Wear Study of Surface Textured A356 Alloy under Wet Condition

Fazil Omer, Arjun C Pankaj, Cris George Toms, C.M. Fayis, G.L. Aswinikumar, V.R. Rajeev
and K. Jayaraj

Abstract— *In the present paper lubricated wear behavior of surface textured A356 alloy was investigated by means of pin–on-disc and pin-on-reciprocating plate tribometers. Surface texture is of circular depressions or called as dimples.The surface texturing on the surfaces of the pin was done by electro chemical machining. The number of dimples in each surface varies from zero to 16.The objective of this study is to find the variation of wear characteristics of A356 alloy with variation in number of circular depressions given on the material surface under wet condition in pin on disc and pin-on-plate wear test rig. A drastic decrease in wear loss was obtained with the surface texture on contacting surface of pins. The surface texture has several advantages as it acts as lubricant reservoir, provision for wear particles and area for hydrodynamic action of lubricant. Thus it can be concluded that surface textures, here dimples, can enhance mixed film state of hydrodynamic lubrication. In mixed film state the friction is least, and this may be the reason for drastic decrement of wear loss.*

Keywords— *A356 Alloy, Surface Textured Pattern, Electro Chemical Machining, ECM, Wet Wear, Mixed Film Hydrodynamic Lubrication*

I. INTRODUCTION

A. Aluminium alloys

ALUMINIUM and its alloys occupy third place among the commercially used engineering materials. In commercial aluminium casting alloys, Al–Si base alloys are perhaps most common, particularly due to its very attractive characteristics such as high strength to weight ratio, good workability, excellent castability, good thermal conductivity and corrosion resistance. Use of Al–Si alloys has received a boost for production of aluminium castings in recent decades. Aluminium castings have played an integral role in growth of aluminium industry since its inception in late 19th century. These are emerging as one of the most dominant materials in number of sectors like transport, military, aviation and general engineering. Aluminium–silicon alloys are popular in three different forms, i.e. hypoeutectic, eutectic and hypereutectic type, classified so depending up on the silicon content. Aluminium–silicon alloys containing 11–13% silicon are termed as eutectic alloys and those having less than 11% silicon are called hypoeutectic and those having more than 13% silicon are commonly known as hypereutectic Al–Si alloys.

B. A356 Aluminium Alloy

A356 is Aluminium-Silicon alloy with Copper and/or Magnesium as the main constituents. A356 aluminium alloys are characterized by very good mechanical properties and low porosity with a globular microstructure which is fine and uniform. The mechanical properties can be further improved through heat treatments such as T5 and T6. These alloys are used for casting general-purpose die castings. The common alloys used are 356-T6 for cast wheels. A356 has largely been replaced by A295 used in permanent mould castings for machine tool parts, aircraft pump parts, automotive transmission cases, aircraft fittings and control parts, water-cooled cylinder blocks, aircraft structures and engine controls, nuclear energy installations, and other applications where high-strength permanent mold or investment castings are required.

- Chemical composition of A356 [1]

A356.0: 0.20% Cu, 0.45% Mg, 0.10% Mn, 6.5% Si, 0.20% Fe, 0.10% Zn, 0.20% Ti, balance Al. This alloy is selected because of its light weight, high strength to weight ratio and low coefficient of thermal expansion. Also it is widely used as piston alloy in the case of reciprocating machineries.

C. Previous Related Studies

In the study of hydrodynamic lubrication of textured steel surfaces under reciprocating sliding conditions, H.L. Costa et al., 2007 [3] investigated the influence of surface topography on lubricant film thickness for the reciprocating sliding of patterned plane steel surfaces against cylindrical counter bodies under conditions of hydrodynamic lubrication. Patterns of circular depressions, grooves and chevrons were used, and the fractional area coverage, depth, width and sliding orientation relative to the texture were systematically varied. Chevron patterns pointing along the sliding direction gave higher film thicknesses than those pointing across. Among the

Fazil Omer, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016. E-mail: fazilomer@gmail.com
Arjun C Pankaj, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.
Cris George Toms, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.
C.M. Fayis, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.
G.L. Aswinikumar, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.
V.R. Rajeev, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.
K. Jayaraj, Department of Mechanical Engineering, College of Engineering Trivandrum, Kerala, India-695016.

patterns investigated, chevrons were the most effective and groove the least effective in increasing hydrodynamic film thickness.

In another study conducted by A.Shinkarenko et al., 2009 [4], a theoretical model was developed to study the potential use of laser surface texturing (LST) in the form of spherical micro-dimples for soft elasto-hydrodynamic lubrication (SEHL). The model consists of mutual smooth elastomeric and LST rigid surfaces moving relatively to each other in the presence of viscous lubricant. The pressure distribution in the fluid film and the elastic deformations of the elastomer are obtained from a simultaneous solution of the Reynolds equation and the equation of elasticity for the elastomer. An extensive parametric investigation is performed to identify the main important parameters of the problem, which are the aspect ratio and area density of the dimples. The parametric analysis provides optimum parameters of the surface texturing and shows that LST effectively increases load capacity and reduces friction in SEHL.

Friction and wear behavior study of laser textured surface under lubricated initial point contact by Andriy Kovalchenko et al., 2011 [5] has shown laser surface texturing (LST) by dimpling analytically and experimentally to enhance mixed, hydrodynamic, and hydrostatic lubrication of conformal sliding components. Improvements such as higher load-carrying capacity, higher wear resistance, and lower friction coefficients were observed in LST mechanical seals and thrust bearings. However, under non-conformal concentrated contact, the dimpled surface may have a different effect on the tribological behavior as a result of increased roughness, which may increase abrasive wear on the counterface. This paper discusses the effect of laser-textured surfaces on the tribological properties under a point ball-on-flat contact configuration. Discs with dimples having different depths and densities were evaluated. Results showed that disks with higher dimple density produced more abrasive wear on the ball specimen. However, this higher wear rate led to faster generation of conformal contacts and a transition from the boundary to mixed lubrication regime, resulting in a rapid reduction in the friction coefficient with increased ball wear. Results of the study may be beneficial for optimization of LST technology for industrial application in friction unit.

In modeling the hydrodynamic support of cylinder bore and piston rings with laser textured surfaces by Eduardo Tomanik[6], a special benefit was predicted when the micro-dimples were on the flat surface of the oil control rings.

D. *Mckee's Investigation*[7]

In hydrodynamic bearings, initially the journal is at rest. There is no relative motion and no hydrodynamic film. Therefore, there is metal to metal contact between the surfaces of journal and bearing. As the journal starts to rotate, it takes some time for the hydrodynamic film to build sufficient pressure in the clearance space. During this period, there is partial metal to metal contact and partial lubricant film. This is thin film lubrication. As the speed is increased more and more lubrication is forced into wedge shaped clearance space and sufficient pressure is built up between surfaces of journal and the bearing. This is thick film lubrication. There is transition between thin to thick film lubrication, called mixed film lubrication, where the coefficient of friction is the least (Fig. 1).

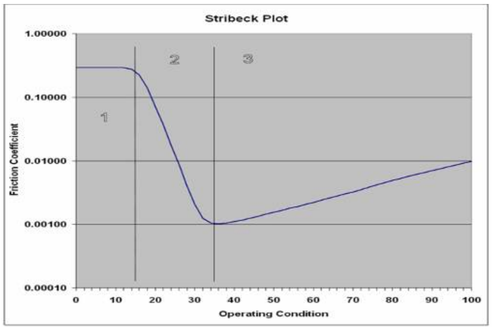

Fig. 1: Mckee's investigation

Operating condition is defined by bearing characteristic number = $(\mu N)/(p)$

Where, μ = *absolute viscosity of lubricant*

N = *speed of journal*

p = *unit bearing pressure*

E. *Objective*

The objective of this paper is to study the variation of wear characteristics of A356 alloy [2] with change in number of circular depressions or dimples present on the contacting surface of pins using a pin-on-disc wear test rig and reciprocating wear test rig under lubricated condition.

F. *Experimental method*

Study is done on two separate test rigs; 12mm pin on unidirectional pin-on-disc wear test rig and 6mm pin-on-reciprocating test rig. Sliding velocity is kept to constant value. Counter surface is EN 31 steel and lubricating oil used is SAE-20 (used engine oil). Test is done on separate velocities. RPM for motor is found from velocity and applied via VARIAC. Time for application of contact wear is found by dividing sliding distance by sliding velocity. Wear loss was measured using shimadzu weighing machine.

Separate observation tables are drawn for each velocity. Graphs are plot for each velocity with load in newton on X-axis and wear in milligram (mg) on Y axis. Curves representing each pattern type are plot for each velocity. In a particular velocity the curves are compared and analyzed. Similarly curves for each velocity are also compared and analyzed.

II. MATERIALS AND TESTS

A. *Pin preperation*

A356 alloy was prepared through tilting furnace casting route [2]. For the testing purpose two types of pins were cut from the cast A356 alloy. One pin was having 6 mm diameter and 30 mm length and the other was12 mm diameter and 60 mm length. The sequential steps for pin preparation are:

- Milling of A356 block
- Turning operation

- Finishing of surface
- Surface texturing

Fig. 2: Pin after Finishing

B. *Surface texturing by Electro Chemical Machining (ECM)*

In surface texturing, the circular surfaces of the cylindrical pins were made into surfaces with different number of dimples. The number of dimples in each surface varies from zero to 16. The surface texturing on the surfaces of the pin was done by electro chemical machining (ECM) (Fig. 3).

In electro chemical machining the material was machined by electro chemical method. First the whole pin was covered by an insulation tape except at the points where we want dimples. Then a copper wire was attached closer to the surface on that have to make dimples (Fig. 4). Then electrical connections were provided for both pin and copper. Pin connected to the positive terminal of an external battery and copper was connected to the negative of the battery. Here the pin was acted as anode and copper wire as cathode. Then it was immersed in electrolyte. Electrolyte was a solution of NaCl in distilled water. By this set up electro chemical reactions occurred at the points those were exposed to electrolyte. Circular depressions were formed eventually on these points. At the end of process require number of dimples were obtained on the surface of the pin.

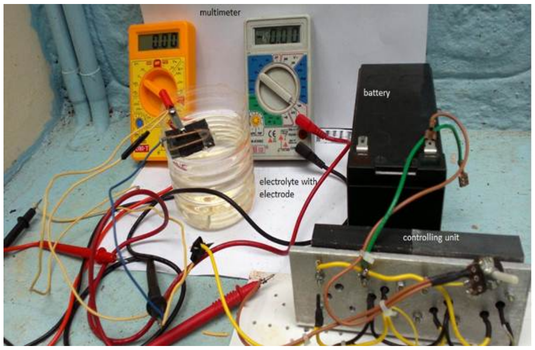

Fig. 3: ECM Set up

The experimental reaction is given as;

$$Al \rightarrow Al^{3+} + 3e^{-} \text{(Anode)}$$

$$Cu^{2+} + 2e^{-} \rightarrow Cu \quad \text{(Cathode)}$$

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$$

$$\tfrac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-}$$

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

$$Al^{3+} + 2OH^{-} \rightarrow Al_2(OH)_3 \text{(aluminium hydroxide)}$$

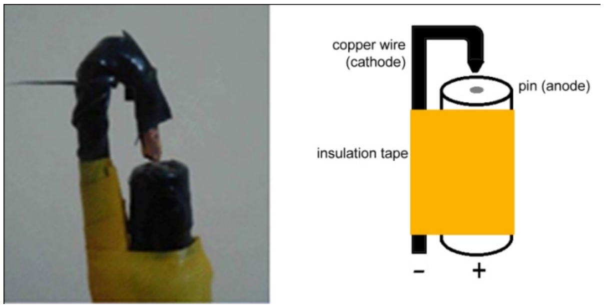

Fig. 4: Anode-Cathode Combination

The above given reaction indicates the chemical reaction that takes place during the electro chemical machining operation. The anode was taken as the Al alloy electrode and the cathode as Cu electrode. NaCl solution was used as the electrolyte. Reduction takes place at cathode and oxidation takes place at anode. As the chemical reaction progress the amount of Al_2OH_3 aluminium hydroxide formed in the solution reduces the voltage and hence reduces the conductivity of the solution. In order to compensate the voltage drop the voltage regulator was adjusted to obtain the intended voltage. Thus the specimen was kept in the solution for 2 minutes till the required pattern is obtained with specified dimple diameter.

C. *Pin on Disc Apparatus*

The pin-on-disc configuration is commonly used for wear tests in laboratories because of its simple arrangement (Fig. 5). With the conventional pin on disc wear test, the pin specimen is held stationary on top of a precision ground rotating disc, EN 31 steel, with the required load applied through the pin. With the use of a variable speed motor, the rotational speed of the disc can be varied.

The linear speed of the disc at the point where the pin is located is:

$$V_{disc} = (2\pi RN)/60$$

"V_{disc}" is the linear speed of rotating disc, "R" is the distance from centre of pin to centre of disc and "N" is rotational speed of disc in rotations per minute (rpm). The conventional pin on disc wear test is conducted with a constant "R" and a small portion of the disc is utilized.

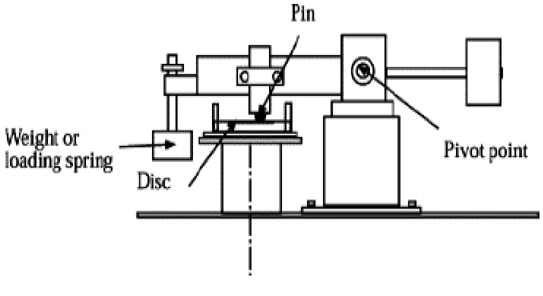

Fig. 5: Pin on disc apparatus 2 Dimensional

D. *Pin-on-eciprocating plate tribometer*

A pin-on-reciprocating plate tribometer [8-9] was used for finding wear characteristics of surface textured A356 alloy. Here reciprocating motion of plate was achieved by connecting rod, motor and crank shaft set up. The pin was held in the pin holder. The pin holder was fixed on the lever arm of the test rig. At one end of the lever arm weight was provided. This weight was acted on the pin. But because of the leverage the actual weight acting on the pin was not equal to the weight provided at the lever arm. The net weight acting on the pin was the product of weight provided and leverage. The speed of motor was controlled by a variac. Using variac reciprocating velocity for testing the specimen was fixed and sliding distance chosen as 350m. Wear loss was found by measuring the initial weight and final weight of the test specimen and taking the difference in weight. The weighing of the test specimen was done using shimadzu weighing machine (Fig. 7). Then the experiment was repeated for different loads at constant velocity. After that we changed the velocity and experiment was conducted on different loads and wear loss was measured. During the testing of the specimen engine oil used for lubrication was SAE 20.

$$\text{Velocity} = (2LN)/60$$

Where, L = Stroke length, m

N = speed of motor in rpm

Time required for testing = (sliding distance)/(velocity)

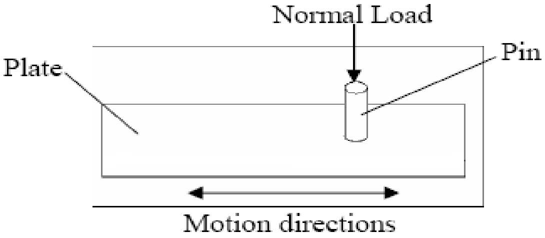

Fig. 6: Schematic diagram showing pin-on-reciprocating plate tribometer[8,9]

Fig. 7: Shimadzu Weighing Machine

III. Results And Discussions

A. Pins after electrochemical machining

Since A356 has good machinability over steel and aluminium, electrochemical machining was fast and almost accurate. Only 2 minutes or less is required for obtaining required dimensions of dimples on pin surface (Fig. 8).

- Diameter of the dimples = 0.8 millimeters (approx.)
- Depth of the dimples = 0.8 millimeters (approx..)
- Voltage = 5V to 8V
- Current required = 1.5A to 2.5A

Fig. 8: Photographic view of ECM surface textured and non-textured A356 alloy pins

B. Pin on Disc Tests

Total 3 tests of different velocities were done on each pin. For each velocity 3 different loads also applied.

- Pins used,
  - With no pattern
  - With 8 dots
  - With 16 dots
- Pin diameter = 12mm
- Sliding distance = 500m
- Velocities and time,
  - 0.4 m/s and 20.8 minutes
  - 0.7 m/s and 11.9 minutes
  - 1 m/s and 8.3 minutes
- Loads applied,
  - 20 N
  - 50 N
  - 90 N

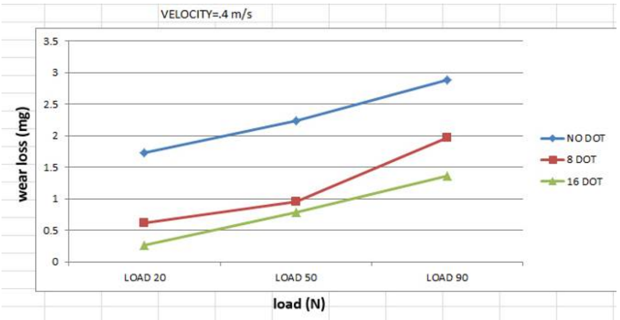

Fig. 9: Wear loss v/s load graph for surface textured and non textured A356 alloyat sliding velocity 0.4 m/s slid through 500m

Fig. 9 shows the variation of wear loss against load of 12mm pin with sliding velocity = 0.4m/s on pin on disc wear test rig (sliding distance =500m). With increase in load wear loss increases for each type of patterned pin. Wear loss decreases with the presence of surface pattern. Similarly the wear loss decreases as the number of dots (or dimples) on surface increases.

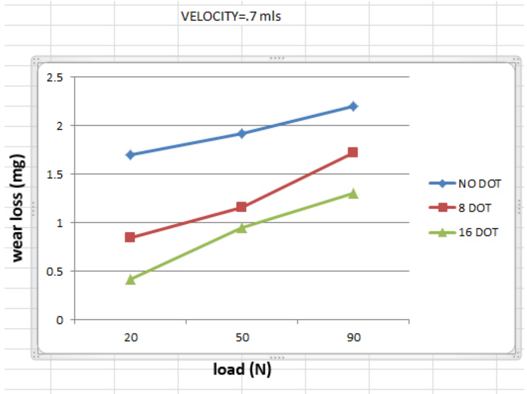

Fig. 10: Wear loss v/s load graph for surface textured and non textured A356 alloy at sliding velocity 0.7 m/s slid through 500m

Fig.10 shows the variation of wear loss against load of 12mm pin with sliding velocity = 0.7m/s on pin on disc wear test rig (sliding distance =500m). With increase in load wear loss increases for each type of patterned pin. Wear loss shows a decrease with the presence of surface pattern. Similarly the wear loss decreases as the number of dots (or dimples) on surface increases.

When compared with the earlier graph of wear loss v/s load for velocity 0.4m/s, wear loss decreases for almost all loads when the velocity is increased from 0.4m/s to 0.7m/s.

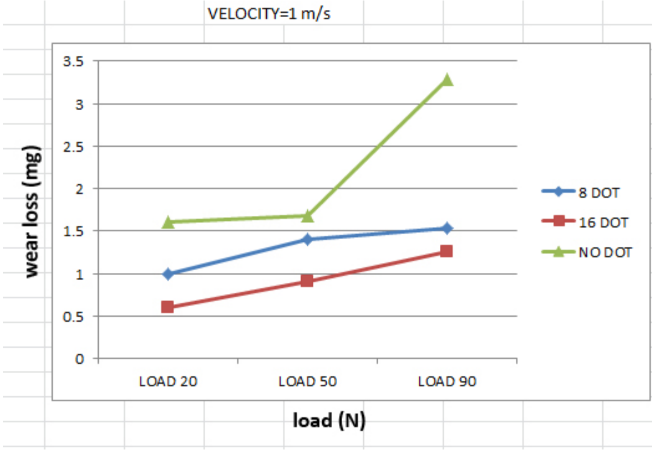

Fig. 11: Wear loss v/s load graph for surface textured and non textured A356 alloy at sliding velocity 1 m/s slid through 500m

Fig. 11 shows the variation of wear loss against load of 12mm pin with sliding velocity = 1m/s on pin on disc wear test rig (sliding distance =500m). With increase in load wear loss increases for each type of patterned pin[10]. Wear loss shows a decrease with the presence of surface pattern. Similarly the wear loss decreases as the number of dots (or dimples) on surface increases.

This graph for velocity 1m/s shows the least wear loss when compared with those graphs for velocities of 0.4m/s and 0.7 m/s.

C. *Tests on reciprocating wear test rig*

Total 3 tests of different velocities were done on each pin. For each velocity 3 different loads also applied.

- Pins used,
    - With no pattern
    - With 3 dots
    - With 6 dots
- Pin diameter = 6mm
- Sliding distance = 350m
- Velocities and time,
    - 0.4 m/s and 14.5 minutes
    - 0.8 m/s and 7.3 minutes
- Loads applied,
    - 15 N
    - 45 N
    - 60 N

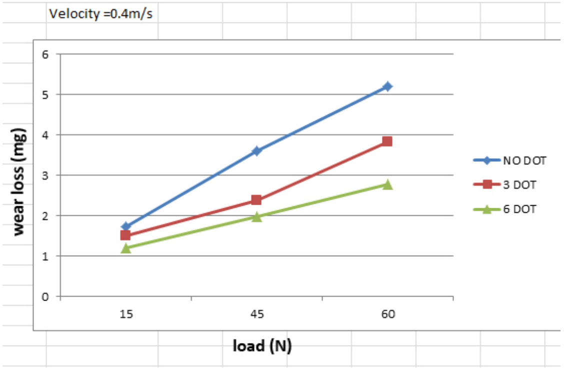

Fig. 12: Wear loss v/s load graph for surface textured and non textured A356 alloy at sliding velocity 0.4m/s slid through 350m

Fig. 12 shows the variation of wear loss against load of 6mm pin with sliding velocity = 0.4m/s on reciprocating wear test rig (sliding distance =350m). With increase in load wear loss increases for each type of patterned pin. Wear loss shows a decrease with the presence of surface pattern. Similarly the wear loss decreases as the number of dots (or dimples) on surface increases.

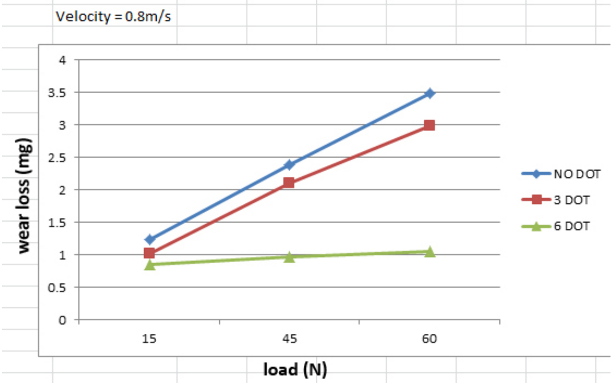

Fig. 13: Wear loss v/s load graph for surface textured and non textured A356 alloy at sliding velocity 0.8m/s slid through 350m

Fig. 13 shows the variation of wear loss against load of 6mm pin with sliding velocity = 0.8m/s on reciprocating wear test rig (sliding distance =350m). With increase in load wear loss increases for each type of patterned pin. Wear loss shows a decrease with the presence of surface pattern. Similarly the wear loss decreases as the number of dots (or dimples) on surface increases.

This graph for sliding velocity 1m/s shows the less wear loss when compared with graph for sliding velocity 0.4m/s.

IV. CONCLUSION

The future work in this area includes the optimization of wear rate of wear test pin against the number of dimples in the specimen. Wear rate should be minimized for maximum number of dimples in the wear test pin. The major conclusions of the present study are reported as below.

1. Increment of wear loss with increase in load was observed in each graph of wear loss v/s load. This proportional variation in wear with load may be due to more metallic intimacy between the surfaces. It is obvious that as load increases, stress on pin in contact with counter surface increases which enhances more metal to metal contact. Thus lubricating film thickness also decreases which in turn causes increment of wear.

2. With increase in velocity of sliding the wear loss decreased for almost all loads and sliding conditions. This variation may be due to the lapse of time of contact between the pin and the counter surfaces.

3. A drastic decrease in wear loss was obtained with the surface texture on contacting surface of pins. The surface texture has several advantages as it acts as lubricant reservoir, provision for wear particles and area for hydrodynamic action of lubricant. Thus it can be concluded that surface textures, here dimples, can enhance mixed film state of hydrodynamic lubrication. In mixed film state the friction is least, and this may the reason for drastic decrement of wear loss.

4. Wear loss was decreasing as the number of dimples on the surface of pins were increased. This may due to the - achievement of uniform mixed film lubrication state over more areas of pin surface.

ACKNOWLEDGMENT

The authors are grateful for the fund received from Centre for Engineering Research and Development (CERD), Government of Kerala for this work; and for the support received from the staff of College of Engineering Trivandrum, Directorate of Technical Education, Government of Kerala, Trivandrum.

REFERENCES

[1] H.R. Lashgari , A.R. Sufizadeh, M. Emamy, "The effect of strontium on the microstructure and wear properties of A356–10%B4C cast composites", Materials and Design 31, 2010, pp. 2187–2195

[2] Renchu, "Casting and wear study of A356 alloy" BTech project approved by Kerala university, 2011, College of Engineering Trivandrum, Trivandrum-16.

[3] H L Costa, I M Hutchings, "Hydrodynamic lubrication of textured steel surfaces under reciprocating sliding conditions", Tribology international 40, 2007, pp. 1227-1238.

[4] A Shinkarenko, Y Kligerman, I Etsion, "The effect of surface texturing in soft elasto hydrodynamic lubrication", Tribology International, 42, 2009, pp. 284-292.

[5] Andriy Kovalchenko, Oyelayo Ajayi, Ali Erdemir, "Friction and wear behaviour of laser surface textured surface under lubricated initial point contact", Wear, 271, 2011, pp. 1719-1725.

[6] Eduardo Tomanik, "Modelling the hydrodynamic support of cylinder bore and piston rings with laser textured surfaces", Tribology International 59, 2013, pp. 90-96.

[7] V B Bhandari, Text book on "Design of Machine Elements", Tata McGraw Hill publishers, 3rd edition, pp. 600-608.

[8] V.R.Rajeev, D.K.Dwivedi, S.C.Jain,"Effect of experimental parameters on reciprocating wear behavior of Al–Si–SiCp composites under dry condition". Tribol Online 4(5), 2009, pp. 115–26.

[9] ASTM G 133-05 standards, "Standard test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear", Annual Book of ASTM Standards.

[10] V.R.Rajeev, D.K.Dwivedi and S.C.Jain, "A Fractional Factorial Design Study of Reciprocating Wear Behavior of Al-Si-SiC$_p$ Compositesat Lubricated Contacts", Journal of Materials Engineering and Performance, ASM International, Volume 20(3), April 2011, 368-376.