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# Experimental Investigation of Friction Coefficient and Wear Rate of Stainless Steel 304 Sliding against Smooth and Rough Mild Steel Counterfaces

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**ABSTRACT**

In the present study, friction coefficient and wear rate of stainless steel 304 (SS 304) sliding against mild steel are investigated experimentally. In order to do so, a pin on disc apparatus is designed and fabricated. Experiments are carried out when smooth or rough mild steel pin slides on SS 304 disc. Experiments are conducted at normal load 10, 15 and 20 N, sliding velocity 1, 1.5 and 2 m/s and relative humidity 70%. Variations of friction coefficient with the duration of rubbing at different normal loads and sliding velocities are investigated. Results show that friction coefficient is influenced by duration of rubbing, normal load and sliding velocity. In general, friction coefficient increases for a certain duration of rubbing and after that it remains constant for the rest of the experimental time. The obtained results reveal that friction coefficient decreases with the increase in normal load for SS 304 mating with smooth or rough mild steel counterface. On the other hand, it is also found that friction coefficient increases with the increase in sliding velocity. Moreover, wear rate increases with the increase in normal load and sliding velocity. The magnitudes of friction coefficient and wear rate are different depending on sliding velocity and normal load for both smooth and rough counterface pin materials.

**Key words:**Friction coefficient; wear rate, SS 304, mild steel, normal load, sliding velocity.

## 1. INTRODUCTION

Numerous investigations [1-13] showed that friction coefficient depends on a number of parameters such as normal load, geometry, relative surface motion, sliding velocity, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, stick-slip, relative humidity, lubrication and vibration. Among

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these factors normal load and sliding velocity are the two major factors that play significant role for the variation of friction. In the case of materials with surface films which are either deliberately applied or produced by reaction with environment, the coefficient of friction may not remain constant as a function of load. In many metal pairs in the high load regime, the coefficient of friction decreases with load. Bhushan [14] and Blau [15] reported that increased surface roughening and a large quantity of wear debris are believed to be responsible for decrease in friction. It was observed that the coefficient of friction may be very low for very smooth surfaces and/or at loads down to micro-to nanonewton range [16,17]. The third law of friction, which states that friction is independent of velocity, is not generally valid. Friction may increase or decrease as a result of increased sliding velocity for different material combinations. An increase in the temperature generally results in metal softening in the case of low melting point metals. An increase in temperature may result in solid-state phase transformation which may either improve or degrade mechanical properties [13]. The most drastic effect occurs if a metal approaches its melting point and its strength drops rapidly, and thermal diffusion and creep phenomena become more important. The resulting increased adhesion at contacts and ductility lead to an increase in friction [13]. The increase in friction coefficient with sliding velocity due to more adhesion of counterface material (pin) on disc.

It was reported [18-21] that friction coefficient of metals and alloys showed different behavior under different operating conditions. In spite of these investigations, the effects of normal load and sliding velocity on friction coefficient of SS 304 sliding against mild steel for smooth or rough counterface are yet to be clearly understood. Therefore, in this study an attempt is made to investigate the effect of normal load and sliding velocity on the friction coefficient of SS 304 sliding against smooth or rough mild steel counterface. The effect of duration of rubbing on friction coefficient of SS 304 is also examined in this study. In addition, the effect of normal load and sliding velocity on wear rate of SS 304 is investigated.

Nowadays, stainless steel-mild steel combinations are widely used for sliding/rolling applications where low friction is required. Due to these wide ranges of tribological applications, SS 304-mild steel combination for smooth and rough counterface has been selected in this research study. It is expected that the applications of these results will contribute to the different concerned mechanical processes.

In this research, it is aimed to find the relation between friction/wear and steel sliding pair with different counterface surface roughnesses. It is also aimed to find the influence of normal load and sliding velocity on friction and wear of SS 304. Within this research, it is sought to better understand and investigate scientifically the possibility of applying controlled normal load and sliding velocity with appropriate choice of counterface surface condition, which may significantly improve the performance of machine elements in industry.

## 2. EXPERIMENTAL

A schematic diagram of the experimental set-up is shown in Fig. 1 i.e. a pin which can slide on a rotating horizontal surface (disc). In this set-up a circular test sample (disc) is to be fixed on a rotating plate (table) having a long vertical shaft clamped with screw from the bottom surface of the rotating plate. The shaft passes through two close-fit bush-bearings which are rigidly fixed with stainless steel plate and stainless steel base such that the shaft can move only axially and any radial movement of the rotating shaft is restrained by the bush. These stainless steel plate and stainless steel base are rigidly fixed with four vertical round bars to provide the rigidity to the main structure of this set-up.

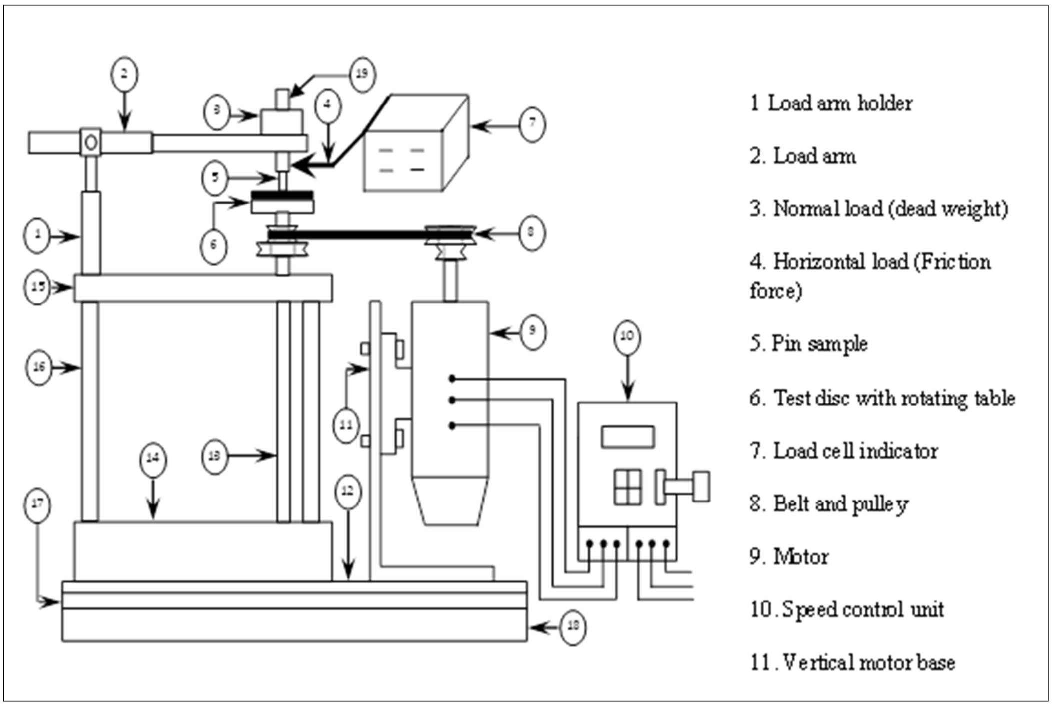


Figure 1. Block diagram of the experimental set-up

The main base of the set-up is constructed by 10 mm thick mild steel plate consisting of 3 mm thick rubber sheet at the upper side and 20 mm thick rubber block at the lower side. A compound V-pulley above the top stainless steel plate was fixed with the shaft to transmit rotation to the shaft from a motor. An electronic speed control unit is used to vary the speed of the motor as required. A 6 mm diameter cylindrical pin whose contacting foot is flat, made of mild steel, fitted on a holder is subsequently fitted with an arm. The arm is pivoted with a separate base in such a way that the arm with the pin holder can rotate vertically and horizontally about the pivot point with very low friction. Sliding speed can be varied by two ways (i) by changing the frictional radius and (ii) by changing the rotational speed of the shaft. In this research, sliding speed is varied by changing the rotational speed of the shaft while maintaining 25 mm constant frictional radius. To measure the frictional force acting on the pin during sliding on the rotating plate, a load cell (TML, Tokyo Sokki Kenkyujo Co. Ltd, CLS-10NA) along with its digital indicator (TML, Tokyo Sokki Kenkyujo Co. Ltd, Model no. TD-93A) was used. The coefficient of friction was obtained by dividing the frictional force by the applied normal force (load). Wear was measured by weighing the test sample with an electronic balance before and after the test, and then the difference in mass was converted to wear rate. To measure the surface roughness of the test samples, Taylor Hobson Precision Roughness Checker (Surtronic 25) was used. In considering the relative humidity of industry where stainless steel used in different types of machineries and sliding mechanisms, 60-75% relative humidity is desirable. In this context, 70% relative humidity has been chosen in this investigation. Each test was conducted for 30 minutes of rubbing time with new pin and test sample. Furthermore, to ensure the reliability of the test results, each test was repeated five times and the scatter in results was small, therefore the average values of these test results were taken into consideration. In the experiments, 90 disc and 90 pin samples were used. The detail experimental conditions are shown in Table 1. The mechanical properties of SS 304 are presented in Table 2.

Table 1.Experimental Conditions

| Sl. No. | Parameters | Operating Conditions |
|---|---|---|
| 1. | Normal Load | 10, 15, 20 N |
| 2. | Sliding Velocity | 1, 1.5, 2 m/s |
| 3. | Relative Humidity | 70 (± 5)% |
| 4. | Duration of Rubbing | 30 minutes |
| 5. | Surface Condition | Dry |
| 6. | Disc material | Stainless steel 304 (SS 304) |
| 7. | Roughness of SS 304, $R_a$ | 0.25-0.35 μm |
| 8. | Pin material | Mild steel |
| 9. | Roughness of mild steel, $R_a$ | (a) Smooth counterface: about 0.3 μm<br>(b) Rough counterface: about 3 μm |

Table 2: Mechanical properties of SS 304

| Mechanical Properties of SS 304 | |
|---|---|
| Density | 8g/cc |
| Hardness, Brinell | 123 |
| Hardness, Rockwell B | 70 |
| Hardness, Vickers | 129 |
| Tensile Strength, Ultimate | 505 MPa |
| Tensile Strength, Yield | 215 MPa |
| Elongation at Break | 70 % |
| Modulus of Elasticity | 193 - 200 GPa |
| Poisson's Ratio | 0.29 |
| Shear Modulus | 80 GPa |

## 3. RESULTS AND DISCUSSION

### 3.1.Variation of Friction Coefficient with Duration of Rubbing at Different Normal Loads

Figure 2 shows the variation of friction coefficient with the duration of rubbing at different normal loads for SS 304 mating with smooth mild steel counterface. During experiment, the sliding velocity and relative humidity were 1 m/s and 70% respectively. Curve 1 of this figure is drawn for normal load 10 N. From this curve, it is observed that during initial stage of rubbing, the value of friction coefficient is 0.23 and then increases very steadily up to 0.3 over a duration of 20 minutes of rubbing and after that it remains constant for the rest of the experimental time. At the initial stage of rubbing, friction is low and the factors responsible for this low friction are due to the presence of a layer of foreign material on the disc surface. This layer on the disc surface in general comprises of (i) moisture, (ii) oxide of metals, (iii) deposited lubricating material, etc. SS 304 readily oxidizes in air, so that, at initial duration of rubbing, the oxide film easily separates the two material surfaces and there is little or no true metallic contact and also the oxide film has a low shear strength. After initial rubbing, the film (deposited layer) breaks up and clean surfaces come in contact which increase the bonding force between the contacting surfaces. At the same time due to the ploughing effect, inclusion of trapped wear particles and roughening of the disc surface, the friction force increases with duration of rubbing. After a certain duration of rubbing, the increase of roughness and other parameters may reach to a certain steady state value and hence the values of friction coefficient remain constant for the rest of the time. Curves 2 and 3 of this figure are drawn for normal load 15 and 20 N respectively and show similar trends as that of curve 1. From these curves, it is also observed that time to reach steady state values is different for different normal loads. Results show that at normal load 10, 15 and 20 N, SS 304-mild steel smooth pair takes 20, 17 and 14 minutes respectively to reach steady friction. It indicates that the higher the normal load, the time to reach steady friction is less. This is because the surface roughness and other parameter attain a steady level at a shorter period of time with the increase in normal load. The trends of these results are similar to the results of Chowdhury and Helali [22, 23].

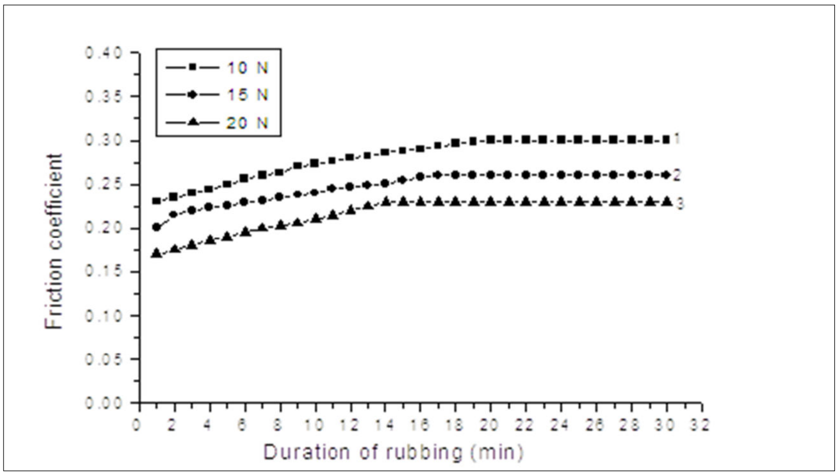


Figure 2. Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s. relative humidity: 70%, test sample: SS 304, pin: Mild steel, smooth)

Figure 3 shows the effect of the duration of rubbing on the value of friction coefficient at different normal loads for SS 304 sliding against rough mild steel counterface at sliding velocity 1 m/s and relative humidity 70%. Curve 1 of this figure drawn for normal load 10 N, shows that during starting of the experiment, the value of friction coefficient is 0.28 which rises for few minutes to a value of 0.34 and then it becomes steady for the rest of the experimental time. Almost similar trends of variation are observed in curves 2 and 3 which are drawn for load 15 and 20 N respectively. From these curves, it is found that time to reach steady friction is different for different normal loads. At normal load 10, 15 and 20 N, SS 304-mild steel rough pair takes 22, 19 and 16 minutes respectively to reach steady friction That is, higher the normal load, SS 304-mild steel rough pair takes less time to stabilize.

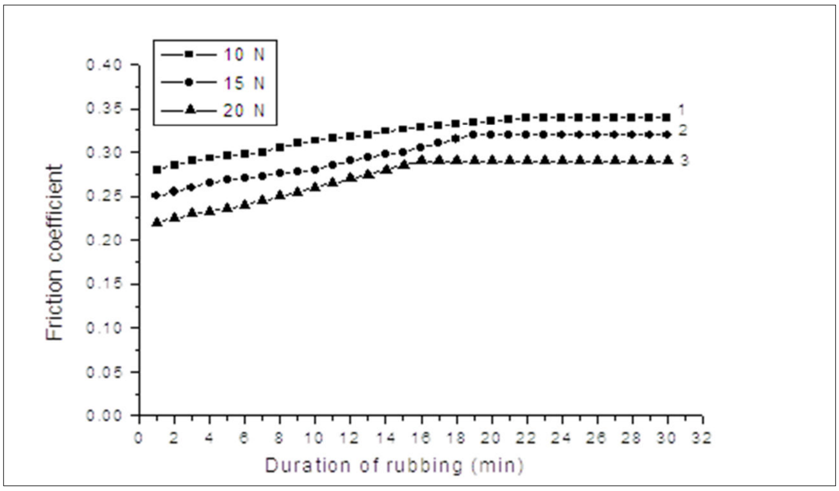


Figure 3. Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: SS 304, pin: M ild steel, rough)

### 3.2. Influence of Normal Load on Friction Coefficient

Figure 4 shows the comparison of the variation of friction coefficient with normal load for SS 304 mating with smooth or rough mild steel couterface. It is shown that friction coefficient varies from 0.3 to 0.23 and 0.34 to 0.29 with the variation of normal load from 10 to 20 N for SS 304-mild steel smooth and SS 304-mild steel rough counterface respectively. These results show that friction coefficient decreases with the increase in normal load. Increased surface roughing and a large quantity of wear debris are believed to be responsible for the decrease in friction [14,15] with the increase in normal load. Similar behavior is obtained for Al–Stainless steel pair [24] i.e. friction coefficient decreases with the increase in normal load. From this figure, it is also found that at identical conditions, the values of friction coefficient of SS 304 mating with smooth counterface is lower than that of SS 304 mating with rough counterface. After friction tests, it was found that the average roughness of SS 304 varied from 0.98-1.23 and 1.22-1.41 m for smooth and rough counterface pins respectively.

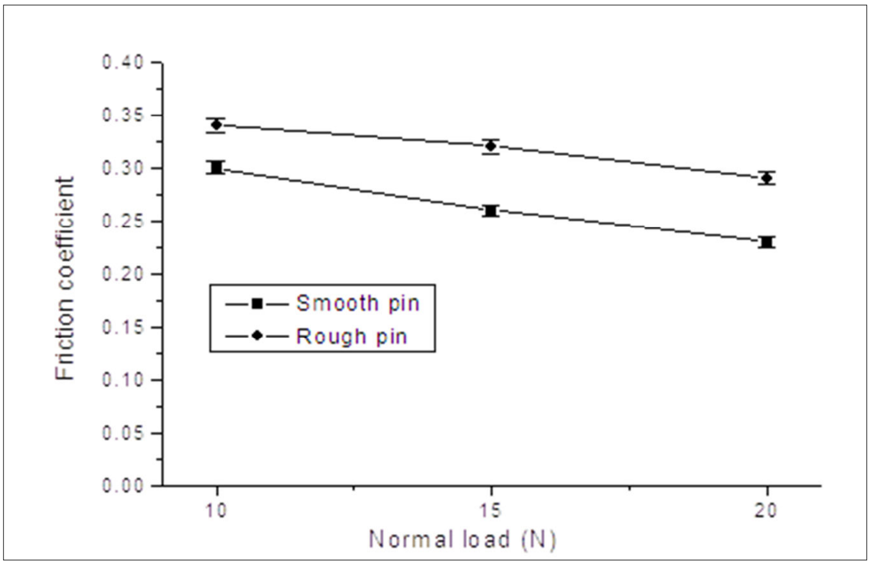


Figure 4. Friction coefficient as a function of Normal load for SS 304
(sliding velocity: 1 m/s, relative humidity: 70%)

### 3.3. Variation of Friction Coefficient with Duration of Rubbing at Different Sliding Velocities

Figures 5 and 6 shows the variation of friction coefficient with the duration of rubbing at different sliding velocities for SS 304-mild steel smooth pair and SS 304-mild steel rough pair respectively at normal load 15 N and relative humidity 70%. Curves 1, 2 and 3 of Fig. 5 are drawn for sliding velocity 1, 1.5 and 2 m/s respectively. Curve 1 of this figure shows that at initial stage of rubbing, the value of friction coefficient is 0.2 which increases almost linearly up to 0.26 over a duration of 17 minutes of rubbing and after that it remains constant for the rest of the experimental time. The increase of friction may be associated with ploughing effect and because of roughening of the disc surface. After a certain duration of rubbing the increase of roughness and other parameters may reach to a certain steady value hence the values of friction coefficient remain constant for the rest of the time. Curves 2 and 3 show that for the higher sliding velocity, the friction coefficient is more and the trend in variation of friction coefficient is almost the same as for curve 1.

From these curves, it is also observed that time to reach steady state value is different for different sliding velocity. From the results it is found that SS 304-mild steel smooth pair at sliding velocity 1, 1.5 and 2 m/s takes to reach constant friction 17, 14 and 11 minutes respectively. It indicates that the higher the sliding velocity, time to reach constant friction is less. This may be due to the higher the sliding velocity, the surface roughness and other parameters take less time to stabilize. From Fig. 6, it can be observed that the trends in variation of friction coefficient with the duration of rubbing are very similar to that of Fig. 5 but the values of friction coefficient are different for SS 304-mild steel rough pair.

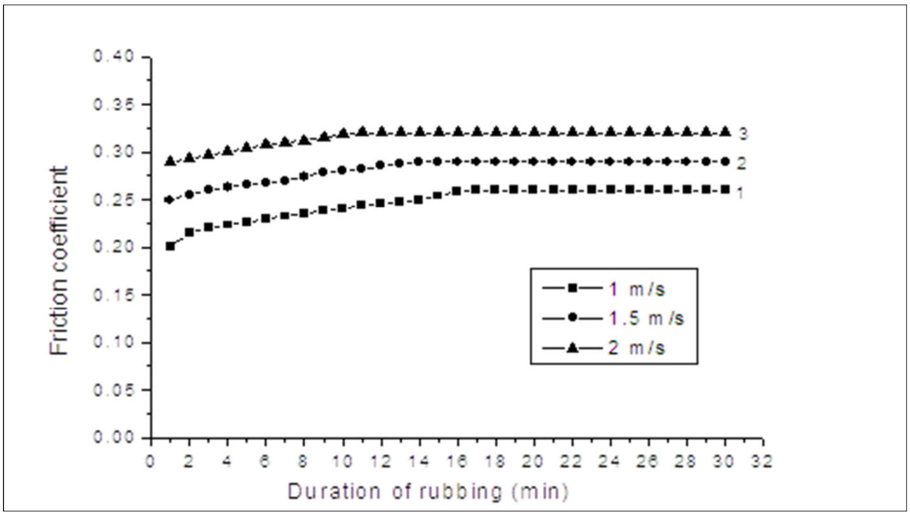


Figure 5. Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N. relative humidity: 70%, test sample: SS 304, pin: M ild steel, smooth)

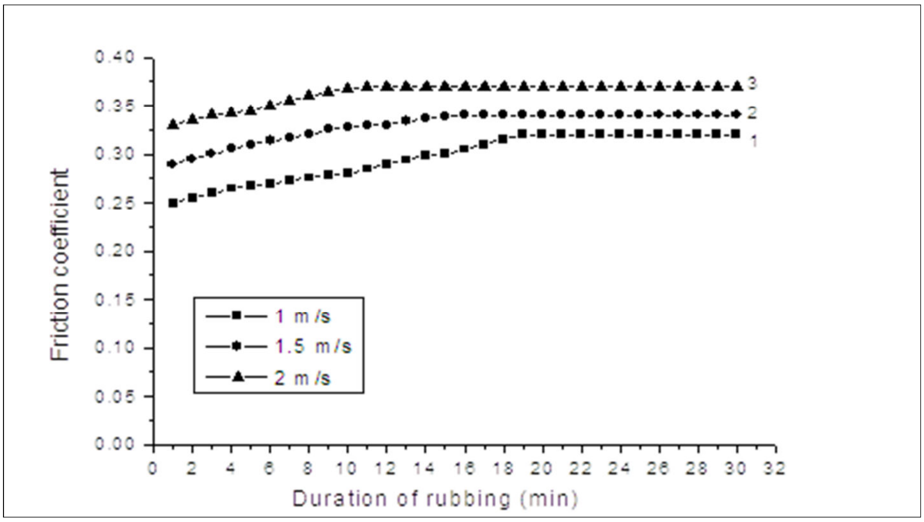


Figure 6. Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N. relative humidity: 70%, test sample: SS 304, pin: M ild steel, rough)

### 3.4. Influence of Sliding Velocity on Friction Coefficient

Figure 7 shows the comparison of the variation of friction coefficient with sliding velocity for the above mentioned material pairs. Curves of this figure are drawn for SS 304-mild steel smooth and SS 304-mild steel rough pairs. It is shown that the friction coefficient varies from 0.26 to 0.32 and 0.32 to 0.37 with the variation of sliding velocity from 1 to 2 m/s for SS 304-mild steel smooth and SS 304-mild steel rough pairs respectively. These results indicate that friction coefficient increases with the increase in sliding velocity. Sliding contact of two materials results in heat generation at the asperities and hence increases in temperature at the frictional surfaces of the two materials. The increase in friction coefficient with sliding velocity due to more adhesion of counterface material (pin) on disc [13]. From this figure, it is also found that at identical conditions, the values of friction coefficient of SS 304 sliding against smooth mild steel counterface is lower than that of SS 304 sliding against rough mild steel counterface. After friction tests, it was found that the average roughness of SS 304 varied from 1.05-1.26 and 1.26-1.47 μm for smooth and rough counterface pins respectively. Friction coefficients of SS 304 at different normal loads and sliding velocities are mentioned in table 3 for smooth and rough counterface pin materials.

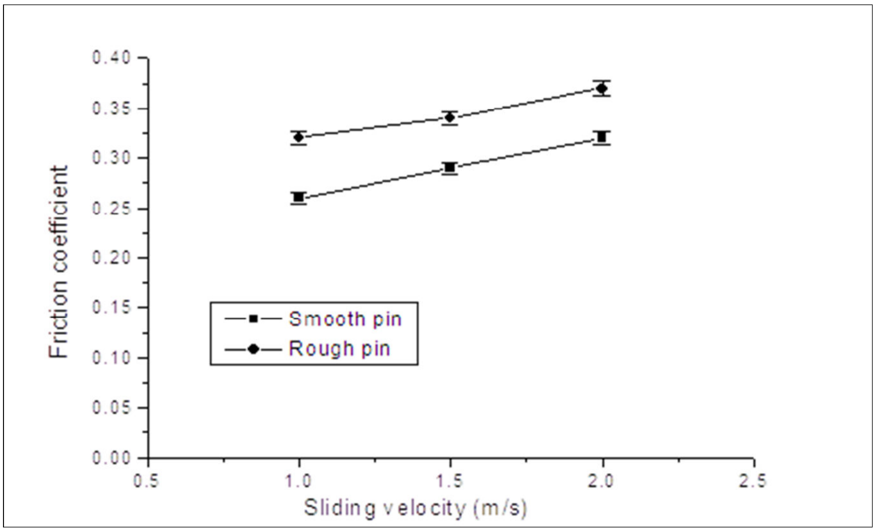


Figure 7. Friction coefficient as a function of sliding velocity for SS 304 (normal load: 15 N. relative humidity: 70%)

Table 3: Friction coefficient at different normal loads andsliding velocities for different sliding pairs

| Sliding velocity (m/s) | Normal load (N) | Friction coefficient (μ) | |
|---|---|---|---|
| | | Sliding pairs | |
| | | SS 304-mild steel, smooth | SS 304-mild steel, rough |
| 1 | 10 | 0.30 | 0.34 |
| 1.5 | | 0.33 | 0.37 |
| 2 | | 0.36 | 0.40 |
| 1 | 15 | 0.26 | 0.32 |
| 1.5 | | 0.29 | 0.34 |
| 2 | | 0.32 | 0.37 |
| 1 | 20 | 0.23 | 0.29 |
| 1.5 | | 0.26 | 0.32 |
| 2 | | 0.29 | 0.35 |

### 3.5. Influence of Normal Load on Wear Rate

Variations of wear rate with normal load are presented in Fig. 8. Results show that wear rate of SS 304 varies from 2.3 to 4.0 and 3.0 to 5.11 mg/min with the variation of normal load from 10 to 20 N for smooth and rough counterface pins respectively. It is observed that wear rate increases with the increase in normal load for both type material combinations. When the load on the pin is increased, the actual area of contact would increase towards the nominal contact area, resulting in increased frictional force between two sliding surfaces. The increased frictional force and real surface area in contact causes higher wear. This means that the shear force and frictional thrust are increased with increase of applied load and these increased in values accelerate the wear rate. Similar trends of variation are also observed for mild steel–mild steel couples [25], i.e wear rate increases with the increase in normal load. From this figure, it is also found that at identical conditions, the values of wear rate of SS 304 mating with smooth counterface is lower than that of SS 304 mating with rough counterface. It is due to the fact that rough surfaces generally wear more quickly and have higher friction coefficients than smooth surfaces.

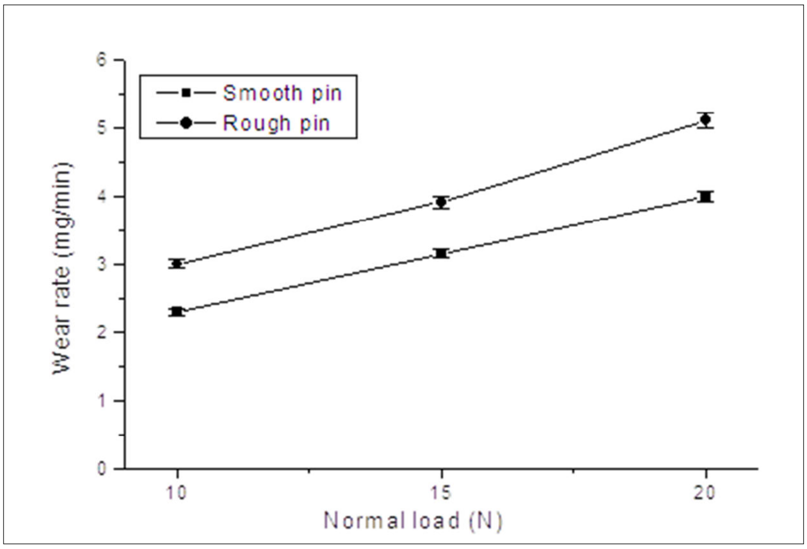


Figure 8. Wear rate as a function of Normal load for SS 304

(Sliding velocity: 1 m/s, relative humidity: 70%)

### 3.6. Influence of Sliding Velocity on Wear Rate

The variations of wear rate with sliding velocity for above mentioned material combinations are also observed in this study and the results are presented in Fig. 9. These results indicate that wear rate of SS 304 varies from 3.15 to 5.25 and 3.91 to 6.12 mg/min with the variation of sliding velocity from 1 to 2 m/s for SS 304-mild steel smooth and SS 304-mild steel rough couples respectively. It is observed that wear rate increases with the increase in sliding velocity for both of these material pairs. This is due to the fact that duration of rubbing is same for all sliding velocities, while the length of rubbing is more for higher sliding velocity. The reduction of shear strength of the material and increased true area of contact between contacting surfaces may have some role on the higher wear rate at higher sliding velocity [13]. From this figure, it is also observed that at identical conditions, wear rates of SS 304 mating with smooth counterface is lower than that of SS 304 mating with rough counterface.

Wear rates of SS 304 at different normal loads and sliding velocities are listed in table 4for smooth and rough counterface pin materials.

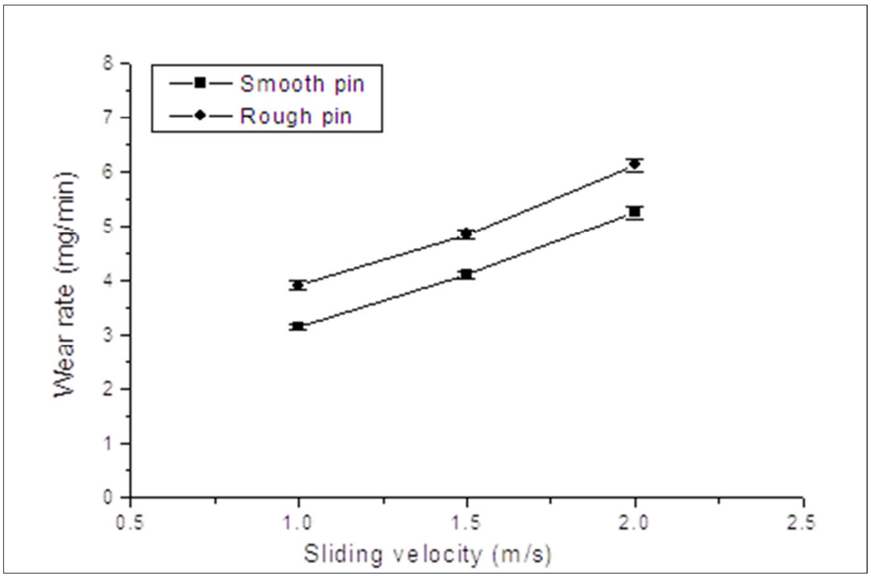


Figure 8. Wear rate as a function of sliding velocity for SS 304
(normal load: 15 N, relative humidity: 70%)

Table 4: Wear rate at different normal loads and sliding velocitiesfor different sliding pairs

| **Sliding velocity (m/s)** | **Normal load (N)** | **Wear rate (mg/min)** | |
|---|---|---|---|
| | | **Sliding pairs** | |
| | | **SS 304-mild steel, smooth** | **SS 304-mild steel, rough** |
| **1** | **10** | **2.3** | **3** |
| **1.5** | | **3.12** | **3.96** |
| **2** | | **3.93** | **4.95** |
| **1** | **15** | **3.15** | **3.91** |
| **1.5** | | **4.1** | **4.85** |
| **2** | | **5.25** | **6.12** |
| **1** | **20** | **4** | **5.11** |
| **1.5** | | **5.14** | **6.03** |
| **2** | | **6.02** | **7.05** |

### 3.7. Analysis of Worn Surfaces

Figure 10 shows the optical pictures of the worn surfaces for different combinations of sliding pairs. The appearance of the worn surface of SS 304 for rough pin counterface is clearly rougher than that of SS 304 for smooth pin counterface. From these photographs, it is also confirmed that the higher the normal load less rougher the SS 304 surfaces for different sliding pairs are observed. In contrast, the higher the sliding velocity more rougher the SS 304 surfaces for smooth or rough counterface pin are seen. It can be noted that these observations are also ensured by measured roughness values of SS 304 for different combinations. The optical microscopy studies of wear surface show abrasive and adhesion wear on the surface of SS 304 for different combinations. The debonding/pullout of the particles are also seen. The particle reinforcement significantly improved wear resistance. The experimental observations indicate that the main wear mechanism for the SS 304 of different sliding pairs is the combination of wear, abrasive and delamination.

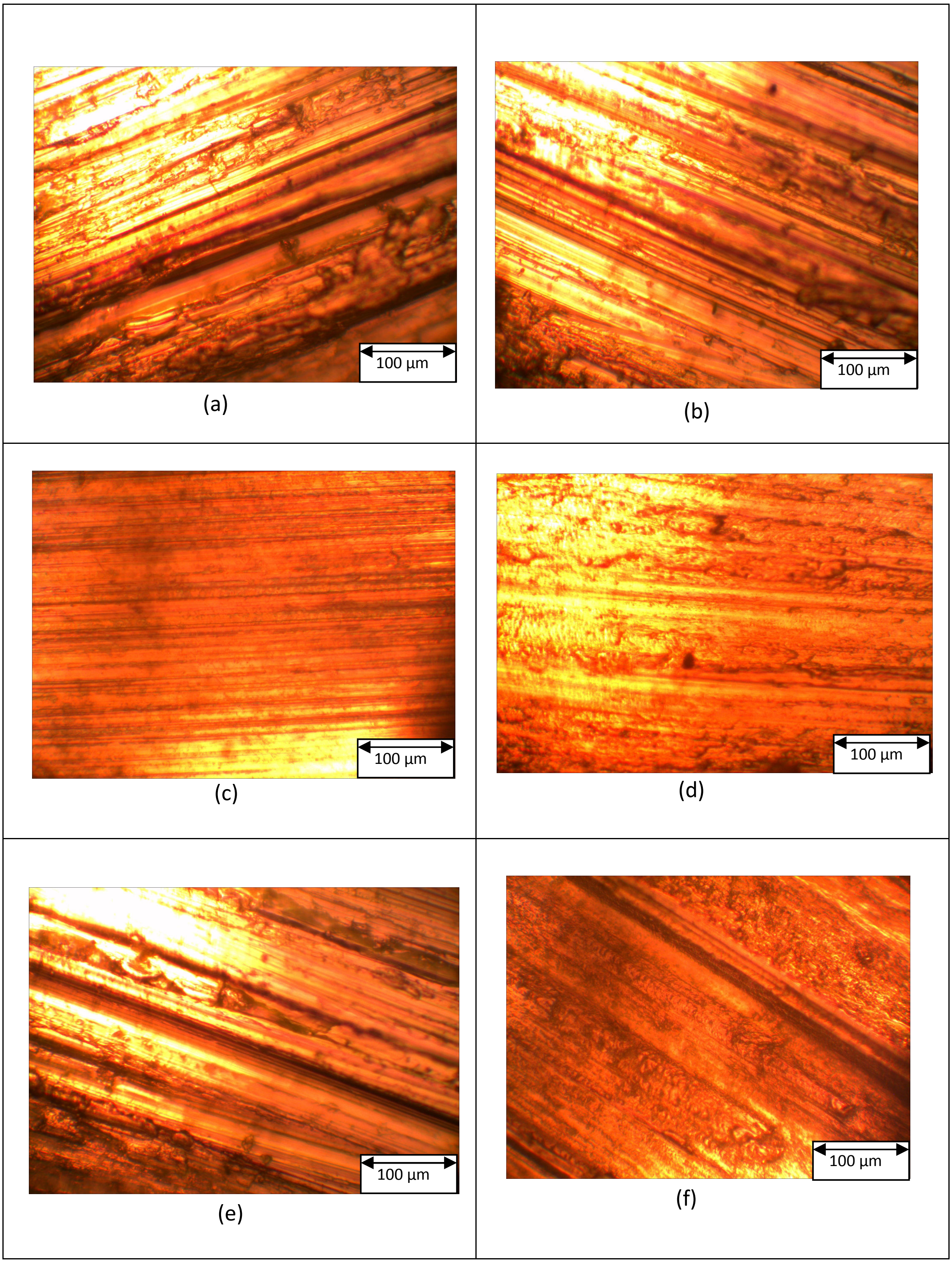


Fig. 10: Optical microscopy of worn surfaces of SS 304 for (a) Rough pin (15 N, 1 m/s) (b) Smooth pin (15 N, 1 m/s) (c) Rough pin (20 N, 1 m/s) (d) Smooth pin (20 N, 1 m/s) (e) Rough pin (15 N, 2 m/s) (f) Smooth pin (15 N, 2 m/s).

## 4. CONCLUSION

The presence of normal load and sliding velocity indeed affects the friction force considerably. Within the observed range, the values of friction coefficient decrease with the increase in normal load while friction coefficients increase with the increase in sliding velocity for SS 304 sliding against smooth or rough mild steel pin. Friction coefficient varies with the duration of rubbing and after certain duration of rubbing, friction coefficient becomes steady for the observed range of normal load and sliding velocity. Wear rates of SS 304 mating with smooth or rough mild steel counterface increase with the increase in normal load and sliding velocity. At identical conditions, the values of friction coefficient and wear rate of SS 304 mating with smooth counterface are lower than that of SS 304 mating with rough counterface.

As (i) the friction coefficient decreases with the increase in normal load (ii) the values of friction coefficient increase with the increase in sliding velocity (iii) wear rate increases with the increase in normal load and sliding velocity and (iv) the magnitudes of friction coefficient and wear rate are different for smooth and rough counterface pins, therefore maintaining an appropriate level of normal load, sliding velocity as well as appropriate choice of counterface surface condition, friction and wear may be kept to some lower value to improve mechanical processes.

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