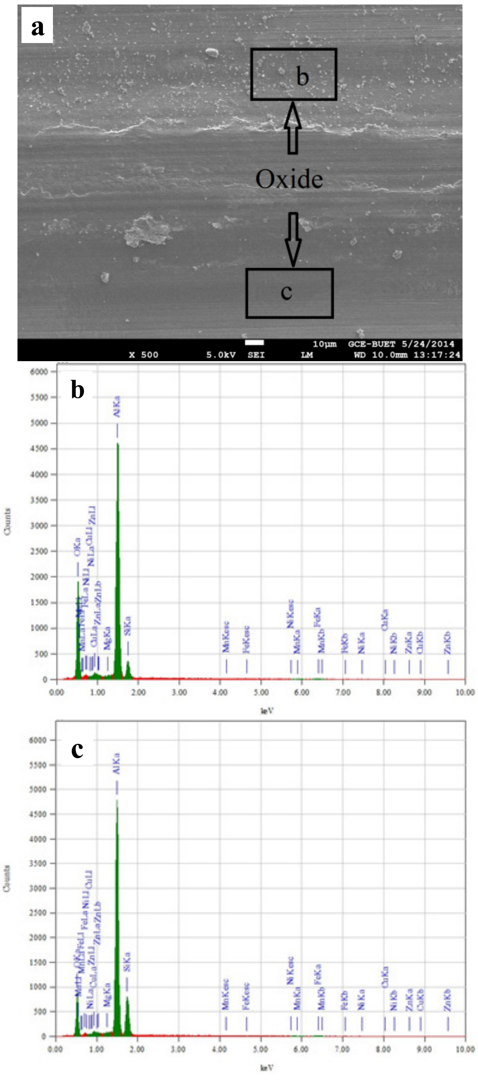

Fig. 8 SEM images of worn surfaces of aluminium engine block after wear at 1.4 MPa applied pressure and sliding distance of 4200m

The corresponding EDX profile analysis of piston alloy for the selected area of the SEM is shown in Figs. 9 (b) and (c). The weight percentage of elements found in these areas were 33.82% O, 0.12% Mg, 48.00% Al, 5.69% Si, 0.17% Mn, 10.61% Fe,0.42 Ni, 1.01% Cu, 0.1% Zn and 33.93% O, .15% Mg, 48.45% Al, 5.99% Si, 0.45% Mn, 9.70% Fe, 0.34% Ni, 0.86% Cu, 0.13% Zn respectively. The EDX data clearly reveals the high oxide content in the selected areas which suggest the oxidative wear was the dominant process. In case of block alloy the EDX analysis of the investigated areas reveals that the oxide content is unevenly distributed. Whereas for piston alloy the oxide content is roughly uniform which can be responsible for lower wear rate for the piston alloy. This can be due to the variation of chemical composition of the alloys.

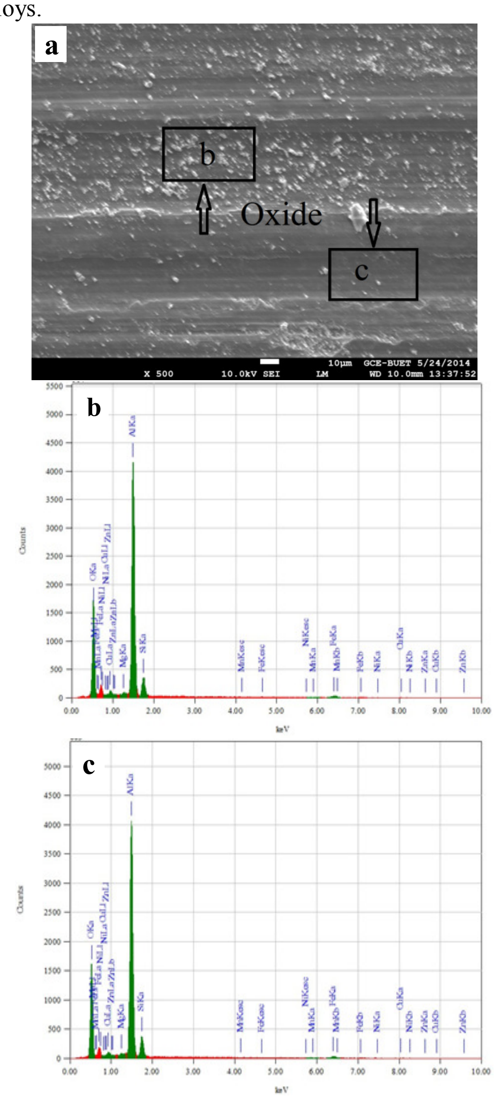

Fig. 9 SEM images of worn surfaces of aluminium engine piston after wear at 1.4 MPa applied pressure and sliding distance of 4200m

Generally, a transferred layer either in continuous or discontinuous form was observed for the samples. The widths of the surface grooves were between 4 µm and 20 µm. In this wear process an aluminium oxide layer (l0-80 µm) formed on both the wearing Al-Si surface and the counter face. Wear occurred firstly by oxidation of the asperities and then secondly by fracture and compaction of the oxidized wear debris into this film. The wear rate was low, due to the amount of metal removed being confined to the thickness of this oxide formation. Some localized deformation of the substrate and fracture of the Si particles was observed. Sliding marks are observed on all the worn surfaces which are of typical ploughing action in comparatively soft metal. It is also seen that the depth and width of the sliding marks increases with increase of applied load and sliding distance. The worn surface is relatively rough and exhibits rather coarse and deep sliding marks. In contrast, the coarseness and deepness of the sliding marks increases with increasing load on the tested alloys. At relatively low speeds and loads, the heat generated by the asperity contact leads to oxide formation on the aluminum surface. The layer is thin and can deform elastically contributing to very low wear rates which can be considered as mild wear. Increasing the load causes adhesion to occur between the two materials in contact and removal of the surface oxide in the form of laminar particles. At low loads the wear debris was characterized by dark-brown coloured powder mixed with Fe, Al, and Si and O, very fine equiaxed particles, small amounts of ribbon shaped particles (Fe chips), and Plate-like particles (Fe-Al-Si-O). At relatively high loads Plate-like particles composed of Fe, Al, and Si and O and metallic Al flakes (Al-Si) was observed [11]. The worn surface was characterized by surface with shallow grooves at loads while the groove width and depth increased as the loads increases.

IV. Conclusions

The load and the sliding distance affect the wear rate of the aluminium engine block and piston alloys. The wear rate increased with increasing load for both the alloys. Wear rate also increases almost linearly at low loads and increase to a maximum then attain a plateau with increasing sliding distance. For both applied loads the piston alloy showed the better performance due to higher Ni and Mg content. The worn surface was characterized by surface with shallow grooves at loads while the groove width and depth increased as the loads increases. Oxidative wear was found to be the predominant mechanisms in the dry sliding of Al-Si alloys at low loads. The significance of aluminium oxide formation regarding the formation of wear debris and the overall wear process still remains controversial.

Acknowledgment

This work is supported by CASR of Bangladesh University of Engineering and technology and is part of project “Studies of recrystallization, wear and corrosion behavior of aluminium piston and piston block”. Thanks to Department of Glass and Ceramics Engineering for providing the laboratory facilities.

References

[1] A. Mazahery and M. O. Shabanih, “Microstructural and abrasive wear properties of SiC reinforced aluminum-based composite produced by compocasting”, Trans. Nonferrous Met. Soc. China, 2013, 23, 1905-1914.

[2] M.M. Haque and A. Sharif, “Study on wear properties of aluminium–silicon piston alloy”, Journal of Materials Processing Technology, 2001, 118, 69-73.

[3] A. D. Sarkar and J. Clarke, “Friction and wear of aluminium-silicon alloys”, Journal of Wear, 1980, 61(1-2), 157-167.

[4] M. M. Maru and D. K. Tanaka, “Influence of loading, contamination and additive on the wear of a metallic pair under rotating and reciprocating lubricated sliding”, J. Braz. Soc. Mech. Sci. & Eng., 2006, 28(3), 278-285.

[5] H. Liao, Y. Sun and G. Sun, “Correlation between mechanical properties and amount of dendritic α-Al phase in as-cast near-eutecticAl-11.6%Si alloys modified with strontium”, Materials Scienceand Engineering A, 2002, 335(1-2): 62-66.

[6] R. Kilaas, V. Radmil, “Structure determination and structurerefinement of Al_2CuMg precipitates by quantitative high-resolutionelectron microscopy”, Journal of Ultramicroscopy, 2001, 88(1), 63−72.

[7] L. Lasa, J. M. Rodrigues-Ibade, “Wear behaviour of eutectic andhypereutectic Al-Si-Cu-Mg casting alloys tested against a composite brake pad”, Materials Science and Engineering A, 2003, 363(1-2),193-202

[8] Z. Muzaffer, K. Erdem and G. Serap, “Influence of Cu addition on microstructure and hardness of near-eutectic Al-Si- xCu-alloys”, Trans. Nonferrous Met. Soc. China, 2011, 21, 1698-1702.

[9] J. Clarke and A. D. Sarkar, “Wear characteristics of as-cast binary aluminium-silicon alloys”, Journal of Wear, 1979, 54(1), 7-16.

[10] R. L. Deuis, C. Subramonian and J. M. Yellup, “Dry sliding wear of aluminium composites- a review”, Journal of composites science and technology, 1996, 57, 415-435.

[11] R. L. Deuis, C. Subramonian and J. M. Yellup, “Reviews on the Influences of Alloying elements on the Microstructure and Mechanical Properties of Aluminum Alloys and Aluminum Alloy Composites”, International Journal of Scientific and Research Publications, 2012, 2(6), 1-7.