# Effect of Counterface Material on Tribological Behavior of AISI 304L Stainless Steel Under Marginally Lubricated Contact

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**Abstract**
The properties of surfaces in contact are known to have significant influence on the tribological behavior of any tribosystem in different contact situations. In the present work, the effect of using different ball counterface material on the tribological behavior of AISI 340L stainless steel under marginally lubricated contact was studied. The frictional behavior was evaluated using a ball-on-flat configuration in reciprocating sliding under marginally lubricated contact condition. 440C stainless steel, Al (2017) alloy and bronze were used as the ball counterface while base-stock synthetic polyalfaolefin oil (PAO10) without additives was used as lubricant. After the friction test, flats and balls surfaces were examined by optical profilometer and optical microscope in order to assess the wear dimension and mechanism. In all the sliding pairs tested at different loads, an initial rapid increase in friction coefficient and a period of transition to a lower steady state friction coefficient were observed. In SS304L-440C pair, wear proportional to applied load occurred in the AISI 340L stainless steel flat by a combination of gross plasticity and abrasion. For both SS304L-Al (2017) and SS304L-bronze pairs, severe wear proportional to applied load, which occurred predominantly by abrasive mechanism was observed in the different ball counterface. The study concluded that the types of materials in contact have significant influence on the tribological property of any tribosystem.

**Keywords:** Friction; Wear; Stainless steel; Bronze; Al alloy

## INTRODUCTION

As technological advances are being made regularly, one of the areas that have received great deal of interest by scientist and engineers is tribology. Tribology can be defined as the science of interacting surfaces in relative motion (Bhushan, 1999). The principal subjects of this interdisciplinary science are friction, wear and lubrication. The tangential resisting force experienced by surfaces in relative motion is called friction. Wear is the progressive removal of material from one or both surfaces in contact due to relative motion between the contacting surfaces (Holmberg *et al*., 2007). Both friction and wear are not a material property but rather a system response (Bhushan, 1999). Lubrication is basically the effect of third body on contacting surface. The third body may be lubricating oil in which the lubricating regime play important role. Lubrication is an effective way of controlling friction and wear.

Stainless steel represents one of the leading groups of engineering materials. The austenitic stainless steel, for example AISI 304L, possesses good corrosion resistance, ductility and formability. It has been utilized extensively for electrical appliances and various machine parts in mechanical systems (Gupta and Mishra, 2013; Aydin *et al*., 2013). However, friction and wear is a major problem to designer and developer of mechanical components that make use of this class of stainless steel (Dykha and Kuz'menko, 2015).

Tribological behavior of steel components and their performance under various working conditions and environment has been the subject of several investigations (Fredrich *et al*., 1991; Bergantin *et al*., 2003; Lelait *et al*., 1993; Dixit *et al*., 2013; Li *et al*., 2012; Mahathanabodee *et al*., 2013; Chowdhury *et al*., 2013a; Tikotkar, 2012; Sapate *et al*., 2012; Chowdhary *et al*., 2013b; Qu *et al*., 2008; Olofinjana *et al*., 2016; Bartolomeu *et al*., 2017). Such investigations have revealed that tribological behaviors of stainless steel depend on many factors such as experimental parameters (normal load, sliding speed, sliding distance, vibration), working environment (temperature, relative humidity), type of materials, lubrication, among others. With respect to type of materials, the properties of the materials in contact have significant influence on the tribological behavior. Such properties include hardness, roughness, microstructure and composition, elasticity, thermal properties and so on.

Nonferrous alloys are now being used where corrosion is a problem and low friction is required. Such applications will require stainless steel and different nonferrous material combinations. Selecting the right material combinations will help in minimizing the twin problem of friction and wear in such applications. Therefore, for effective applications, more detailed research on the interaction of stainless steel – nonferrous metal couples are necessary, hence this study. In the present work, the effect of using different ball counterface materials on the tribological behavior of AISI 304L stainless steel under marginally lubricated contact was studied.

## EXPERIMENTAL DETAILS

Friction and wear tests were conducted with a ball-on-flat contact configuration in reciprocating sliding using a high frequency reciprocating rig (HFRR). AISI 304L stainless steel with nominal dimension of 25 mm x 50 mm x 6 mm was used as the flat specimen. The elastic modulus (E) is 193 GPa with Poisson's ratio (v) of 0.3 and hardness of 1.7 GPa (87$R_B$) (Lehocka *et al*. 2020). Manual wet grinding using silicon carbide papers from 60 to 120 grit was done to arrive at a 2-D surface finish (Sa) of 215 nm.

The ball specimens are commercially finished 440C stainless steel, Al (2017) alloy and bronze. The elastic modulus of the ball specimens is 200 GPa, 72.4 GPa, 97 GPa for 440C stainless steel, Al (2017) alloy and bronze respectively. The hardness of 440C stainless steel, Al (2017) and bronze ball specimens are 6.7 GPa (62$R_C$), 1.2 GPa (66$R_B$), 385 MPa (63$R_C$) respectively. All the balls have isotropic and texture surface with 2-D surface finish (Sa) of 881 nm, 785 nm, 850 nm for 440C stainless steel, Al (2017) alloy and bronze respectively. All the ball specimens are 12.7 mm (0.5 in) in diameter.

Tests were conducted with constant dead weights of 5, 10 and 15 N at room temperature and normal relative humidity under marginal lubrication condition by putting one drop of oil between the contact at the start of each test. Base-stock synthetic polyalfaolefin oil (PAO10) was used as lubricant. The viscosity and specific gravity of the lubricant are 71.1 cSt at 40 °C and 0.837 respectively. The reciprocating frequency was 1 Hz with a stroke length of 10 mm which is equivalent to a linear speed of 1 cm/s. All tests were conducted for 30 mins duration.

At the start of each test, one drop of oil was added to the contact and the load was initiated by applying dead weights to the pin assembly. Frictional force was observed from which the friction coefficient was calculated. At the end of each test, ball and flat samples were thoroughly cleaned after which surface of ball and flat were assessed using optical profilometry and optical microscopy.

## RESULTS AND DISCUSSIONS

### *Friction Behavior*

Figure 1 shows the variation of friction coefficient with time for different pairs during reciprocating sliding under marginally lubricated condition at normal loads of 5, 10 and 15 N. Since it is a marginally lubricated test, the friction (and wear) behavior will still depend on the nature and interaction between asperities in the near surface of the interacting materials (Kovaci *et al*., 2018). Such interaction will also depend on the surface roughness, texture and waviness (Guezmil *et al*., 2016). Hardness and work-hardening exponent can also play a prominent role in the magnitude of friction and wear (Ruggiero *et al*., 2015). The pairs of 304L stainless steel flat with 440C stainless steel ball, Al alloy (2017) ball and bronze ball are represented in the figure by SS440C, Al2017 and Bronze respectively. At all the tested loads, a range of frictional variation was observed for all pairs over the test duration.

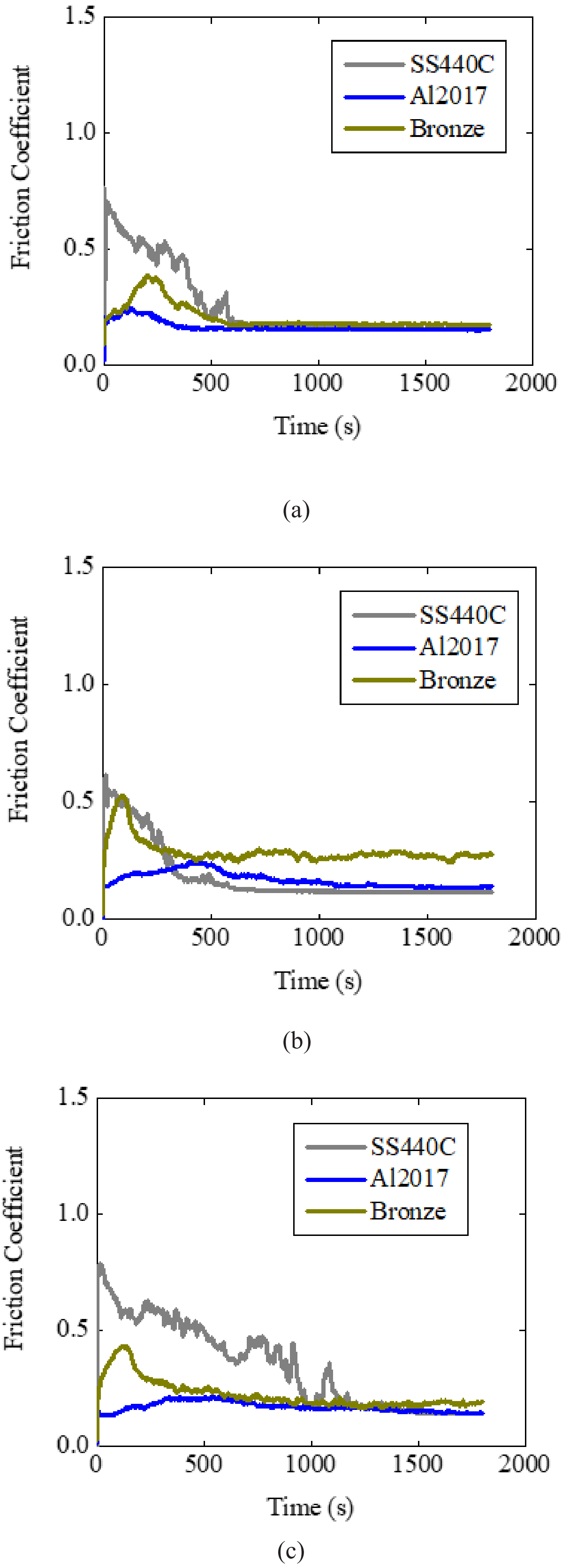



**Figure 1:** Variation of friction coefficient with time at (a) 5 N (b) 10 N (c) 15 N for the pairs.

In all the sliding pairs tested at different loads, two main stages of friction behavior can be observed. The first stage is a period of initial rapid increase in friction coefficient while the second stage is a period of transition to a lower steady state (or nearly steady state) friction coefficient. The initial rapid increase in friction which occurred in the early part of the test is usually termed "run-in", "wear-in" or "break-in" period. Such run-in or wear-in period can be as a result of frictional anisotropy due to local plastic deformation. This effect was also observed by Ajayi *et al*., 2009; where the observed frictional anisotropy was attributed to lack of adequate fluid film at real areas of contact leading to micro-elastohydrodynamic (EHD) lubrication in which asperity acts as individual contact. Based on this proposed mechanism for frictional anisotropy, high shear stresses at the contact areas, which can result in uneven plastic flow (Olofinjana *et al*., 2015) leading to intense plastic deformation (Rigney, 2000; Rainforth, 2000) depending upon the test condition and materials (Rainforth *et al*., 2002) is thus expected.

***Wear Behavior***

The wear behavior of each pair is strongly related to the friction behavior for the respective pair. In SS304L-SS440C pair, wear occurred in all the SS304L flat specimen tested at different loads while material transfer from the flat to the SS440C ball material was evident at all tested loads. As a result of this, an assessment of wear was done by measuring the wear in the SS304L flat for each test. Figure 2 shows the 3D profile of a typical SS304L flat and SS440C ball surface after friction test. A comparison of wear volume in the flat specimen tested under different loads (plotted on a log scale) is shown in Figure 3. It is clear that wear volume increased with load. Figure 4 shows the optical micrograph of a typical SS304L flat and SS440C ball surface after friction test.

As the harder 440C stainless steel ball counterface slide through the softer 304L stainless steel flat surface, the high shear stresses formed exceed the material strength of the 304L flat (Holmberg *et al*., 2007). The softer material then deforms to the extent that it results in severe plasticity, ploughing out grooves and detachment of material (Figure 3a) that is proportional to the applied load. Some of the wear debris can also cause scratches in the direction of sliding which then results in abrasive wear (Figure 4a). With this, wear occurs in the 304L stainless steel flat by combination of plasticity and abrasion. As sliding goes on, mechanical mixing of wear debris generated with oil together with oxidation of metal may occur causing tribolayer to be deposited on the ball counterface as can be seen in Figure 4b. Once enough wear occurs on the SS304L flat, a change in contact geometry from point non-conformal contact to a more conformal contact is then expected. Both the tribolayer and

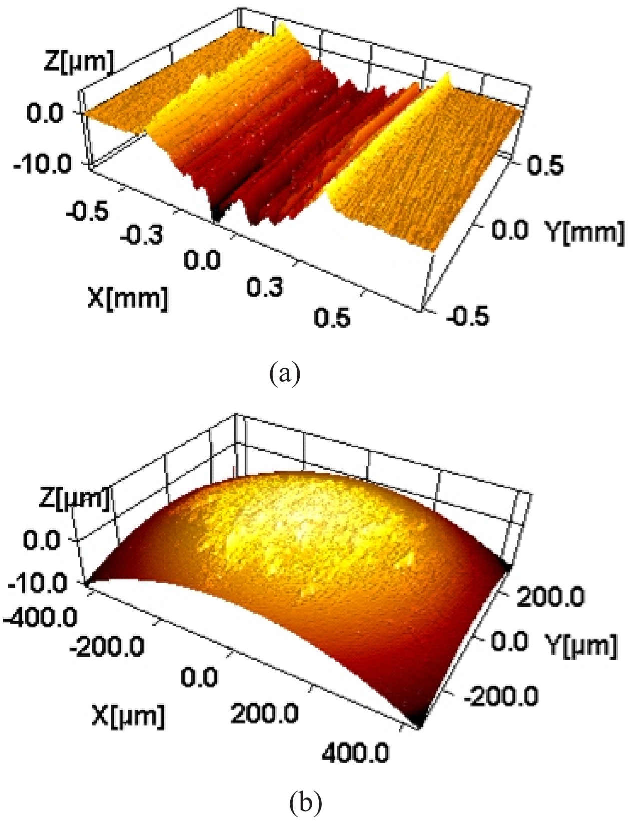



**Figure 2:** Optical profile of (a) SS304L flat and (b) SS440C ball after friction test.

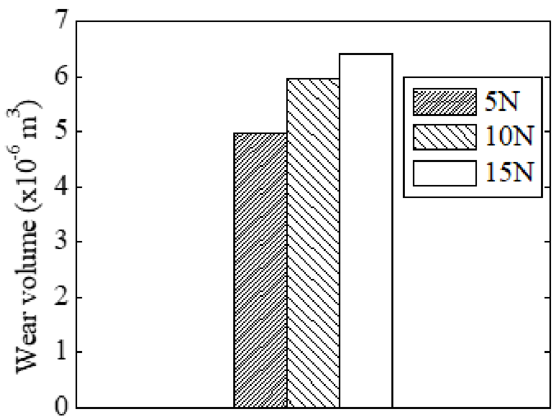
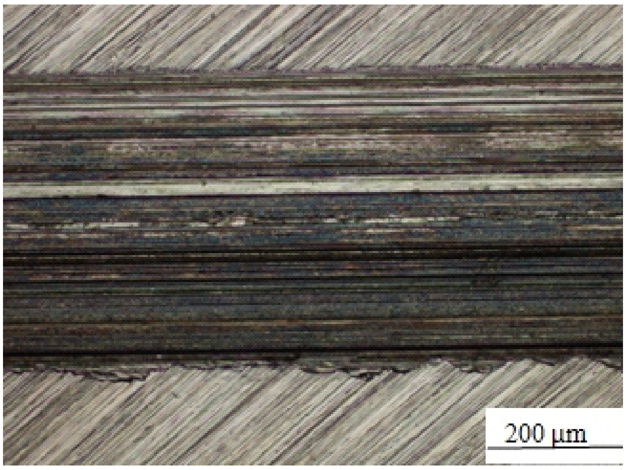


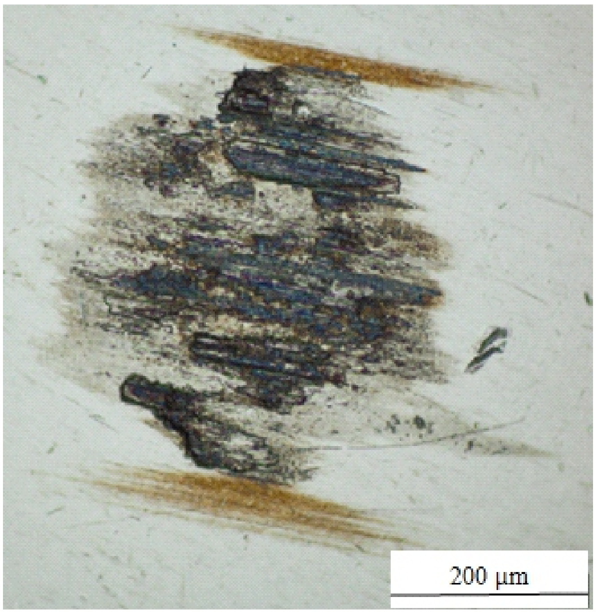

**Figure 3:** Wear volume of SS304L after friction test for SS304L-440C pair

change in contact geometry lead to significant friction reduction to a steady state (Schon, 2004), as observed in the friction test.

Both SS304L-Al alloy (2017) and SS304L-bronze pairs showed similar features for both the flat and ball samples at all loads. Figures 5 and 6 show 3-D optical profile of flat and ball samples for the different pair after friction test. Since wear occurred only in the respective ball sample, assessment of wear was conducted by measuring the wear in the ball sample for each test. A comparison of wear volume in the ball specimen tested under different load is shown in Figures 7 and 8. From both figures, it can be seen that




(a)

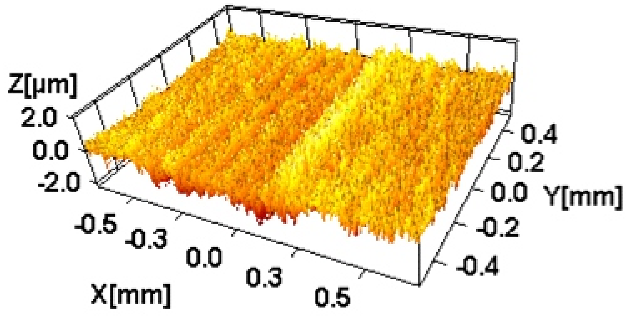



(b)

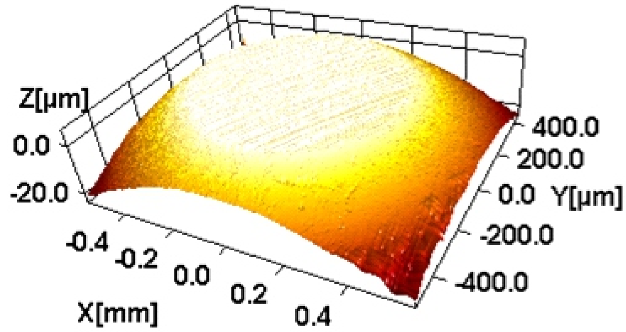
**Figure 4:** Optical micrograph of (a) SS304L flat and (b) SS440C ball after friction test.

wear volume is proportional to load. Hardness of materials plays prominent role in both SS304L-Al (2017) and SS304L-bronze pairs. Figures 9 and 10 show the optical micrograph of a typical flat and ball surface after friction test for each pair. As observed from the optical micrograph (Figures 9b and 10b), wear in the ball sample occurred predominantly by abrasive mechanism as indicated by the deep scratches in the direction of sliding. For all the flats in these pairs, material transfer from the various balls occurred. Such transfer layer formed new tribolayers on the surface of the SS304L flat as shown in Figures 9a and 10a. Again, hardness of materials plays prominent role in both SS304L-Al (2017) and SS304L-bronze pairs.

The formation of tribolayer on the SS304L flat samples may be the reason for the steady state value of friction coefficient exhibited by the SS304L-Al (2017) and SS304L-bronze pairs after the run-in period.

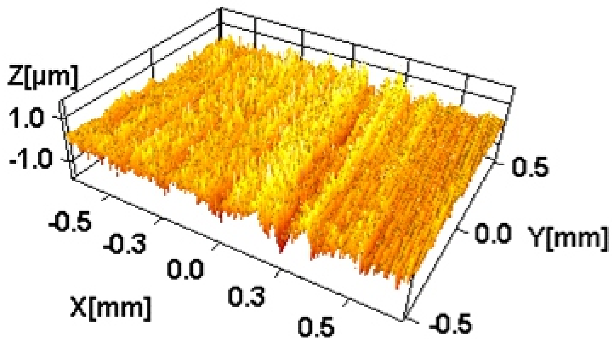



(a)

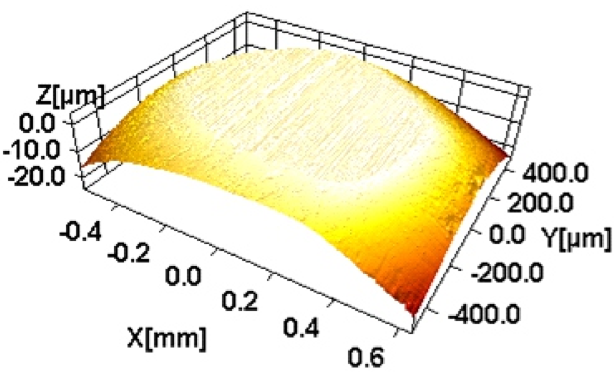



(b)

**Figures 5:** Optical profile of (a) SS304L flat and (b) Al alloy (2017) ball after friction test.

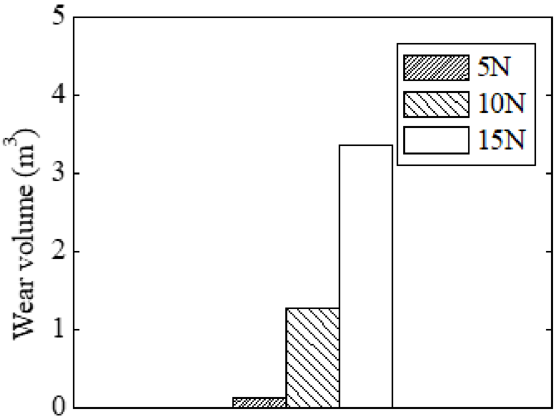



(a)

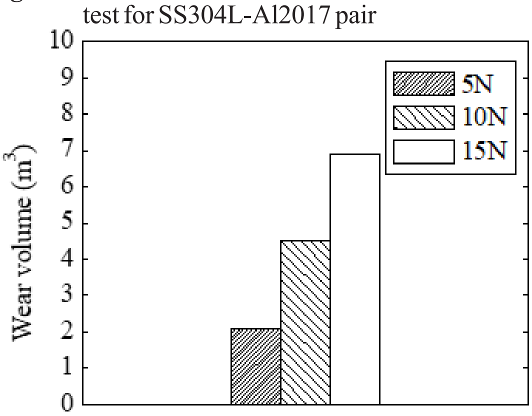



(b)

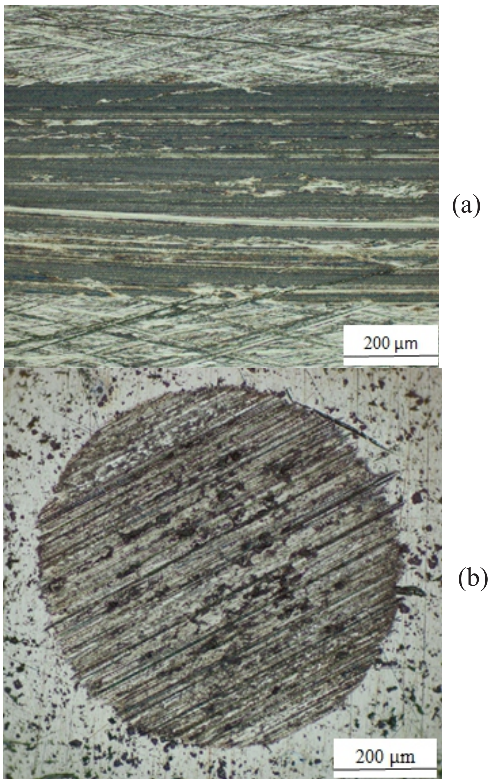
**Figures 6:** Optical profile of (a) SS304L flat and (b) bronze ball after friction test.




**Figures 7:** Wear volume of Al 2017 ball after friction test for SS304L-Al2017 pair




**Figures 8:** Wear volume of bronze ball after friction test for SS304L-bronze pair




**Figures 9:** Optical micrograph of (a) SS304L flat and (b) Al alloy (2017) ball after friction test.

After run-in period, mechanical mixing of wear debris from softer ball counterface, oxides of metals and lubricating oil can occur and accumulate to build up a tribolayer on the respective SS304L flat samples. Therefore, when the friction coefficient stabilizes, the contacting surfaces probably have a tribolayer between them, which separate the contacting surfaces, and determine the friction coefficient. Sometimes, there can be a sequence of build-up and collapse of tribolayer during sliding. This leads to the friction coefficient becoming unstable (Qu *et al*., 2008). The slight variation in friction coefficient observed in SS304-bronze pair at 10 N after the run-in period may then be due to such build up and collapse.

## CONCLUSION

This paper presented the results of evaluation of the effect of using different ball counterface material on the tribological behavior of AISI 340L stainless steel under lubricated contact. Friction test was conducted with a ball-on-flat contact configuration in reciprocating sliding using HFRR. Wear dimension and mechanisms were assessed using 3-D profilometry technique and optical microscopy.

In all the sliding pairs tested at different loads, two main stages of friction behavior were observed - a period of initial rapid increase in friction coefficient and a period of transition to a lower steady state (or nearly steady state)

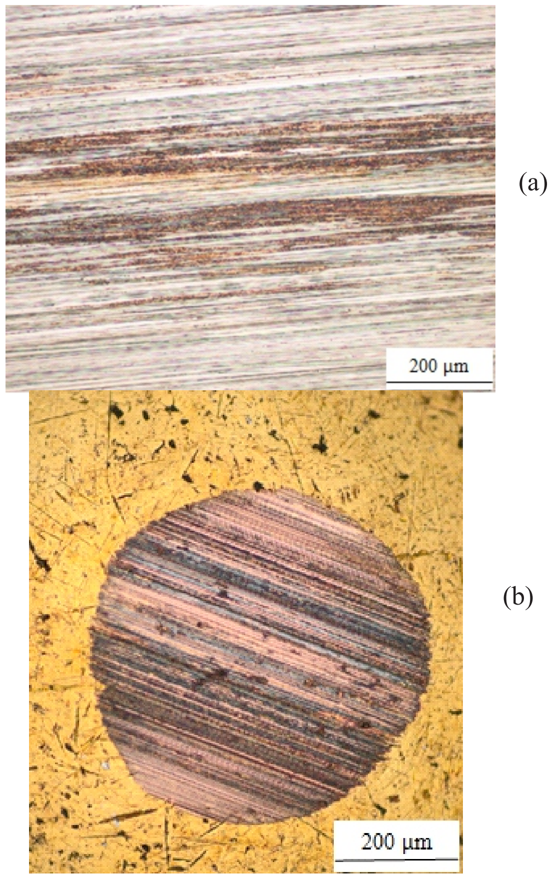



**Figure 10:** Optical micrograph of (a) SS304L flat and (b) bronze ball after friction test.

friction coefficient. The initial rapid increase in friction, which occurred in the early part of the test usually is termed “run-in”, “wear-in” or “break-in” period and can be attributed to frictional anisotropy as a result of local plastic deformation. Both the tribolayer and change in contact geometry led to significant friction reduction to a steady state. The formation of tribolayer on the SS304L flat samples led to the steady state friction coefficient observed in SS304L-Al (2017) and SS304L-bronze pairs.

With the obtained results, it is obvious that the tribological property under marginally lubricated condition is not material property but a combined response, which characterizes a specific tribosystem in contact undergoing relative motion. The types of materials in contact have significant influence on the tribological property of any tribosystem.

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