The Effect of Hardness of Base Material on Tribological Properties of VG-46 Lubricant in Mixed Lubrication Regime

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The Effect of Hardness of Base Material on Tribological Properties of VG-46 Lubricant in Mixed Lubrication Regime

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Abstract: Lubrication is a technique of using a lubricant to reduce friction & wear. There are four major lubrication regimes i.e., boundary, mixed, elasto-hydrodynamic & hydrodynamic. Most of the industrial machines & equipment's moving surfaces in contact, works in the mixed lubrication regime. Almost the entire major breakdown related to surface pitting & wear resulted from high friction occurs in this regime only. A lot of study & research is required in this field for improving the tribological performance of the surfaces in contact. Hardness of the base material always plays an important role in the performance of the tribological pair in all lubrication regimes especially in mixed lubrication. Therefore, authors consider the tribo pair of brass & EN31 as base material for conducting the study of the effect on various tribological parameters in mixed lubrication regime with VG-46 lubricant. Authors have also focused themselves to investigate the effect of the hardness of the base material (EN31) on the friction & wear parameters for the above mentioned tribo pair & lubricant in mixed lubrication regime because of its wide practical & industrial applications in most of the equipment & machines Also, this tribological pair is the most imperative pair used in enormous industrial applications. VG-46 is also an effective lubricant used in various industrial setups.

Keywords: Wear, Frictional Force, Mixed Lubrication, Hardness, Brass, EN31, VG-46

1. Introduction

Lubrication is a technique of using a lubricant to reduce friction & wear. There are four major lubrication regimes i.e., boundary, mixed, elasto-hydrodynamic & hydrodynamic. Most of the industrial machines & equipment moving surfaces in contact, works in the mixed lubrication regime. Almost the entire major breakdown related to surface pitting & wear resulted from high friction occurs in this regime only. A lot of study & research is required in this field for improving the tribological performance of the surfaces in contact.

H.A. Spikes[1)] has reviewed various researches in the field of mixed lubrication. Limitations of the earlier prototypes for below certain levels of surface roughness parameters are highlighted by him. He has emphasized on the scope of improvement & area of further research & progress in this field especially in electrical contact resistance & optical interferometry study. Spike et al.[2)] have thoroughly studied the various theoretical & experimental investigations conducted between smooth surfaces with very thin lubricating film & rough surface lubricated contacts. They have concluded that there are two types of lubrication regimes these are micro elastohydrodynamic & mixed lubrication regimes which exist between lubricated rough surfaces. They also informed that various modelling & experimental work is in progress at various levels in this field of mixed lubrication & still there is lot of further scope for improvement. Hugh Spikes[3)] has described Modelling & Simulation of thin & mixed film lubricant films as one of the five emergent & trending areas of research and technological advancements on the basis of his thorough review of the research.

As per Koji Kato[4)], most of the modern lubricated machines such as automobiles, machining tools & equipment require dedicated study of the frictional & wear behaviour along with their control mechanisms. In current scenario these high-end equipment are working under severe operating conditions leading to adverse effects on their performance. Environmental issues & shortage of resources urgently demand enhanced efficiency and reliability of machines together with their longer life. Boundary and mixed lubrication regimes are key regimes in which major wear of these equipment are taking place. Author has provided nine wear models in tribochemical, mechanical & lubricated wear of steels to improve the performance of these equipment. H S Cheng[5] has provided insight on the latest analytical modeling developments in mixed lubrication regime.

Illner[7] has performed his study on the sliding contact of diesel injection pump under transient conditions in mixed lubrication regime and found that the results were as good as were evaluated with simulation techniques. Issakson et al. and Nilsson et al.[8-10] have conducted simulation study on partial journal bearings with cast iron bush & steel rollers having hydraulic oil lubrication along with additional supply of lubricant pipe for film build up support. For most of the surface roughness conditions in mixed lubrication, the friction force parameters resulted in this study are in agreement with the measured values.

Sahlin et al.[11,12] have focused on a similar study considering two flat surfaces and found that the results match the measured values a lot. Priestner et al.[13], Allmaier et al.[14–16], and Sander et al.[17–19] have studied the frictional force comparison in mixed lubrication regime for journal bearings & detailed results are presented. Greenwood and Tripp[6] is one of the common models used for the perseverance of the asperity contact pressure in all above-mentioned researches. Albers and Lorentz et al.[20] have managed the mixed lubrication microscopic study for analyzing the influence of surface topography on the coefficient of friction and thermal dissipations. Akchurin et al.[21] have envisioned line contacts friction forces via simulation methods. S.Fricke et al[22] have analyzed the impact on friction between surfaces because of varying surface forms in mixed lubrication regime. Anthony et al.[23] have studied the effect of the addition of nano particle additives in the lubricant on reduction in wear & friction between sliding surfaces. Norfazillah et al.[24] have modified the jatropha oil by adding activated carbon nanoparticle as additive. They have investigated the tribological parameters of this modified jatropha oil & its performance capability of being used in metal working fluid applications. Aiman et al.[25] have established the reduction in the frictional parameters of the flat sliding surfaces after having micro pitting on the same. Changru et al.[26] have illustrated the effect of lubricants on heat pump performances.

W.K Shafi et al.[27] & Love Kerni et al.[28] have explored the effect of various vegetables oils on the wear & friction parameters of sliding surfaces in mixed lubrication regime. K.P. Shaha et al.[29] have studied the effect of the hardness of ball on the tribological properties of the nano composites' coatings. K.M Chen et al.[30] have conducted dry sliding wear test on tribopair of titanium alloy & steel. They have concluded that this pair is highly suitable for the high temperature applications. Mayank Chouhan et al.[31] have worked on the anti-wear performance optimization of the ferro-magnetic lubricants. Sachin Mittal et al.[32] have experimentally investigated on the tribological properties in mixed lubrication regime & compared the same considering VG-32 & VG-46 lubricants. Simulation studies & numerical modeling of the tribo pairs are the common approached areas by various researchers in the field of mixed lubrication regime. Few recent researches are also targeting the tribological analysis of the nano particles as lubricant additives. But this area of experimental analysis in mixed lubrication regime remains untouched. Experimental study of the various industrial tribo pairs & lubricants in mixed lubrication regime, to analyze the effect on the friction & wear is absolute necessity in current scenario. Even, the effect of the properties of material on tribological parameters in mixed lubrication regime has not been studied by researchers & has a lot of scope for research. In the current study we have focused our self to investigate the effect of the hardness of the base material (EN31) on friction & wear parameters for the tribo pair of EN31 & brass with VG-46 lubricant in mixed lubrication regime. We have considered this tribo pair of EN 31 & brass because of its wide applicability as combination of shafts & bushes in enormous industrial rotor and bearing applications. VG-46 oil, one of the premium grade minerals based hydraulic oil, is being considered for the experimentation. Secondly in most industrial setups, VG-46 oil is the best fit due to its anti-wear, anti-corrosion & low temperature sustainability properties. In all bearing applications, shafts are manufactured from hardened steel to avoid wear & bushes are made from soft material like brass so that wear can take place and it can act as sacrificial material. As high cost & manufacturing time is involved, we cannot afford the wear of the base shaft material. Therefore, we have varied the hardness of the base material & analyzed the effect on the tribological parameters so that the design of the shaft can be improved for better & smoother operation in mixed lubrication regime. It will surely help to bridge the gap for the study of the effect of hardness of base material in mixed lubrication regime.

2. Materials & methods

2.1 Base oil

ISO VG 46 oil has applicability in a wide variety of automotive & industrial applications because of its high thermal stability, anti-corrosion, anti-wear, low oxidation, low foaming & air entrainment properties.

Table 1. Physico-chemical properties of VG-46 hydraulic oil

S. No.	Properties	Value
1	Viscosity (mm^2/s) at 40^0C	46.0
2	Density (Kg/m^3) at 40^0C	$0.861 * 10^3$
3	Flash point (^0C)	232
4	Pour point (^0C)	-27
5	Viscosity Index	98

This oil is also having high viscosity index resulting high shear stability. VG-46 lubricant physico-chemical properties are shown in Table 1. The above-mentioned properties are of ENKLO 46 PREMIUM (Brand Name) oil which is manufactured by HP. These properties are taken from the technical data sheet of the oil provided by the manufacturer.

2.2 Tribopair

EN 31 steel discs having exceptional abrasion resistance & hardness properties were prudently chosen as base material for this research. EN 31 discs of varying hardness of 60 & 40 HRC were prepared by various heat treatment techniques. Brass spherical balls were used for making point contact on EN 31 discs. Brass is most commonly used material in bearings applications and hence the same was selected because of its practical acceptability. Table 2 depicts the mechanical properties of both the selected materials. The diameter of the ball was 12.7mm & that of disc was 40.0+/-0.1 mm. The particular disc used was of 4 mm thickness.

Table 2. Mechanical properties of disc & ball materials

S. No.	Properties	EN 31 steel	Brass
1	Yield strength (N/mm^2)	450	140
2	Tensile strength (N/mm^2)	750	360
3	Hardness (HRC/HRB for Brass)	60, 40	93
4	Density (g/cm^3)	7.81	8.39
5	Mod. of elasticity (N/mm^2)	215000	117000
6	Poisson's ratio	0.27-0.30	0.34

2.3 Experimentation

Friction & wear testing was conducted using ASTM G-99 standard on a Pin/Ball-on-disc tribometer with EN-31 discs & brass ball taking VG 46 lubricant. Experimental setup's photographic view is shown in Fig 1. Frictional forces were measured from the load cells available in the instrument. Digital instrument having display to demonstrate the rpm of disc, duration of the test, wear & frictional forces. Computer was in synchronization with the digital instrument through DUCOM software. All the data from this instrument was gathered in the software and accordingly various graphs were plotted for future reference.

Disc had been placed & tightened in the provided fixture. Lubricant was applied on the disc. Pitch circle diameter for the ball's point of contact on the disc was set as 6 mm using the linear scale adjustment mechanism.

A series of tests were conducted on the selected tribo pair with load of 120 N & speed varying from 85 to 170 rpm i.e., from 0.054 m/s to 0.107 m/s after setting PCD as 6mm. The room temperature & humidity was maintained at 22^{O}C & 60% respectively during the test. Stribeck curve for the tribopair & lubricant was plotted taking COF values on the Y axis & Speed/Load values on the X axis.

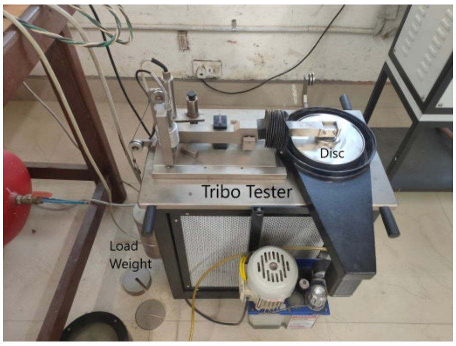
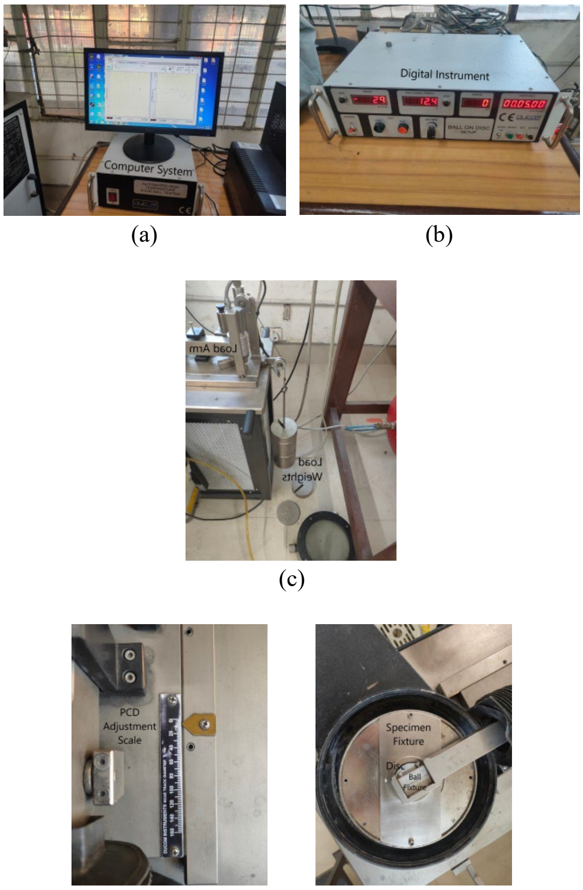


Fig. 1: Ball/Pin on disc tribometer (DUCOM).



(a) (b)

(c)

(d) (e)

Fig. 2: Tribometer Parts (a) Computer system (b) Digital instrument (c) Load mechanism (d) Disc adjustment (e) Pitch adjustment scale.

Mixed lubrication regime was selected from the Stribeck curve which was further used for experimentation. Several parts of the tribometer are illustrated in Fig 2.

3. Results and discussions

3.1 Stribeck curve

Stribeck curve shows that the dimensionless parameter of lubrication bears relationship with contact load between two surfaces, entrainment speed & viscosity of lubricant. This dimensionless parameter is defined as below.

$$\lambda = (\mu . N)/P$$

The first basic objective of our experimentation is to define the mixed lubrication regime for the selected tribo pair of Brass & EN-31 having VG-46 as lubricant in between. Stribeck curve for a lubricant & tribo pair clearly defines the various lubrication regimes. So, we have conducted various experiments by varying the contact load & rotational speed of the disc and tabulated the values of coefficient of friction. Stribeck curve is plotted taking COF on y axis & N/P on x axis which is shown in Fig 3. It is clear from the curve that there is a slight increase in the value of the COF from 0.212 to 0.215 while increasing the N/P values from 0.71 to 0.75. Further increase in the value of N/P resulted in a decrease in the COF value from 0.215. This transition point w.r.t to N/P value of 0.75 & COF 0.215 can be termed as initiation point of mixed lubrication regime. This phenomenon of decrease in the COF values with increase in N/P value continues till the N/P value is 1.17. The corresponding value of COF for this point is 0.172. Increasing the value of N/P further from this point leads to an increase in COF value. This transition point is labeled as the end point of the mixed lubrication regime. Hence the complete mixed lubrication regime is established from the experimentation. This regime range can be used for the study of the effect of the hardness of the base material on the tribological factors i.e., frictional force, wear.

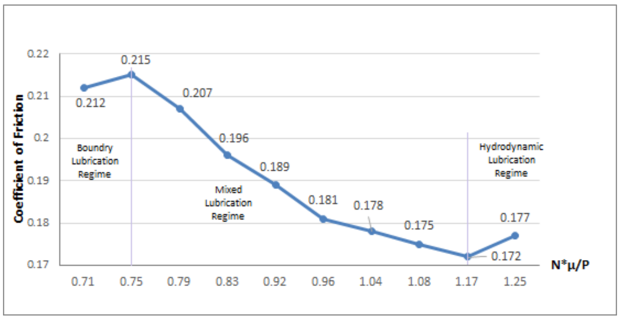


Fig. 3: Stribeck curve for VG-46 oil.

3.2 Frictional force & COF behavior

We have already finalized the mixed lubrication regime for the selected tribo pair & VG-46 lubricant from the plotted Stribeck curve. To analyze the effect of the hardness of the material on the frictional force & coefficient of friction we have used EN 31 discs with varying hardness of 60 HRC & 40 HRC.

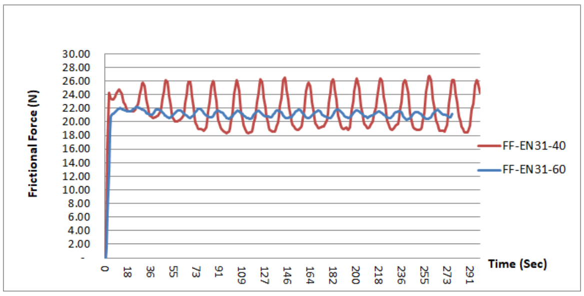


Fig. 4: Friction force behaviour at load of 120N.

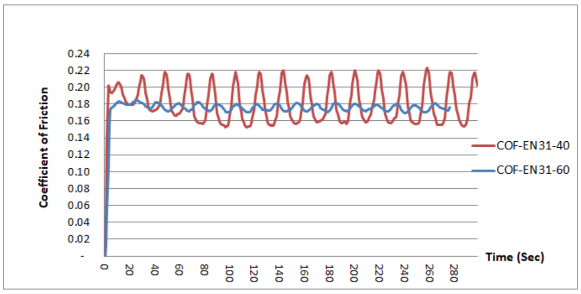


Fig. 5: Coefficient of Friction behaviour at load of 120N

These are prepared using heat treatment processes. Experimentation has been conducted on both the hardened surfaces at speed of 105 rpm & 115 rpm after applying load of 120 N. N/P values for the experimentation are 0.875 & 0.958, which are well in between the mixed lubrication regime. Frictional force & COF values for both the hardened surfaces are plotted w.r.t. time for further comparison analysis. Fig 4 illustrates the friction force behaviour comparison w.r.t time for EN 31 discs of 60 HRC & 40 HRC. COF comparison for both the hardened surfaces is shown in Fig 5.

It is distinct from both the plots that for mixed lubrication regime there is sudden increase in the value of frictional force & COF initially for a period of 10-20s. Continuous fluctuations are observed in both the parameters behavior after 20s. Wear has been observed majorly in the soft brass material during sliding on EN 31 discs in mixed lubrication regime. The wear particles are moving between the surfaces in contact & coming between the asperities & valleys. This has led to an increase in the frictional forces & COF between the surfaces when the wear particles are coming between the asperities & decrease in the frictional forces & COF when they are coming between valleys. This behaviour of the wear particles between the sliding surfaces in mixed lubrication regime has led to sudden increase & decrease in the values of frictional forces & COF & hence huge fluctuations are observed.

It is also evident from the graphs that frictional force & COF values are less for the more hardened surfaces. EN 31 discs with hardness of 60 HRC have less frictional & COF values as compared to values for 40 HRC discs in mixed lubrication regime. We are aware of the fact that frictional forces arise from the shearing of junctions & plastic deformation of the surfaces. In our study, we have applied a constant load of 120 N on the tribo pairs. We have witnessed comparatively large disruption & damage in the oxide layer of 40 HRC hardness discs as compared to 60 HRC hardness discs. This has resulted in more shearing of junctions & deformations of the surfaces on 40 HRC hardness discs & hence more frictional forces are observed in 40 HRC discs as compared to 60 HRC discs. Also, the ratio of shear strength & hardness of sliding metals is equal to Coefficient of friction. So, similar behaviour persists for the COF also i.e., more COF values are observed for 40 HRC discs as compared to 60 HRC discs in mixed lubrication regime.

Fluctuations in the value of the frictional forces & COF are less in more hardened surfaces in mixed lubrication regime. This behaviour is attributed to the fact that for hard surface the tearing & pick up of the material is less which results in smooth sliding between the surfaces.

3.3 Effect of speed on coefficient of friction

The effect on the coefficient of friction is analyzed on the tribo discs of EN 31 bearing hardness of 60 HRC & 40 HRC by varying the speed of the discs and maintaining the constant applied load of 120N.

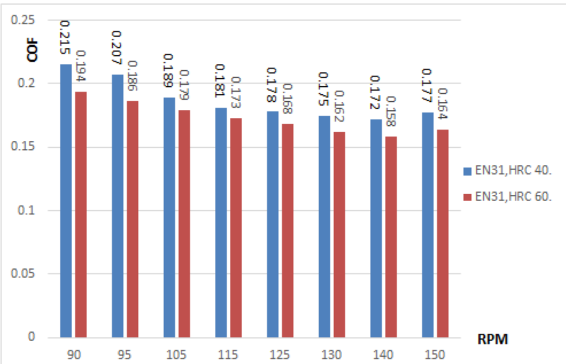


Fig. 6: Effect of speed on coefficient of friction.

Minimum speed of 90 rpm & maximum speed of 150 rpm is considered for the experimentation at a constant load of 120N. This is to keep the N/P values between the range of 0.75 to 1.25, which is well within the mixed lubrication regime for the tribo pair. Fig. 6 clearly describes the variation in the values of the COF w.r.t. different values of disc speed for both HRC 60 & HRC 40 hardened EN 31 discs.

Both types of the discs show similar behaviour pattern of the COF variation with disc speed. At speed of 90 rpm, COF values of 0.215 & 0.194 are observed. On increasing the speed further till the value of 140 rpm there is a continuous decrement in the values of the COF. Reversed trend is observed in the value of COF after increasing the disc speed further from 140rpm to 150 rpm.

The major reason attributable to this behaviour is that the thickness of the lubricating film between the sliding surfaces is very minimal at low discs speed. This has resulted in direct contact between asperities & hence higher frictional forces and coefficient of friction between them. This direct contact between the asperities gets reduced after increasing the speed because of thick film lubrication introduction between the surfaces. This results in reduction in the value of coefficient of friction at higher speed in mixed lubrication regime.

It is also evident from the figure that for a given speed & load, the COF values for the EN-31 HRC 40 disc is higher as compared to EN-31 HRC 60 disc. This behaviour is already concluded in the above section.

3.4 Wear behaviour

Mixed lubrication regime for the considered tribo pair of EN-31 & brass having VG-46 as lubricant has been already established in the earlier sections of this paper. We have analyzed the effect of the varying hardness of the base metal on the frictional forces & coefficient of friction during sliding in mixed lubrication regime in one of the earlier sections. Wear behaviour analysis is also one of the important parameters in various tribological studies. So, we have focused our study to understand the effect of the varying disc hardness on the wear rate in mixed lubrication regime.

Experimentation has been conducted on both the hardened surfaces at speed of 105 rpm & 115 rpm after applying load of 120 N. N/P values for the experimentation were 0.875 & 0.958, which are well in between the mixed lubrication regime. Fig 7 illustrates the variation in the wear for both the HRC 60 & HRC 40 hardened EN-31 discs for the above selected mixed lubrication regime.

We can clearly infer from the figure that the wear is increasing drastically at the initiation of the sliding movement. Maximum wear of approx. 25 microns for HRC 60 discs & 35 microns for HRC 40 discs are observed during the test. The reason behind this is that at the initiation of the test, both the surfaces are in contact, and the thickness of the lubricating film is very minimal. Also, as brass is a soft material and sliding of this soft material on the hardened EN-31 discs with minimal lubricant film thickness resulted in large amount of wear in brass ball. It is also clear from the plot that the wear is more in HRC 40 hardened discs as compared to HRC 60 hardened discs because of improved surface properties of HRC 60 discs. HRC 60 & 40 hardness discs surfaces are manufactured after various heat treatment processes. The microstructure in the HRC 60 hardness discs surface is comparatively more uniform & refined as compared to HRC 40 hardness discs. Hence the HRC 40 hardness discs are slightly more brittle & susceptible to high wear as compared to HRC 60 hardness discs.

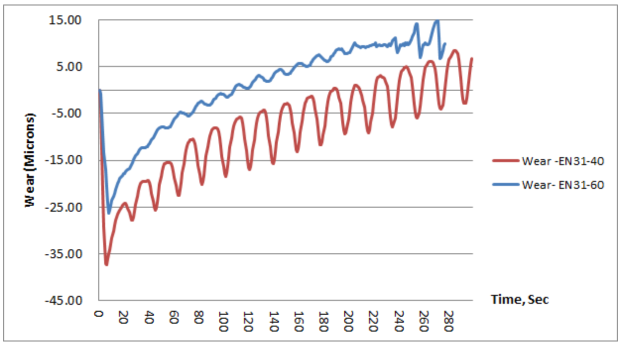
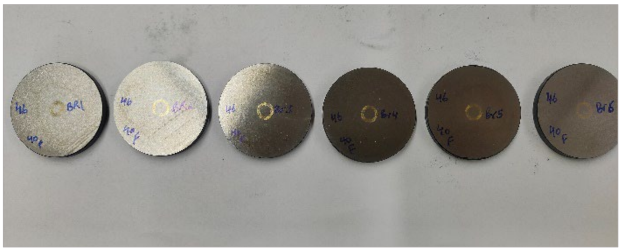
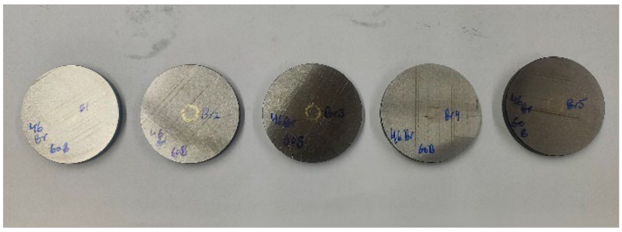


Fig. 7: Behaviour of Wear at the load of 120N.

As most of the wear has already been happened & lubrication film thickness will also start increasing with time. So gradual decrease in wear rate is observed after achieving this maximum value for both the hardened discs. Fig 8 shows the patterns of the wear on the EN31 discs after completion of the experiments.



(a)



(b)

Fig. 8: Worn out images of EN31 specimens.
(a) Hardness of HRC 40 (b) Hardness of HRC 60

4. Conclusion

We have concluded the study on the tribopair of EN 31 steel with varying hardness of 60 HRC & 40 HRC as base material and brass as sliding material with VG-46 as lubricant in mixed lubrication regime. Mixed lubrication regime for the same is achieved by plotting the Stribeck curve. Following conclusions are drawn from the study as below:

1. In mixed lubrication regime, the value of coefficient of friction & frictional forces are relatively low in case of more hardened surfaces as compared to less hardened surfaces. This is because the frictional forces arise from the shearing of junctions & plastic deformation of the surfaces. We have witnessed comparatively large disruption & damage in the oxide layer of 40 HRC hardness discs as compared to 60 HRC hardness discs. This has resulted in more shearing of junctions & deformations of the surfaces on 40 HRC hardness discs & hence more frictional forces are observed in 40 HRC discs as compared to 60 HRC discs. Also, the ratio of shear strength & hardness of sliding metals is equal to Coefficient of friction. So, similar behaviour persists for the COF also.
2. This is concluded from the study that with increase in the sliding speed of the discs the value of the coefficient of friction decreases gradually in mixed lubrication regime.
3. Wear rate for more hardened discs is less as compared to soft surfaces in mixed lubrication regime as microstructure in the HRC 60 hardness discs surface is comparatively more uniform & refined as compared to HRC 40 hardness discs. Hence the HRC 40 hardness discs are slightly more brittle & susceptible to high wear as compared to HRC 60 hardness discs.

Therefore, it can be concluded from the study that more hardened surfaces will have less frictional force, coefficient of friction & wear rate as compared to soft surface. These are preferable for use as base material of sliding contacts in mixed lubrication regime with VG-46 oil.

Nomenclature

P	Load (kgf)
N	Speed (RPM)
VG	Viscosity grade
COF	Coefficient of friction
PCD	Pitch circle diameter

Greek symbols

λ	Specific film thickness
μ	Dynamic viscosity of lubricant

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