Dry wear characteristics of nickel rich Al-Si-Cu piston alloys

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Abstract—Wear and friction characteristics of Al-Si-Cu-Ni piston alloys have significant importance in the field of automobile industry by considering the environmental and economic factors. The present study aims to investigate the effect of varying Ni weight percentage from 2 wt. % to 2.6 wt. % on the microstructural, physical and mechanical characteristics of the Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. Wear and friction characteristics of the Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys were investigated at different sliding velocities (0.2-1 m/s) by using pin-on-disc tribometer under constant normal load of 30 N and sliding distance 500m. The microstructural observations showed that the needle like β eutectic silicon's are fragmented, spheroidized and evenly dispersed in the α-Al matrix after heat treatment under T6 conditions. It has been observed that the maximum hardness of 136 BHN obtained for Al-12.6Si-3Cu-2.3Ni Piston alloy. The maximum ultimate tensile strength of 230 MPa obtained for Al-12.6Si-3Cu-2.3Ni Piston alloy among the Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. Wear loss of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys decreases with the addition of 2.3 wt. % of Ni. A transition in the wear loss observed at a critical velocity of 0.6 m/s for the Al-12.6Si-3Cu-(2-2.6 wt. %) Ni Piston alloys. However considerable decrease in the wear loss occurred by the addition of 2.3 wt. % of Ni and the minimum wear loss observed in the case of Al-12.6Si-3Cu-2.3Ni piston alloy in all the sliding conditions such as constant normal load 30N, constant sliding distance 500 m and sliding velocities in the range of 0.2-1 m/s.

Index Terms—Piston Alloys, Gravity casting, Wear loss, Coefficient of friction, eutectic silicon, Microstructure, Hardness.

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1 INTRODUCTION

Al-Si-Cu-Ni alloys are widely used in automobile industry for the production of piston and associated components due to its high strength to weight ratio, low density, good castability, low thermal expansion as well as high elevated temperature strength [1], [2]. Wear behaviour of such alloys have more significance in terms of economic and environmental factors [3]. In order to reduce the hydrocarbon emission it is required to reduce the crevice volume of internal combustion engines which leads to the requirement of stronger piston alloy with improved mechanical properties and wear characteristics. Addition of alloying element is one of the most important and practical methods to improve the elevated-temperature properties of Al–Si piston alloys, and many elements have been examined during the past decades[4]–[8].Ni has been known as the most important alloying element to improve the properties of Al-Si multicomponent piston alloy. Ni rich intermetallic phases formed by the addition of Ni on such alloys have significant role in the elevated temperature properties [4], [6]. The Al_3Ni, Al_3CuNi and Al_7Cu_4Ni phases have much bigger contributions to the elevated temperature properties of Al-Si piston alloys owing to their better thermal stability, mechanical properties, morphologies and distributions [6], [9].

In this study, attempts were made to investigate the effect of Ni addition on the microstructural, physical, mechanical, and wear characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys.

2 EXPERIMENTALMETHODS

2.1 Materials Preparation

Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys were prepared by using Al-6061 alloy, Al-50%Si master alloy, Al-50%Cu master alloy and Al-20%Ni master alloy.Table.1 describes the chemical composition of piston alloys used in this study.

TABLE I

Alloy	Si	Cu	Ni	Mg	Fe	Mn	Ti	Cr	Al
Alloy A	11.86	3.19	2.12	0.86	0.26	0.049	0.013	0.008	Balance
Alloy B	12.62	2.96	2.31	0.74	0.23	0.05	0.008	0.009	Balance
Alloy C	12.34	2.86	2.62	0.79	0.31	0.044	0.036	0.046	Balance

CHEMICAL COMPOSITION OF AL-12.6SI-3CU-(2-2.6 WT. %) NI PISTON ALLOYS

The gravity die casting technique was used to prepare the piston alloys. The melting process was carried out by using diesel fired tilting cast furnace .The preheated ingots were charged in to the furnace when the crucible attains a tempera-

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ture of 700°C.The melting temperature was maintained at 750±5°C.The molten melt was continuously degased by bubbling Ar gas into the melt. The molten metal was poured at temperature of 720-730°C in to the open preheated metal mould and after solidification mould allows to water quenching.

2.2 Heat Treatment

The T6 heat treatment process was carried out by using electrical muffle furnace. Solutionizing of the specimens were carried out at 450±5°C for 6 hrs. , followed by water quenching at a temperature of 20°C .After 15 minutes the specimens were removed and dried. The ageing or precipitation treatment carried out at a temperature of 180°C for 10hrs and the specimens were removed from the furnace and followed by air cooling [9].

2.3 Metallography

Metallographic specimens were prepared by the normal polishing techniques. The specimens were polished with sand paper having grit size 320 to 2000, followed by fine polishing with diamond paste up to 0.25 microns on velvet cloth and then etched with Keller's reagent. The internal structure of cleaned and dried specimens inspected by using optical microscope.

2.4 Hardness and Tensile Test

The hardness of samples were tested using Brinell Hardness Tester (INDENTEC). Samples with dimension 12mm x 12mm x12mm were cut from heat treated piston alloys. Surface of the samples were polished with 600 grit size SiC paper. The indentation was provided on the polished surface with a ball of diameter 2.5mm for a load of 62.5kg. Diameter of the impression was measured using a microscope with an accuracy of ±0.01mm. The tensile test of heat treated samples were performed by using Instron tensile testing machine in accordance with the ASTM E8M standard and each tensile test data was an average of three tensile specimens of accuracy. The dimensions of the specimens are given in Figure. 1.

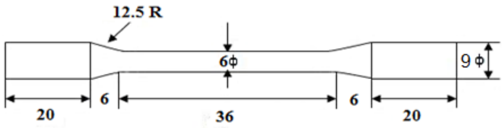

Fig. 1 Dimensions of Tensile Sample (All dimensions are in mm).

2.5 Wear Test

A pin-on-disc wear test rig was used to investigate the dry wear characteristics of Al-Si-Cu-Ni piston alloys in accordance with the ASTM G99-05 standards. A cylindrical pins of 6.0 mm diameter and length 30 mm cut from the heat treated samples was held on a rotating En 31 steel disc of diameter 200mm having a hardness of 60HRC. The diameter of the wear track (d) was taken as 63.5 mm .Each revolution of the disc attain an average periphery of the wear track length equal to πd =π *63.5≈200mm. Both the pin and the counter body were polished flat with 600 grit SiC abrasive paper to a surface roughness of 0.35 and 0.27μm, respectively and then cleaned with acetone and dried before each sliding tests. All the tests were carried out using piston alloy pin with an applied load 30N and sliding velocity of 0.2–1 m/s range.The relative humidity of the laboratory atmosphere during the wear testing was measured to vary between 60-65%. The initial weight of the specimen was measured in a single pan electronic weighing machine (Zhimadzu) with least count of 0.01mg. After running through a sliding distance of 500m continuously as per the case, the specimens were removed, cleaned with acetone, dried and weighed to measure theweight loss due to wear. The difference in the weight of specimen before and after test was used as a measure ofsliding wear. The frictional force was measured by using a load cell attached to the lever arm and the data acquisition system (Agilent U2352A).

3 RESULTS AND DISCUSSIONS

3.1 Microstructural Analysis

Fig.2 shows the as cast microstructure of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. The average grain size varies with respect to the addition of Ni. The difference in the size and shape of different features are evident. The microstructure consists of α- aluminium dendritic halos with eutectic Si and complex intermetallic compounds segregated into the interdendritic regions. The features of the microstructures of the alloy in T6 condition undergo changes upon heat treatment. Microstructural observation showed that the secondary arm spacing is reduced for the heat treated alloys. Most of the intermetallic phases were partially dissolved and tend to spherodize, i.e., sharp corners have become rounded. The morphology change of the eutectic Si is obvious after heat treatment. The plate-like eutectic Si in the as cast condition is broken into small particles. That is, the Si particles break down into smaller fragments and become gradually spheroidized. The changes in size and morphology of the discontinuous silicon phase are significant since they have a direct influence on the tensile properties [4].The massive rod like Si particles has been changed to a fine spherical shape besides the intermetallic phases distributing evenly along the grain boundaries. Further refinement in the grain size is also noticed after T6 heat treatment. The intermetallic phases are the main elevated-temperature strengthening phases in Al-Si-Cu-Ni piston alloys, especially Ni- rich phases [6]. At elevated temperature, the thermally stable Ni-rich phases could impose drag on boundaries and hinder the slide of α-Al grains. Therefore, Ni-rich phases can be called the main strengthening phases in Al-Si-Cu-Ni piston alloys at elevated temperature. Generally, the intermetallic phases found in these alloys are

Al_2Cu, Mg_2Si, Al_3CuNi, Al_7Cu_4Ni, Al_3Ni and $Al_5Cu_2Mg_8Si_6$ and so on [10].

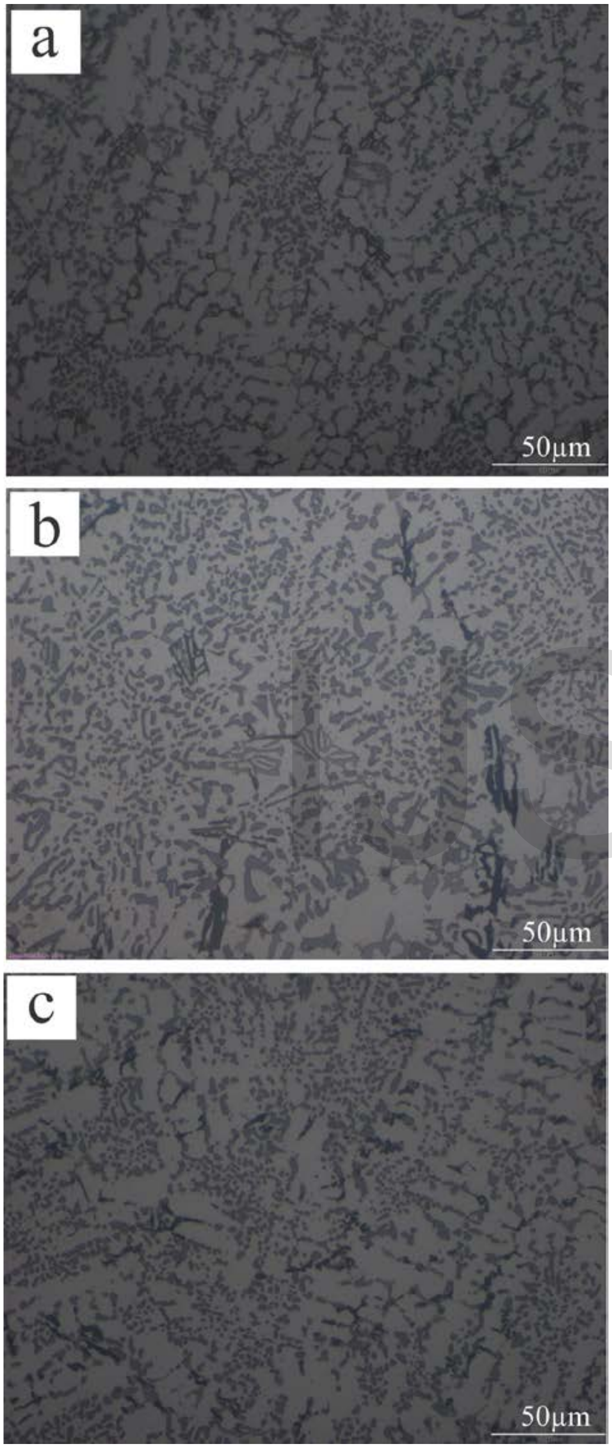

Fig. 2. Microstructure of Al-12.6Si-3Cu-(2-2.6) wt. %Ni piston alloys, a) Alloy A, b) Alloy B, c) Alloy C.

3.2 Tensile Characteristics

Fig.3 shows the tensile properties of the T6 samples. For the Alloy A, alloy B and alloy C samples in heat treated condition, the values of UTS are 96 MPa, 230 MPa and 197 MPa respectively. The ultimate tensile strength of Alloy B samples are more than 58 % and 14% than those for the Alloy A and Alloy C respectively. It can be observed that the ultimate tensile strength of Al-12.6Si-3Cu-(2-2.6) wt. %Ni piston alloys considerably improved by the addition of 2.3 wt. % of Ni.

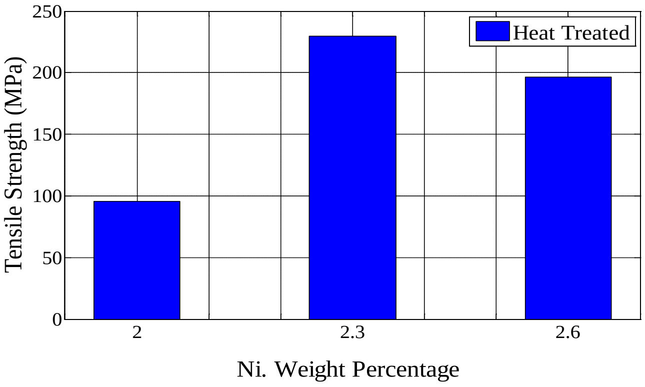

Fig. 3 Tensile Strength versus weight percentage of Ni for heat treated Al-Si-Cu-Ni (2-2.6 wt. %) Piston alloys.

3.3 Physical Characteristics

Fig.4. Shows hardness values for all the piston alloys are increased after heat treatment and the hardness values of as cast Alloy A, Alloy B and Alloy C specimens are 61, 99 and 87 BHN respectively. After heat treatment the hardness for the same are increased to 94, 136 and 112 BHN respectively. This indicates T6 heat treatment is effective in these casting methods for increasing the hardness. This hardening effect is due to the precipitation of Al_2Cu and Mg_2Si phases during heat treatment [9].

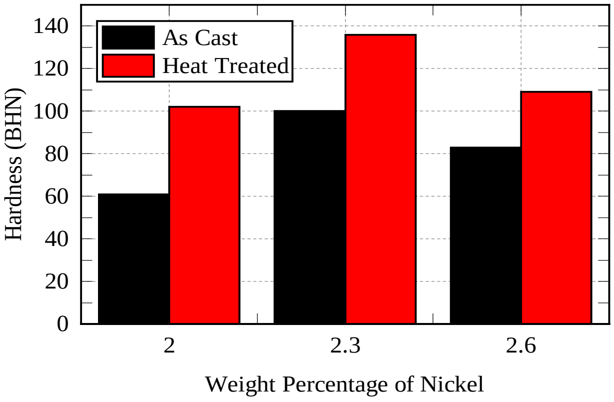

Fig. 4 Brinell hardness versus weight percentage of Ni for as cast and heat treated Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys.

3.4 Wear and Friction Characteristics

The effect of sliding velocity on wear loss: Fig.5 shows the effect of sliding velocity on wear loss of the Al-12.6Si-3Cu-(2-2.6) wt. %Ni piston alloys against En 31 Steel counter surface under the constant normal load of 30N and sliding distance of 500m.It has been observed that the wear loss of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys decreases with an increase of sliding velocity from 0.2 to 0.6 m/s. and a rapid increase observed beyond the sliding velocity of 0.6m/s. Another aspect common to all the materials represented in Fig. 5 exhibited a transition from mild wear to severe wear beyond a critical value of sliding velocity at 0.6 m/s. These results are in good agreement with the previous investigations of the same author [11].This transition behaviour of wear loss characteristics at the critical velocity is due to the formation and fracture of mechanically mixed layer (MML) on the sliding surfaces[12]–[14]
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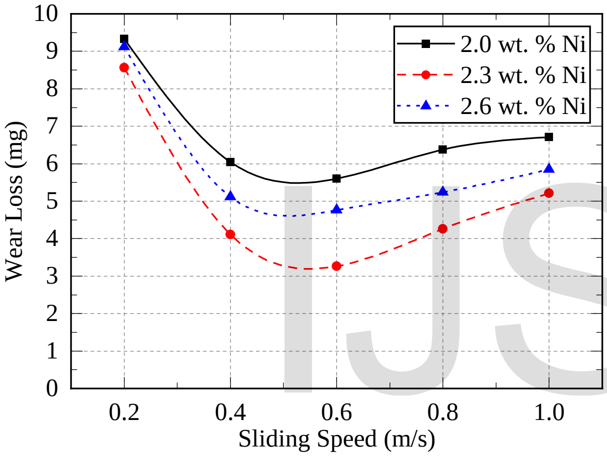

Fig. 5 Wear loss characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloy as a function of Sliding speed under the constant normal load of 30N and sliding distance of 500m.

The effect of sliding velocity on the coefficient of friction: Fig. 6 shows the effect of Ni weight percentage on the coefficient of friction of the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys as a function of sliding distance. It was observed that the coefficient of friction varies with the addition of Ni weight percentage. Alloy B exhibited the lowest coefficient of friction under the constant normal load of 30N and sliding velocity 0.6 m/s. In general, coefficient of friction is noted to be reduced due to addition of 2 to 2.3 wt. % of Ni among the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys. Further addition of weight percentage of Ni from 2.3 to 2.6 wt. % in Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys the coefficient of friction was found to be increase [15].Fig.7 shows the Coefficient of Friction of Alloy B as a function of sliding distance under the varying sliding speed (0.2 to1.0 m/s) and normal load of 30N.It is clear that the coefficient of friction decreases with the increase in the sliding speed and tends to increase beyond the critical velocity[16]. Alloy B observe the lowest average coefficient of friction of 0.29 at critical velocity 0.6 m/s.

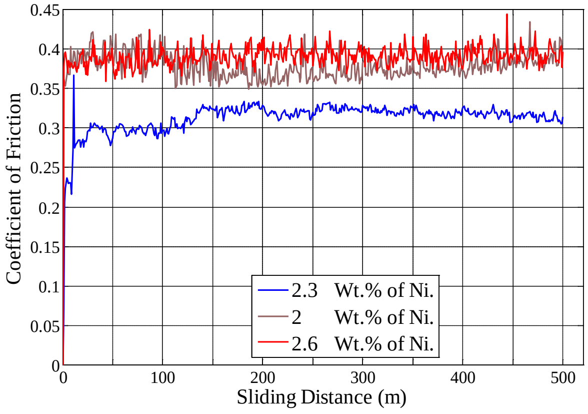

Fig. 6 Coefficient of Friction of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys as a function of sliding distance under the constant normal load of 30N and sliding speed of 0.6 m/s.

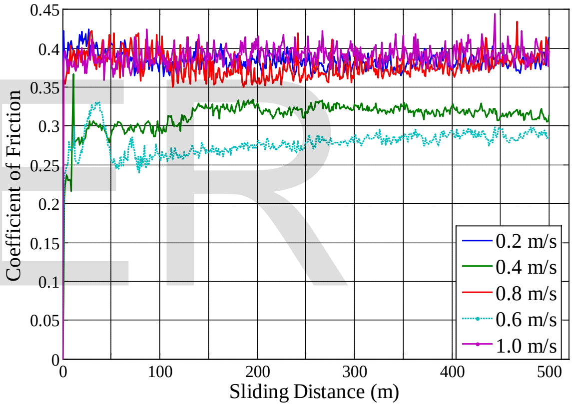

Fig. 7 Coefficient of Friction of Al-12.6Si-3Cu-2.3Ni Piston alloy as a function of sliding distance under the varying sliding speed (0.2 to1.0 m/s) and normal load of 30N.

4 CONCLUSIONS

1) The plate like β-eutectic silicon are more fractured and spheroidized and evenly dispersed in the α-Aluminium dendritic haloes by the addition of Ni. The average grain size and degrees of fineness of β-eutectic silicon increased by the addition of 2.3 wt. % Ni in the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The difference in the size and shape of different features are evident.

2) A significant improvement in the ultimate tensile strength of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys observed by the addition of Ni. Al-12.6Si-3Cu-2.3Ni piston alloy exhibited the maximum tensile strength of

236 MPa and is more than 58% and 14% that of Al-12.6Si-3Cu-2Ni and Al-12.6Si-3Cu-2.6Ni piston alloys respectively.

3) By the addition of Nickel on the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys improved the hardness. The maximum Brinell hardness of 99 and 136 observed for the Al-12.6Si-3Cu-2.3Ni Piston alloy in the as cast and heat treated conditions respectively among the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys.

4) A significant reduction in the wear loss obtained by the addition of 2.3 wt. % of Ni on the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys. A transition in wear loss characteristics observed at critical velocity of 0.6 m/s.

5) Al-12.6Si-3Cu-2.3Ni Piston alloy experienced a lowest coefficient of friction in the means of Ni weight percentage and by varying the sliding velocity from 0.2 to 1 m/s.

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REFERENCES

[1] R. X. Li, R. D. Li, Y. H. Zhao, L. Z. He, C. X. Li, H. R. Guan, and Z. Q. Hu, ‘Age-hardening behavior of cast Al-Si base alloy’, Materials Letters, vol. 58, no. 15, pp. 2096–2101, 2004.

[2] M. M. Haque and M. A. Maleque, ‘Effect of process variables on structure and properties of aluminium – silicon piston alloy’, Journal of Materials Processing Technology, vol. 77, pp. 122–128, 1998.

[3] H. Ye, ‘An overview of the development of Al-Si-alloy based material for engine applications’, Journal of Materials Engineering and Performance, vol. 12, no. June, pp. 288–297, 2003.

[4] Z. Qian, X. Liu, D. Zhao, and G. Zhang, ‘Effects of trace Mn addition on the elevated temperature tensile strength and microstructure of a low-iron Al-Si piston alloy’, Materials Letters, vol. 62, no. 14, pp. 2150–2153, 2008.

[5] A. M. Hassan, A. Alrashdan, M. T. Hayajneh, and A. T. Mayyas, ‘Wear behavior of Al-Mg-Cu-based composites containing SiC particles’, Tribology International, vol. 42, no. 8, pp. 1230–1238, 2009.

[6] Y. Li, Y. Yang, Y. Wu, L. Wang, and X. Liu, ‘Quantitative comparison of three Ni-containing phases to the elevated-temperature properties of Al-Si piston alloys’, Materials Science and Engineering A, vol. 527, no. 26, pp. 7132–7137, 2010.

[7] Y. Li, Y. Wu, Z. Qian, and X. Liu, ‘Effect of co-addition of RE, Fe and Mn on the microstructure and performance of A390 alloy’, Materials Science and Engineering A, vol. 527, no. 1–2, pp. 146–149, 2009.

[8] N. Belov, D. Eskin, and N. Avxentieva, ‘Constituent phase diagrams of the Al–Cu–Fe–Mg–Ni–Si system and their application to the analysis of aluminium piston alloys’, Acta Materialia, vol. 53, no. 17, pp. 4709–4722, Oct. 2005.

[9] M. Zeren, ‘The effect of heat-treatment on aluminum-based piston alloys’, Materials and Design, vol. 28, no. 9, pp. 2511–2517, 2007.

[10] Y. Yang, K. Yu, Y. Li, D. Zhao, and X. Liu, ‘Evolution of nickel-rich phases in Al – Si – Cu – Ni – Mg piston alloys with different Cu additions’, Materials and Design, vol. 33, no. 1, pp. 220–225, 2012.

[11] V. R. Rajeev, D. K. Dwivedi, and S. C. Jain, ‘Effect of load and reciprocating velocity on the transition from mild to severe wear behavior of Al-Si-SiCp composites in reciprocating conditions’, Materials and Design, vol. 31, no. 10, pp. 4951–4959, 2010.

[12] B. Venkataraman and G. Sundararajan, ‘Correlation between the characteristics of the mechanically mixed layer and wear behaviour of aluminium, Al-7075 alloy and Al-MMCs’, Wear, vol. 245, no. 1–2, pp. 22–38, 2000.

[13] J. Clarke and A. D. Sarkar, ‘Topographical features observed in a scanning electron microscopy study of aluminium alloy surfaces in sliding wear’, Wear, vol. 69, pp. 1–23, 1981.

[14] D. K. Dwivedi, T. S. Arjun, P. Thakur, H. Vaidya, and K. Singh, ‘Sliding wear and friction behaviour of Al-18% Si-0.5% Mg alloy’, Journal of Materials Processing Technology, vol. 152, no. 3, pp. 323–328, 2004.

[15] J. Kováčik, Š. Emmer, J. Bielek, and L. Keleši, ‘Effect of composition on friction coefficient of Cu–graphite composites’, Wear, vol. 265, no. 3–4, pp. 417–421, Jul. 2008.

[16] C. Subramanian, ‘Some considerations towards the design of a wear resistant aluminium alloy’, Wear, vol. 155, no. 1, pp. 193–205, 1992.