Friction Coefficient and Wear Rate of Copper Mating with Smooth and Rough Stainless Steel 304 Counterfaces

Dr. Mohammad Asaduzzaman Chowdhury [1], Dr. Dewan Muhammad Nuruzzaman [2], Biplov Kumar Roy [1], Muhammad Mahmudur Rahman [1], Md. Abul Kalam Azad [1], Md.Mijanur Rahman [1], Shazib Bhumik [1]

[1] Department of Mechanical Engineering, Dhaka University of Engineering and Technology, Gazipur, Gazipur1700, Bangladesh, [2.] Faculty of Manufacturing Engineering University Malaysia Pahang, Malaysia.
asadzmn2003@yahoo.com

Abstract: In the present study, friction coefficient and wear rate of copper sliding against SS 304 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 SS 304 pin slides on copper 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 and sliding velocity for copper mating with smooth or rough SS 304 counterface. 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.

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Keywords: Friction coefficient; wear rate, copper, SS 304, normal load, sliding velocity

1. Introduction

Study of mechanics of friction and the relationship between friction and wear dates back to the sixteenth century, almost immediately after the invention of Newton's law of motion. It was observed by several authors [1-13] that the variation of friction depends on interfacial conditions 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 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 materials combinations. The coefficient of kinetic friction as a function of sliding velocity generally has a negative slope. Changes in the sliding velocity result in a change in the shear rate which can influence the mechanical properties of the mating materials. The strength of many metals and nonmetals is greater at higher shear strain rates [18, 19] which results in a lower real area of contact and a lower coefficient of friction in a dry contact.

It was reported [20-23] 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 copper sliding against SS 304 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 copper sliding against smooth or rough SS 304 counterface. The effect of duration of rubbing on friction coefficient of copper is also examined in this study. In addition, the effect of normal load and sliding velocity on wear rate of copper is investigated.

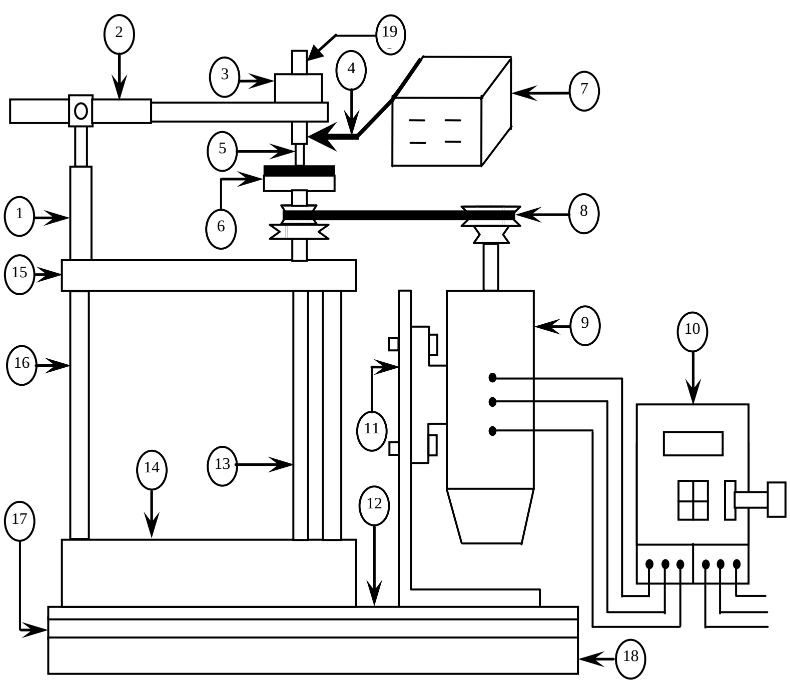
Nowadays, copper-SS 304 combinations are widely used for sliding/rolling applications where low friction is required. Due to these wide ranges of tribological applications, copper-SS 304 combination for smooth and rough counterface has been selected in this research study. It is expected that the applications 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 copper-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 copper. 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

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.

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.



1 Load arm holder
2. Load arm
3. Normal load (dead weight)
4. Horizontal load (Friction force)
5. Pin sample
6. Test disc with rotating table
7. Load cell indicator
8. Belt and pulley
9. Motor
10. Speed control unit
11. Vertical motor base
12. 3 mm Rubber pad
13. Main shaft
14. Stainless steel base
15. Stainless steel plate
16. Vertical square bar
17. Mild steel main base plate
18. Rubber block (20 mm thick)
19. Pin holder.

Fig. 1 Block diagram of the experimental set-up

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-

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. 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. The detail experimental conditions are shown in Table 1.

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	Copper
7.	Roughness of copper, R_a	0.40-0.50 μm
8.	Pin material	Stainless steel 304 (SS 304)
9.	Roughness of SS 304, R_a	(a) Smooth counterface: about 0.3 μm (b) Rough counterface: about 3 μm

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 copper mating with smooth SS 304 counterface. During experiment, the sliding velocity and relative humidity were 1 m/s and 70% respectively.

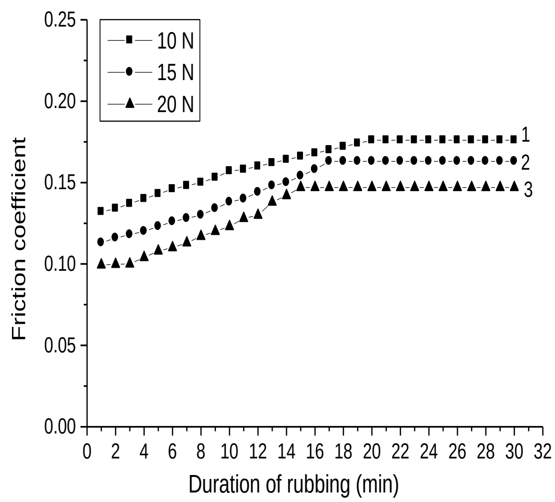


Fig. 2: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: copper, pin: SS 304,smooth)

Curve 1 of this figure is drawn for normal load 10 N. From this curve, it is observed that during the starting, the value of friction coefficient is 0.132 and then increases very steadily up to 0.176 over 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. Copper 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, copper-SS 304 smooth pair takes 20, 17 and 15 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 [24, 25].

Figure 3 shows the effect of the duration of rubbing on the value of friction coefficient at different normal loads for copper sliding against rough SS 304 counterface at speed of 1 m/s and 70% of relative humidity.

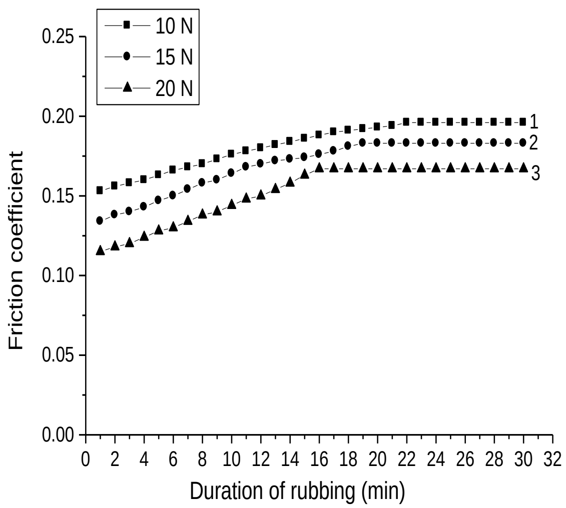


Fig. 3: Friction coefficient as a function of duration of rubbing at different normal loads (sliding velocity: 1 m/s, relative humidity: 70%, test sample: copper, pin: SS 304,rough)

Curve 1 of this figure drawn for normal load 10 N, shows that during starting of the experiment, the value of friction coefficient is 0.153 which rises for 22 minutes to a value of 0.196 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, copper-SS 304 rough pair takes 22, 19 and 16 minutes respectively to reach steady friction That is, higher the normal load, copper-SS 304 rough pair takes less time to stabilize.

3.2 Influence of normal load on friction coefficient

Figure 4 shows the comparison of the variation of friction coefficient with normal load for copper mating with smooth and rough SS 304 couterface.

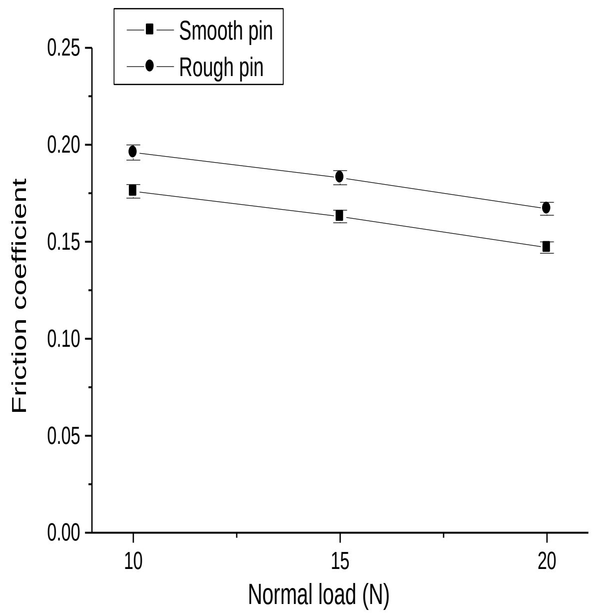


Fig. 4: Friction coefficient as a function of Normal load for copper (Sliding velocity: 1 m/s, relative humidity: 70%)

Curves of this figure are drawn for copper under SS 304 smooth and rough counerface conditions. It is shown that friction coefficient varies from 0.176 to 0.147 and 0.196 to 0.167 with the variation of normal load from 10 to 20 N for copper-SS 304 smooth and copper-SS 304 rough pairs 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 [26] 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 copper mating with smooth counterface is lower that that of copper with rough counterface. After friction tests, it was found that the average roughness of copper varied from 0.71-0.90 and 0.88-1.13 μm for smooth and rough counterface pins respectively.

3.3 Variation of friction coefficient with duration of rubbing at different sliding velocities

Figures 5 and 6 show the variation of friction coefficient with the duration of rubbing at different sliding velocities for copper-SS 304 smooth and copper-SS 304 rough pair respectively at 15 N normal load.

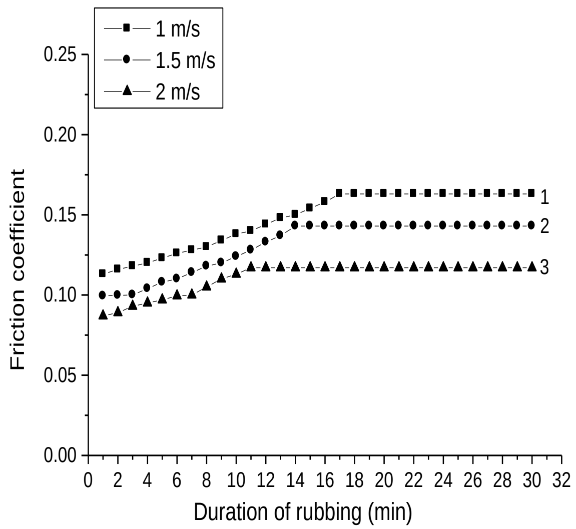


Fig. 5: Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N, relative humidity: 70%, test sample: copper, pin: SS 304,smooth)

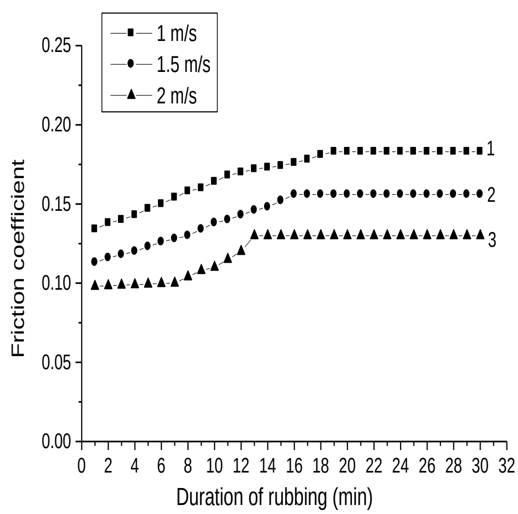


Fig. 6: Friction coefficient as a function of duration of rubbing at different sliding velocities (normal load: 15 N, relative humidity: 70%, test sample: copper , pin: SS 304,rough)

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 during the starting, the value of friction coefficient is 0.113 which increases almost linearly up to 0.163 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 speed, the friction coefficient is less 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 values are different for different sliding velocities. From the results it is found that copper-SS 304 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, the time to reach constant friction is less. This may be due to the higher the sliding speed 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 copper-SS 304 rough pair.

3.4 Influence of sliding velocity on friction coefficient

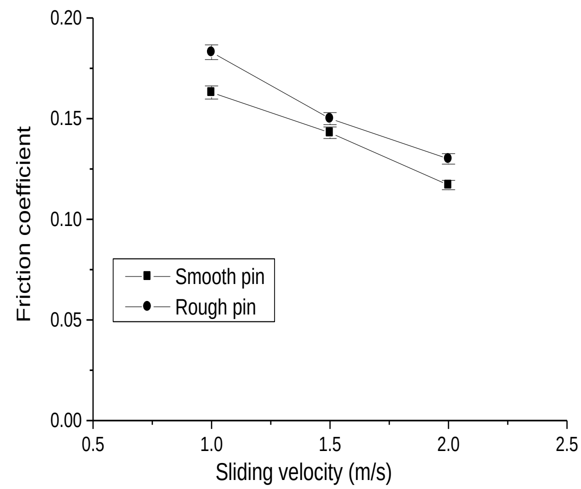


Fig. 7: Friction coefficient as a function of sliding velocity for copper (normal load: 15 N, relative humidity: 70%)

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 copper-SS 304 smooth and copper-SS 304 rough pairs. It is shown that the friction coefficient varies from 0.163 to 0.117 and 0.183 to 0.13 with the variation of sliding velocity from 1 to 2 m/s for copper-SS 304 smooth and copper-SS 304 rough pairs respectively. These results indicate that friction coefficient decreases with the increase in sliding velocity. The decrease of friction coefficient of copper-SS 304 smooth and copper-SS 304 steel rough pairs with the increase of sliding velocity may be due to the change in the shear rate which can influence the mechanical properties of the mating materials. The strength of these materials is greater at higher shear strain rates [18,19] which results in a lower real area of contact and a lower coefficient of friction in dry contact condition. These findings are in agreement with the findings of Chowdhury and Helali [25] for mild steel, ebonite and GFRP sliding against mild steel. From this figure, it is also found that at identical conditions, the values of friction coefficient of copper sliding against smooth mild steel counterface is lower that that of copper sliding against rough SS 304 counterface. After friction tests, it was found that the average roughness of copper varied from 0.78-1.10 and 0.96-1.24 μm for smooth and rough counterface pins respectively. Friction coefficients of copper at different normal loads and sliding velocities are mentioned in Table 2 for smooth and rough counterface pin materials.

Table 2: Friction coefficient at different normal loads and sliding velocities for different sliding pairs

Sliding velocity (m/s)	Normal load (N)	Friction coefficient (μ)	
		Sliding pairs	
		Copper-SS 304, smooth	Copper-SS 304, rough
1	10	0.176	0.196
1.5		0.156	0.167
2		0.137	0.148
1	15	0.163	0.183
1.5		0.143	0.156
2		0.117	0.13
1	20	0.147	0.167
1.5		0123	0.137
2		0.098	0.108

3.5 Influence of normal load on wear rate

Variations of wear rate with normal load are presented in Fig. 8.

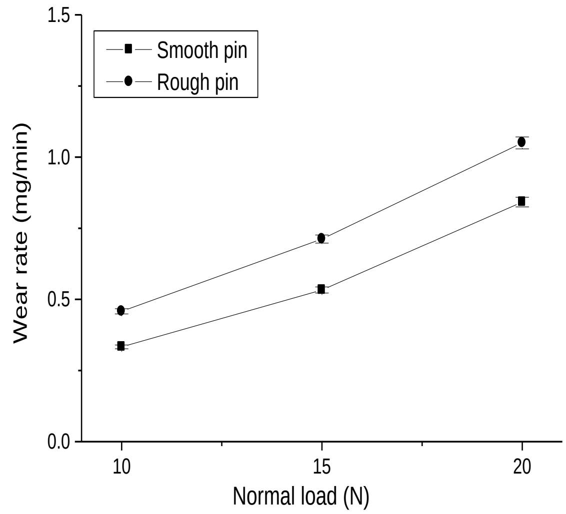


Fig. 8: Wear rate as a function of Normal load for copper (Sliding velocity: 1 m/s, relative humidity: 70%)

Results show that wear rate of copper varies from 0.333 to 0.842 and 0.458 to 1.05 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 [27], 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 copper mating with smooth counterface is lower than that of copper 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

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 copper varies from 0.533 to 0.965 and 0.712

to 1.18 mg/min with the variation of sliding velocity from 1 to 2 m/s for copper-SS 304 smooth and copper-SS 304 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 copper mating with smooth counterface is lower than that of copper mating with rough counterface.

Wear rates of copper at different normal loads and sliding velocities are listed in Table 3 for smooth and rough counterface pin materials.

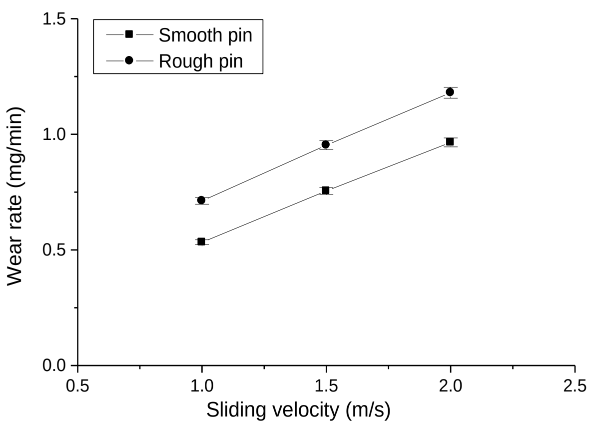


Fig. 9: Wear rate as a function of sliding velocity for copper (normal load: 15 N, relative humidity: 70%)

Table 3: Wear rate at different normal loads and sliding velocities for different sliding pairs

Sliding velocity (m/s)	Normal load (N)	Wear rate (mg/min)	
		Sliding pairs	
		Copper-SS 304, smooth	Copper-SS 304, rough
1	10	0.333	0.458
1.5		0.533	0.712
2		0.842	1.05
1	15	0.545	0.668
1.5		0.755	0.953
2		1.15	1.45
1	20	0.755	0.872
1.5		0.965	1.18
2		1.372	2.05

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 and sliding velocity for copper sliding against smooth or rough SS 304 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 copper mating with smooth or rough SS 304 counterface increase with the increase in normal load and sliding velocity. At identical conditions, the values of friction coefficient and wear rate of copper mating with smooth counterface are lower than that of copper mating with rough counterface.

As (i) the friction coefficient decreases with the increase in normal load and 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.

Corresponding Author:
Dr. Mohammad Asaduzzaman Chowdhury
Professor
Department of Mechanical Engineering
Dhaka University of Engineering and Technology,
Gazipur,Gazipur-1700, Bangladesh
E-mail: asadzmn2003@yahoo.com

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