Shiv Pratap Singh Yadav

AssistantProfessor
NITTE Meenakshi Institute of Technology
Bangalore,
India

S. Ranganath

Professor
University Visveswaraya College of
Engineering
Bangalore,
India

Salim Sharieff

AssistantProfessor
HKBK College of Engineering
Banhgalore,
India

R. Suresh

Associate Professor
Dept. of Mechanical and Manufacturing
Engineering
MS Ramaiah University of Applied Sciences
Bangalore,
India

L. Avinash

Assiistant Professor
NITTE Meenakshi Institute of Technology
Bangalore,
India

Investigations on the Change in State of Stress with respect to the Sliding Direction in Dry Sliding Wear of Hard Elastic Material with Different Geometry and Orientation on Ductile Flat Surface

In the present study, experiments have been carried out by sliding hard elastic material on ductile flat surface. The different state of stress has been achieved by changing the geometry of hard material and different orientation of changed geometry with respect to sliding direction. Experiments have been carried out using pin on disc wear test rig. The tests were conducted with Al6061 alloy disc and EN8 alloy steel pin with different tip geometries and orientations. The obtained results revealed that coefficient of friction was higher at lower loads compared to higher loads in hemisphere pin geometry. An exception has been found at 90° orientation at low loads. It has been attributed to adhesive effect. The state of stress and its configuration with respect to direction of sliding was found to influence the sliding phenomenon. Micrograph studies revealed damages due to adhesion, abrasion and extrusion.

Keywords: Dry sliding wear; Non-conforming static contacts; Normal load;Pin Geometry;Orientation; Coefficent of Friction; Surface Analysis.

1. INTRODUCTION

Mechanical design of sliding surfaces require low coefficient of friction and wear resistance on contact surfaces. The shear forces due to sliding lead to higher wear of ductile materials ultimately leads to component failures. The friction behaviour has a great influence on the quality of the component and the energy requirement for the metal forming and other manufacturing processes. Tribological parameters of the contact surfaces and surface topology greatly influence many of the industrial applications. The study of frictional behaviour between contacting surfaces is generic and the results obtained are applicablein die design for both cold and hot extrusion of aluminium alloys. Also, the study helps in understanding and redesigning non-conforming contacts particularly in ball and roller bearing journal and valve trains.

In the load transfer from one element to another, where the contacting surfaces are non-conforming, the stress state is not uniform. Addressing the stress state was attempted by Hertz [1]. When two identical spheres are made to transfer load, the contact area was found to be of circular cross section and stress was maximum in the centre of circle and zero at the periphery of contact area. Solution for sliding contact was introduced and analysed in [2-4]. Hamilton and Goodman [5] analysed theoretically the stress field created by the sliding contact. The theoretical prediction shows a compressive stress at sliding edge and tensile stress on a trailing edge. The magnitude of maximum of both tensile and compressive stresses were found to be dependent on the coefficient of friction.

Several researchers have attempted conducting experiments in the laboratory in order to understand the effect of phenomenon like subsurface plastic deformation, material properties and surface structures of contacting surface. Rigney and Hirth [6] developed a model considering near surface deformation recovery and microstructure during steady state sliding. They found that model predicted the phenomenon observed in the experiment due to change in load, sliding distance, surface temperature and microstructure. Murray et al. [7] conducted experiment using pin on drum test rig. They studied the effect of hardness accomplished by different heat treatment processes on friction and wear.

Brizmeret al. [8] studied the role of contact conditions, which affect the transition from elastic to plastic deformation. Mascia et al. [9] conducted an abrasive experiment making use of lapping principle. They identified mode depending upon the hardness of the substance, such as sliding, rolling and abrasive. Karto [10] and Blau [11] independently identified that the state of stress at contact surfaces are reported to be parameters influencing the wear and friction. Sherbiney and Halling [12] conducted experiments on iron plated soft metallic films. The result showed that with increase in rolling cycle the friction coefficient drastically increased. The high coefficient of friction was found to increase maximum tensile stress at the trailing edge [13]. Diaoet al. [14] reported that the high tensile stress at the trailing edge combined with local yield of the coating resulted in delamination. Experiment conducted on brittle glass by sliding hot sphere resulted in ring crack [15].

Ramesh et al. [16] conducted wear experiments using pin on disc tester for evaluating the performance of Titanium diboride (TiB$_2$) reinforced AL7075 composites. The results showed that 12% TiB2 resulted in better tribological response. Sathickbasha et al. [17] conducted tribological studies using chase testing machine for evaluating effect of steel family fibres on friction and stiction behaviour of brake pads. The result showed that there is decrease in coefficient of friction up to 300 °C and then stabilized afterwards. Sachit and Mohan [18] conducted experiments using pin on disc test rig for evaluating tribological behaviour of aluminium LM4 reinforced with hybrid nano composites of WC and Ta/NbC. The result showed that there is an improvement in tribological performance of the composite when it is reinforced with hybrid WC and Ta/NbC particles. Surendran et al. [19] conducted experiments using pin on disc tester for evaluating aluminium alloy composites wherein nano-aluminium was added. The addition of nano alumina improved wear performance.

The literature review indicates the effect of state of stress on damages on surface and subsurface. The studies of the researchers referred in literature concentrate on lower magnitude of stress and symmetric configuration state of stress on sliding phenomenon with respect to sliding direction [20-23].

The literature does not reflect on the role of higher magnitude of stress and non-symmetric configuration of sate of stress with respect to sliding directions on sliding phenomenon. A lesser amount of work has been done in identifying the role of state of stress in case of ductile materials with different pin geometries and orientations.

The present study aims at investigating aluminium steel pair performing sliding test with pin on disc configuration to reproduce solid/solid interaction. In the present investigation, different state of stress configurations, are achieved by sliding full sphere tipped and differently oriented half-hemisphere tipped EN8 alloy steel pin on soft aluminium disc.

2. EXPERIMENTAL DETAILS

In the present investigation attempts have been made to understand the role of state of stress on sliding phenomenon for a ductile substrate. The change in state of stress is achieved by employing full sphere and half sphere, which have been differently configured to the sliding direction. The hard element of the pair is made out of EN8 alloy steel. The other element of the pair, a ductile Al6061alloy was a precipitation-hardened aluminium alloy, containing magnesium and silicon as its major alloying elements.The pins have been machined out of EN8 steel stock bar and hemisphere was cut by wire EDM machine. Sphere pin and hemispherical tipped pin along with dimension are shown in Figure 1.

Wear test was conducted using pin on disc test rig as per ASTM G99 is as shown in Figure 2. Experiments have been conducted with a normal load of 0.5 kg, 3 kg and 5 kg. All experiments have been conducted over a sliding time of 120 seconds and speed of 250 rpm.
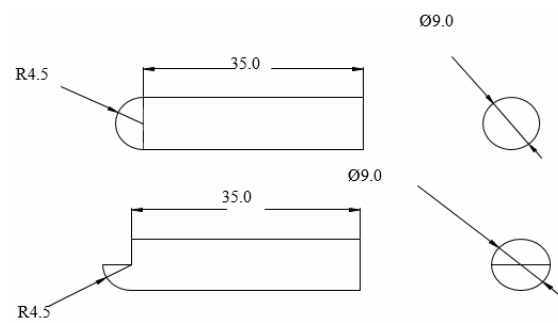

Figure 1. Sphere and hemisphere pin geometry

Figure 2. Pin on disc wear test rig

The different configured state of stress has been achieved by holding pin in different orientation with respect to sliding direction and details are tabulated in Table 1.

Table 1. Orientation of pin with respect to sliding direction of disc

| Sl. No.	Orientation of pin
1	Full Sphere
2	Hemisphere 0° configured stress state
3	Hemisphere 45° configured stress state
4	Hemisphere 90° configured stress state

3. RESULTS AND DISCUSSIONS

Different state of stress configuration with respect to sliding direction is achieved by holding straight edge of full sphere and half sphere with 0°, 45° and 90° to the sliding direction.

Figure 3 shows the variation of coefficient of friction with sliding time for full sphere pin for normal Load of (a) 0.5 kg (b) 3 kg & (c) 5 kg. The coefficient of friction from start to over a period of 7 second from sliding was found to be steadily increased from nil to approximately 0.40. The coefficient of friction, after sliding time of 7 seconds and up to 30 seconds, was found to be steadily increasing from 0.40 to 0.70. The coefficient of friction was found to stabilize with a value of 0.7 until experiment was completed i.e. up to 120 seconds.

3.1 Results of Sliding Sphere on Aluminium Disc- Full Sphere

The average values of coefficient of friction are plotted with respect to corresponding normal loads and shown in Figure 4.The minimum value of coefficient of friction
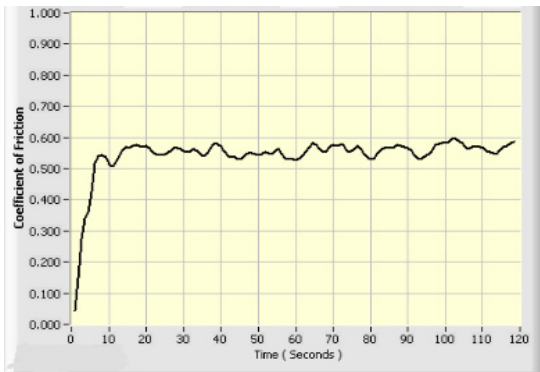
is 0.54 for normal load of 3 kg and maximum value ofcoefficient of friction is 0.7 for normal load of 0.5 kg.The average coefficient of friction was found to decrease from 0.70 to 0.56 when normal load increases from 0.5 kg to 5 kg. It is observed that the average coefficient of friction was found to be stabilized with further increase in normal load.
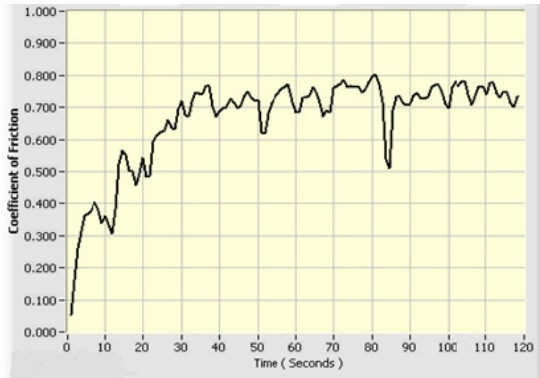
(a)
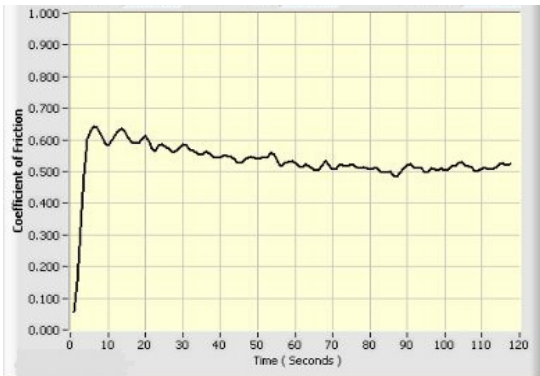
(b)

(c)

Figure 3. Graph of Coefficient of friction with sliding time for full sphere pin for (a) Normal Load of 0.5 kg (b)Normal Load of 3 kg & (c) Normal Load of 5 kg.
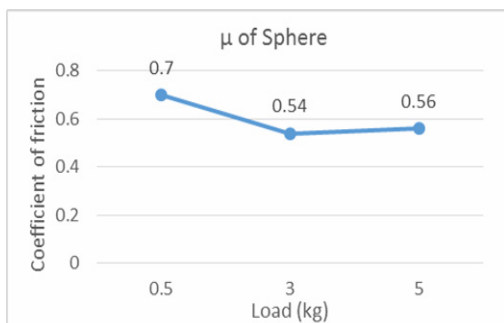

Figure 4. Dependency of Coefficient of friction on normal loads for Disc-Full Sphere

3.2 Microstructural Examination o Aluminium Disc Track Surface for Full Sphere

For elucidating the dependency of friction on normal load and configuration of stress state, Scanning Electron Microscope (SEM) was used. Figure 5 indicates the wear of aluminium disc track surface for full sphere at different load conditions.The tests were performed at. Figure 5(a) shows the adhesion wear of disc track surface load at 0.5 kg load condition. It can be observed that the adhesion wear with uneven damages on the contact surface of disc. The damages were occurs because of ductility of the material under low load condition. Also, abrasive was found to be shorter in length and these features attribute to the observed dependency of coefficient of friction on sliding time.

Figure 5(b) and 5(c) are exhibiting adhesion and abrasion wear mode of disc track surface at higher load at 3kg and 5kg conditions. The damage occurs due to abrasion wear and it is found to be more predominant when compared to adhesive wear at 0.5 kg load condition (Figure 5(a)). The damage due to abrasive are found to be steadier. The extent of extrusion features are also be observedFigure 5(b) and 5(c).
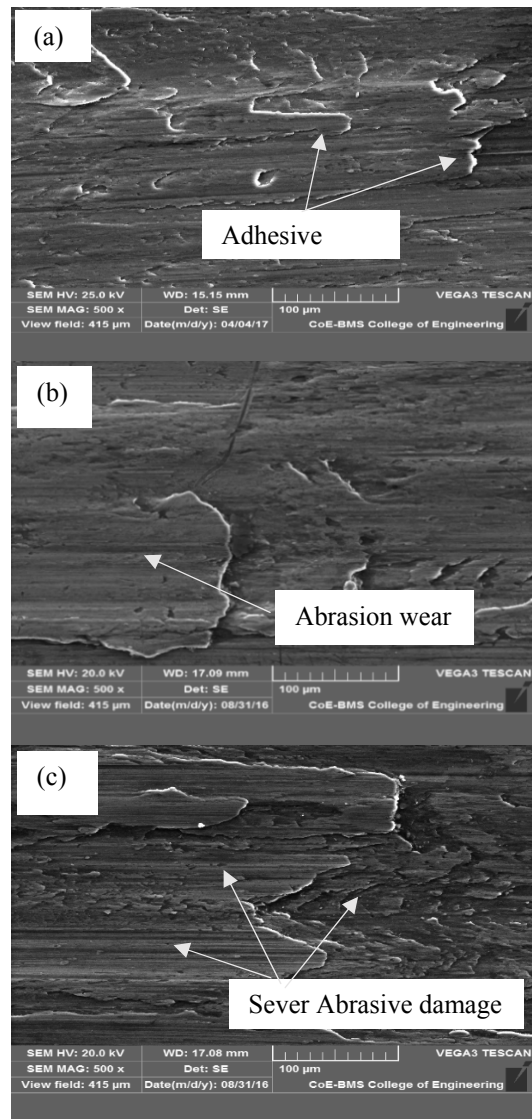

Figure 5. Micrographs of Al6061 disc track surface at a load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg.

3.3 Results of Sliding Hemisphere on Aluminium Disc at 0° Configured Stress State

The average value of coefficient of are plotted with respect to corresponding normal loads for sliding hemisphere at 0° is as shown in Figure 6. The maximum value is 0.68 for normal load of 0.5 kg and minimum value of coefficient of friction is 0.53 for 5 kg. The average coefficient of friction was found to be 0.64 for a normal load of 0.5 kg, 0.58 for a normal load of 3 kg and 0.53 for 5 kg. The average coefficient of friction was found to decrease from 0.64 to 0.53 when normal load changes from 0.5 kg to 5 kg. The reason is that the perceptiveness on a hard surface (EN8 alloy steel) slides against the softer counterface, the softer surface (Aluminium alloy) will flow plastically and a conformal groove to be formed on the disc surface.
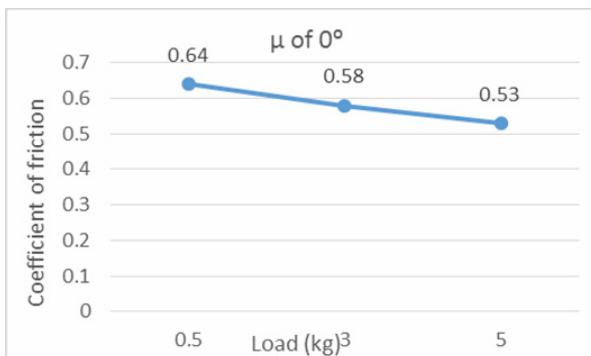

Figure 6. Dependency of Coefficient of friction on normal loads for Disc-0° configured stress state

3.4 Results of Sliding Hemisphere on Aluminium Disc at 45° Configured Stress State

The average values of coefficient are plotted with respect to corresponding normal loads for sliding hemisphere at 45° is as shown in Figure 7. The maximum value is 0.69 for normal load of 0.5 kg and minimum value of coefficient of friction is 0.54 for 5 kg. It is observed that decrease of the coefficient of friction at 3 kg load condition and it is further stabilized. Similar observation is found in the 0.5 kg load condition. It is due to the increased load, huge amount of material accumulated in the contact area and it act as third body. Therefore, three body wear mechanism was accountable for the reduction in coefficient of friction. It reveals that the effect of coefficient of friction was found to get stabilized with further increase in normal load conditions of 0.5 kg to 5 kg.
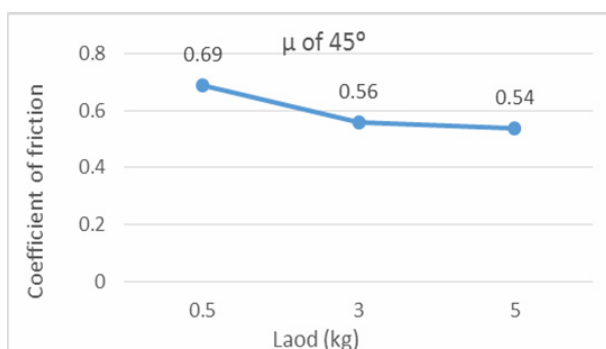

Figure 7. Dependency of Coefficient of friction on normal loads for Disc-45° configured stress state

3.5 Results of Sliding Hemisphere on Aluminium Disc at 90° Configured Stress State

The average value of coefficient of are plotted with respect to corresponding normal loads forsliding hemisphere at 90° is as shown in Figure 8. The average coefficient of friction was found to be 0.31 for a normal load of 0.5 kg, 0.60 for a normal load of 3 kg and 0.50 for 5 kg. The average coefficient of friction was found to increase from 0.31 to 0.60 when normal load changes from 0.5 kg to 3 kg and further decreases from 0.60 to 0.50 when the increases of normal load of 5 kg.The reason is that the average coefficient of friction is decreased with further increase in normal loadof 5 kg and also the contact pressure consistently decreased to some extent at which load is supported, which is purely elastic.
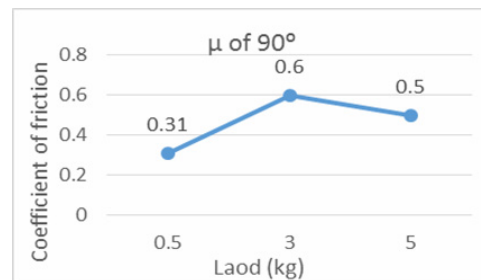

Figure 8. Dependency of Coefficient of friction on normal loads for Disc-90° configured stress state

The difference between the maximum and minimum value of coefficient of friction at a given load from the values shown in Figure 9. This difference is called the range of COF for a given load. The coefficient of friction was in the range of 0.62 to 0.70 for configuration of 0°, 45° and full sphere at a load of 0.5 kg. As load increases from 0.5 to 3 and 5 kg, the coefficient of friction was found to be stabilizes over a range of 0.44 to 0.58. The coefficient of friction was found to decrease in case of stress state configured at 0°, 45° and 90°. The coefficient of friction is 0.31 for configuration of 90° at 0.5 kg. The coefficient of friction was found to increase in the case of full sphere.
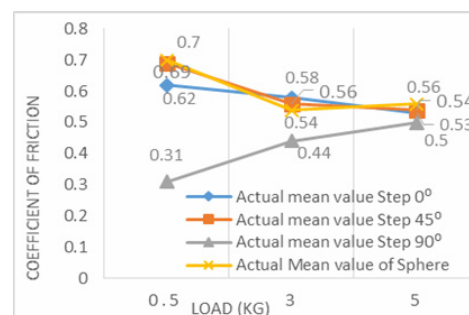

Figure 9. Dependency of Coefficient of friction on normal loads for Disc-45° configured stress state

The dependency of coefficient of friction on range of different load conditions configured stress state is as shown in Fig. 10. It is observed that the range is 0.39 at normal load of 0.5 kg and 0.14 at normal load of 3 kg and 0.06 at normal load of 5 kg. The range of coefficient of friction is maximum at lower load of 0.5 kg and gets reduced as normal load increases. It is mainly due to the interfacial coefficient friction between hard

asperity (EN8 alloy) and mechanical properties of the softer material (Aluminium alloy), increased load condition and also repeated pass on the track.
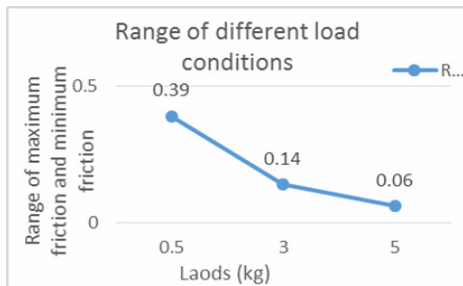

Figure 10. Dependency of Coefficient of friction on range of different load conditions configured stress state

3.6 Microstructural Examination of Full sphere Pin Surface

Figure 11 shows the SEM images of full sphere pin surface wear at load conditions of 0.5 kg, 3kg and 5kg. Figure 11 (a) indicates the evident of aluminium transfer due to adhesion effect on pin surface. The pile up of aluminium at the trailing end exhibits feature of metal transfer due to adhesion. The feature of metal transfer in Figure 11(b) and (c) are almost similar. Feature of adhesion is not much predominant. The coverage of transfer aluminium material on pin surface exhibits a pattern of ellipse (major axis in the direction of sliding). It indicates that the material transfer occure due to extrusion and abrasion.

3.7 Microstructural Examination of Hemisphere Pin Surface at Disc at 0° configured stress state

Figure 12 shows the hemisphere pin surface wear at 0° configured stress state with 0.5 kg, 3kg and 5kg load conditions. Aluminium transfer due to adhesion effect on pin surface is more evident in Figure 12(a). The pile up of aluminium at the trailing end exhibits feature of metal transfer due to adhesion.
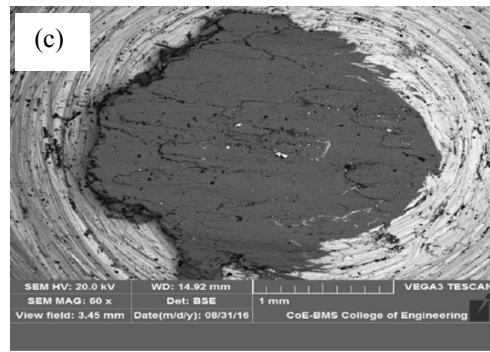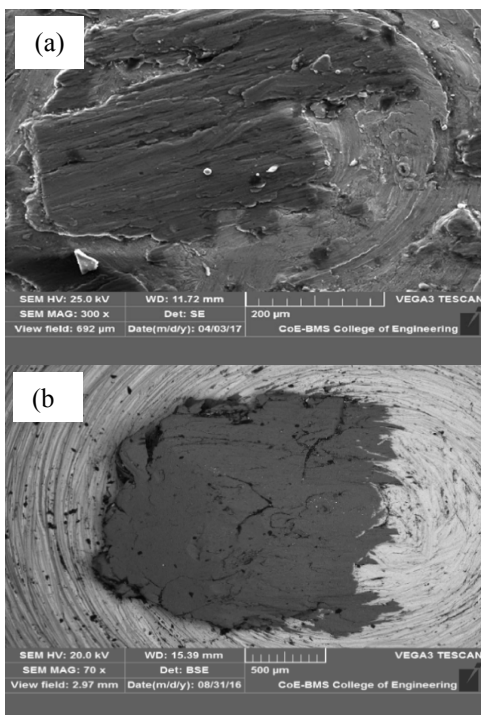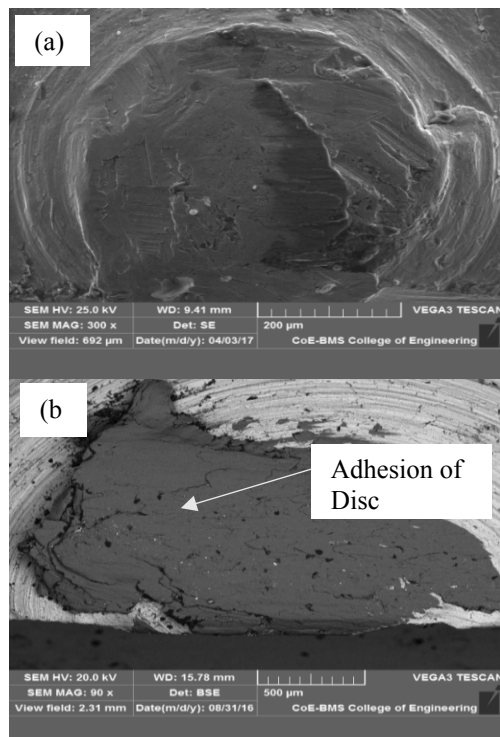

Figure 11.The worn surface micrographs of full shere pin at load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg.

Micrographs in Figure 12(b) and 12(c) are the disc material transfer layer on the pin at normal load 3 kg and 5 kg respectively. The feature of disc meterial transfer in Figure 12(b) and 12(c) are similar. It can be revealed that the increase in load deteriorate the ability of the specimen to resist wear and this leads to higher wear rates.

3.8 Microstructural Examination of Hemisphere Pin Surface at Disc at 45° configured stress state

Figure 13 shows the worn surface micrographs of hemisphere pin at 45° configured stress state with normal load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg. Figure 13(a) indicates the small transfer layer of disc material on the pin at the normal load of 0.5 kg. The feature of the transfer layer are irregular indicating dominance of adhesion.

Micrographs of Figure 13(b) and 13(c) are the disc material transfer layer on the pin at normal load of 3 kg and 5 kg respectively. It appears to be almost similar dominance of extrusion effect. It is observed that the dependency of coefficient of friction on normal load can be attributed to competing effect of adhesion and abrasion phenomenon which have been identified in worn surface micrographs.
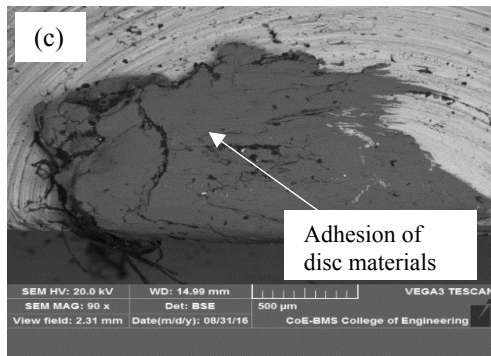
Figure 12.The worn surface micrographs of hemisphere pin at 0° configured stress state with load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg.

3.9 Microstructural Examination of Hemisphere Pin Surface at Disc at 90° configured stress state

Figure 14 shows the worn surface micrographs of hemisphere pin at 90° configured stress state with normal load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kgfor identifying the possible sliding mechanism. Micrographs Figure 14(a) shows the disc material transfer layer of pin for the normal load at 0.5 kg. The features of the transfer layer indicates the lack of adhesion and also observed the smaller amount of material transfer.
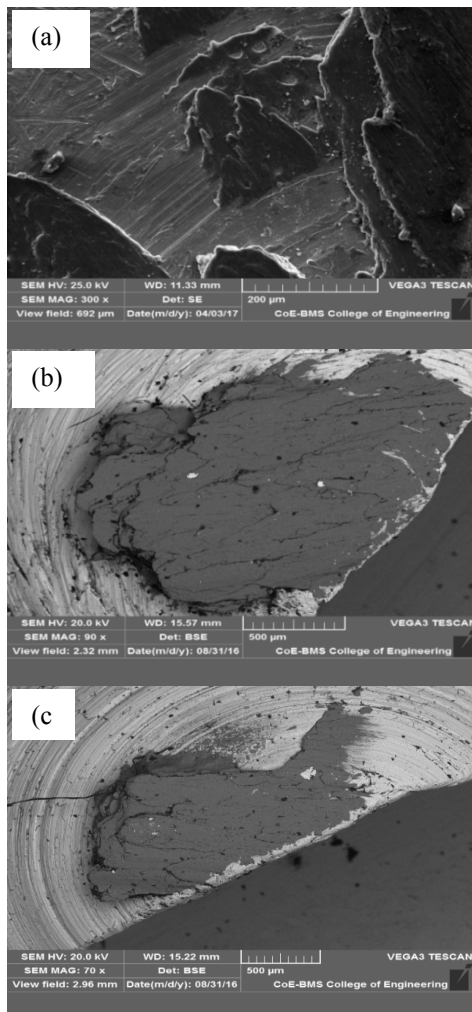

Figure 13. The worn surface micrographs of hemisphere pin at 45° configured stress state with load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg.

Micrographs Figure 14(b) and 14(c) corresponds to disc material transfer layer of pin for the normal load of 3 kg and 5 kg respectively. It indicates the quantum of transfer layer is larger when compared to transfer layer found in micrograph Figure 14(a). The feature of transfer layer in micrographs Figure 14(b) and 14(c) reveals abrasion mode of sliding.

From the above discussion, it indicates the behaviour of metals in dry sliding wear indicates great dependence on mechanical properties of the material, geometry, orientation and environment conditions like microstructure, hardness, etc. It can be revealed that the increasing load and stresses generally lead to an increase in wear.
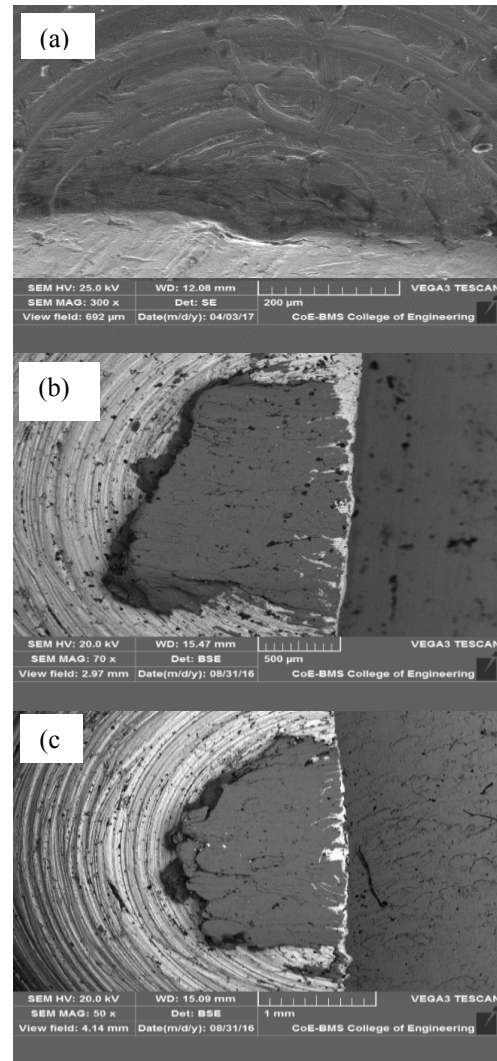

Figure 14. The worn surface micrographs of hemisphere pin at 90° configured stress state with load conditions of (a) 0.5 kg (b) 3 kg (c) 5 kg.

4. CONCLUSION

Based on output results, the following conclusions are given below,

- The state of stress and its configuration with respect to direction of sliding and geometry of the pin are found to influence the coefficient of friction.
- The dependency of coefficient of friction decreases with increase of increase in load for all configured stress states. Also, the amount of transferred layer on the pin surface is increased.

- At lower load condition, the adhesive mode of sliding is dominatingfor sphere and hemisphere pin geometries.
- The unique behaviour for sliding at 90° configured stress stateat lower loads is attributed to material discontinuity in contact owing to pin tip shape and also to the controlled flow for the soft disc material.
- Higher loads, for all states of stress and its configuration with respect to sliding direction, are dominated by abrasive mode of sliding.
- Worn disc surface micrographs indicate the adhesion, abrasion and severe plastic deformation with full sphere and hemisphere pin. And also transfer layer was found in pin surface.

REFERENCES

[1] Johnson, K.L.: *One Hundred Years of Hertz Contact.* Proc InstnMechEng, Vol. 196, No. 1, pp. 363-378, 1982.

[2] Mindlin, R.D.: *Compliance of elastic bodies in contact,*J. Appl. Mech., Vol. 71, pp. 259-268, 1949.

[3] Archard, J.F.: *Elastic Deformation and the Laws of Friction. Proceedings of the Royal Society A: Mathematical,* Proc Roy Soc A, Vol. 243, pp. 190-250, 1957.

[4] Greenwood J.A., Williamson, J.B.P.: *Contact of Nominally Flat Surfaces,* Proc Roy SocA, Vol. 295 pp. 300-319, 1996.

[5] G.M. Hamilton, L.E. Goodman, *The Stress Field created by a circular sliding contact*, Journal of applied mechanics, Trans.ASME, pp. Vol. 33, No. 2, 371-376, 1966.

[6] Rigney, D.A., Hirth, J.P.: *Plastic Deformation and sliding friction of metals*, Wear, Vol. 53, pp. 345-370, 1979.

[7] Murray, M.J., Mutton, P.J., Watson, J. D.: *Abrasive wear mechanisms in steels*, Journal of lubrication technology,Trans.ASME, Vol. 104, pp. 9-16, 1982.

[8] Brizmer, V. et al.: *The effect of contact conditions and material properties on the elasticity terminus of a spherical contac*t, International Journal of solids and structures, Vol. 43, No. 18-19, pp. 5736-5749, 2006.

[9] Mascia, R. et al. D.:*Effect of pressure and counter body hardness in the abrasive wear behaviour of tool steels*, Wear, Vol. 303, pp. 412-418, 2013.

[10] Kato, K.: *Wear Mechanisms*, New Dir. Tribol. Published at the First World Tribology Congress, I Mech E.pp. 39-56,1997.

[11] Blau, P.J.: *Four great challenges conforming our understanding and modelling of sliding friction*, in:D. Dowson(Ed.), Tribology for Energy Conservation (Leeds-Lyon 24), Tribol. Scr. Vol. 34, pp.117-128, 1997.

[12] Sherbiney, M.A., Halling, J.: *Friction and wear of ion-plated soft metallic films,* Wear,Vol. 45, pp. 211-220, 1977.

[13] Diao, D. F., Kato, K., Hayashi, K.:*The maximum tensile stress on a hard coating under sliding friction,* Tribol. Int., Vol. 27, No. 4, pp. 267-272, 1994.

[14] Diao, D. F., Kato, K., Hayashi, K.:*The Local Yield Map of Hard Coating under Sliding Contact, Tribology Series,* Vol. 25, pp. 419-427,1993.

[15] Bowden F. P., Tabor, D.: *The Friction and Lubrication of solids*, Part 2, Oxford University Press,Oxford,1964.

[16] M. Ramesh Jafrey, Daniel D M., Ravichandran: *Investigation on Mechanical Properties and Wear Behaviour of Titanium Diboride Reinforced Composites,* FME Transactions, Vol 47, pp.873-879,2019.

[17] Sathickbasha K, Selvakumar A S, Sai Balaji M A, Surya Rajan B: *Effect of Steel Family Fibers on Friction and StictionBehavior of Brake Pads,* FME Transactions, Vol 47, pp.856-864,2019.

[18] Sachit T. S., Mohan,N.: *Wear Behavior of Aluminum LM4 Reinforced with WC and Ta/NbC Hybrid Nano-Composites Fabricated Through Powder Metallurgy Technique,* FME Transactions, Vol 47, pp.534-542,2019.

[19] Surendran, R., Manibharathi, N., Kumaravel,A.:*Wear Properties Enhancement of Aluminium Alloy with Addition of Nano Alumina,* FME Transactions, Vol 45, pp.83-88,2017.

[20] Lakshmikanthan, A.,Bontha, S.,Krishna, M., Koppad,P. G., Ramprabhu,T.:*Microstructure, mechanical and wear properties of the A357 composites reinforced with dual sized SiC particles,* J. Alloys Compd., vol. 786, pp. 570–580,2019

[22] Charoo, M.S., Wani M. F., Hanief, M., AmanChetani, Rather, M. A.: *Tribological characteristics of EN8 and EN24 steel against aluminium alloy 6061 under lubricated condition*, Advanced Materials Proceedings, Vol. 2(7), pp. 445-449, 2017.

[22] Avinash, L.,Ramprabhu, T., Bontha,S.: *The Effect on the dry sliding wear behavior of gravity cast A357 reinforced with dual size silicon carbide particles*, Applied Mechanics and Materials, vol. 829, pp. 83–8,2016.

[23] Xie, Y., and Williams, J. A., "The Prediction of Friction and Wear When a Soft Surface Slides Against a Harder Rough Surface," Wear,196 (1–2), pp.21–34, 1996.

ИСТРАЖИВАЊЕ ПРОМЕНЕ СТАЊА НАПОНА У ОДНОСУ НА ПРАВАЦ КЛИЗАЊА КОД ХАБАЊА ПРИ СУВОМ КЛИЗАЊУ ТВРДОГ ЕЛАСТИЧНОГ МАТЕРИЈАЛА СА РАЗЛИЧИТОМ ГЕОМЕТРИЈОМ И ОРИЈЕНТАЦИЈОМ НА РАВНОЈ ЖИЛАВОЈ ПОВРШИНИ

С.П.С. Јадав, С. Ранганат, С. Шариф, Р. Суреш, Л. Авинаш

Извршен је експеримент клизања тврдог еластичног материјала на жилавој равној површини. Промена геометрије тврдог материјала довела је до промене

стања напона, а промена оријентације довела је до промене геометрије у односу на правац клизања. Експерименти су обављени помоћу пин-он-диск опреме за тестирање хабања. Тестиран је диск од легуре Al6061 и пин од легираног челика EN8, са различитом геометријом и оријентацијом врха. Добијени резултати су показали да је коефицијент трења већи при мањем оптерећењу у поређењу са већим оптерећењем геометрије пина хемисфере, изузев код оријентације од 90^0 при малом оптерећењу. Разлог томе је ефекат адхезије. Утврђено је да на појаву клизања утиче стање напона и његова конфигурација у односу на правац клизања. Микрографска анализа је показала да оштећења настају услед адхезије, абразије и екструзије.