The Influence of The Temperature on Dry Friction of AISI 3315 Steel Sliding Against AISI 3150 Steel

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Abstract: In this paper, the effects the influence of frictional heating on the wear of AISI 3315 Steel were investigated experimentally using a pin-on-ring geometry. All the tests were carried out in air without any lubricant. In order to understand the variation in frictional coefficient and temperature with load and speed, the friction tests were carried out at a speed of 1 m/s and loads in the range 115-250 N, and at a speed range 1-4 m/s, a load of 115 N. The sliding distance was 1500 m. The bulk temperature of the specimen was measured from the interface surface at a distance of 1 mm from the contact surface by using type K thermocouples (Ni-Cr-Ni). The coefficient of friction was determined as a function of test load and speed. The steady state coefficient of friction of the test material decreases with increasing load and speed due to the oxide formation. But the unsteady state coefficient of friction increases with an increase in load and speed.

Keywords: Sliding wear, bulk temperature, coefficient of friction.

1.Introduction

Friction occurs whenever two solid bodies slide against each other. It takes place by a variety of mechanisms in and around the real area of contact between the sliding bodies. It is through frictional processes that velocity differences between the bodies are accommodated. It is also through these processes that mechanical energy is transformed into internal energy or heat, which causes the temperature of the sliding bodies to increase. Although the word tribology was first coined almost 450 years after the death of Leonardo da Vinci, it is clear that Leonardo was fully familiar with the basic tribological concepts of friction, lubrication and wear [1]. Amontons and Coulomb who has established the earliest mechanical friction theory have found the basic friction laws as follows [2-3];

   1.The friction is independent of the apparent area of contact between the bodies.

   2.The friction force F_s is proportional to the normal load F_N between the bodies and there is a constant between F_s and F_N as known the friction coefficient $\mu = F_s/F_N$

   3.The frictional coefficient is independent of the sliding velocity.

It is well known that the most important factor in friction is the interaction of surface asperities and the sliding involves the riding of rigid asperities on one surface over the other. Tabor [3] assumed that adhesion was the main source of friction and that surface asperities were deformed themselves elastically, plastically, viscoelastically or brittle. The friction process is an energy process, and studies have shown, a very complex phenomenon. In the common phenomenological view of the friction process, it has appeared that friction depends on the properties of mated materials, sliding speed, load and environmental conditions [5]. Some studies showed that increasing normal load increases the

coefficient of friction [6]. Other studies showed that increasing this test parameter decreases this friction characteristic (7-9). In addition, some authors studied the effect of sliding speed on the tribological behaviour of a number of steels; they found that increasing sliding speed decreases the coefficient of friction. It has been studied the wear of medium carbon steel with different microstructures and found that oxidative wear was prevalent under low normal loads. Once the normal load reached a critical value, a mild to severe wear transition occurred, and subsequently an extrusive wear prevailed and abruptly increased the wear rate but reduced the coefficient of friction [10]. Some authors found that the coefficient of friction decreased with increasing surface hardness [11]. Moreover, it has been reported that lower friction is usually associated with harder surfaces [6]. A great deal of research has been carried out concerning the sliding friction characteristics of metals at the low loads and speeds [12-17]. Also the experimental conditions were chosen so that the temperature rise was minimal. Hence thermal aspects could be neglected. However, it is well known that it is at temperatures above one-half of the absolute melting point of metals [12]. The effect of temperature on the friction behaviour of metals cannot be neglected because oxidation plays an increasingly important role in high load and speed sliding friction [17]. This work aims to investigate the effects of normal load, sliding speed and frictional heating on the coefficient of friction of AISI 3315 steel dry sliding against AISI 3150 steel.

2.Experimental details

2.1. Material

The friction characteristics of the AISI 3315 steel used in manufacturing many machine elements such as gears, bearings and piston liners were investigated. The test samples were cut from the same batch of hot rolled materials, and they were machined with 16 mm long and 15 mm in diameter (i.e. pin). The AISI 3150 steel which is a hot working tool steel has been chosen as the counter test material (i.e ring). The counter test samples were rings 16 mm thick with 50 mm outer and 20 mm inner diameter. The nominal contact area was about 1.77×10^{-4} m^2. The sample configuration is illustrated in Fig.1 and Fig.2 AISI 3315 contains % C 0.15, % Mn 0.7, % Si 0.21, % P0.03, % S 0.029, % Cr 0.8, % Ni 3.5, and AISI 3150 contains % C 0.48, % Mn 0.85, % Si 0.2, % P 0.02, % S 0.21, % Cr 0.85, % Ni 1.25. The pin specimens is homogenised and its hardness is 260 $HV_{30.}$ The ring homogenised and hardened in oil, so its hardness is 750 HV_{30}. As shown in Fig.1，the surfaces of the pins were machined to conform to the surface of the ring in order to provide a more realistic contact model. Thus, the investigation of the frictional coefficient for both the unsteady state and steady state sliding regimes could be possible. The pin-on-ring geometry used here has many advantages over other sliding configurations. First, conformity of the sliding surfaces enables a calculation of the nominal normal pressure, which remains constant during the entire test. Second, the sliding velocity (which determines the rate of heat generation) at the contact is the same over the entire contact are. Finally, it is possible to calculate the surface temperature with simple assumptions, because the sliding geometry does not change during the wear test and the heat flow into the specimen is at the most two dimensional. Both the specimen and the ring were grinded before testing. After grinding, the average roughness values R_a of the pins and rings were measured as 0.5 μm and 0.3 μm respectively. The specimen and the ring were cleaned with trichloroethylene before testing.

2.2. Test methods

All the tests were carried out at room temperature (30 °C) in dry sliding friction. The friction tests were carried out at a speed of 1 m/s and loads in the range 115-250 N, and at a load of 115 N and speeds in the range 1-4 m/s. The sliding distance was 1500 m. The wear tests were carried out on a wear machine working by pin-on-ring sliding principle. It is possible to measure the frictional force by means of a deflection beam, one end of which is fixed on the machine plate and the other is free (Fig.1). The maximum deflection of the free end of the beam is calculated as $Y_{max} = F_s L_k^3 / 3EI$ [m]. Where F_s is the frictional force, L_k is the effective length of the beam (0.14 m), E is the elastic module

of the beam material (21×10^{10} N/m^2), and I is the inertia moment of the beam section (I=bh^3/12 =3.5×10^9 m^4). Thus, the experimental frictional force is obtained as $F_s = 80 \times 10^4 \cdot y_{max}$ [N]. The deflection of the beam was measured by a displacement transducer and all the deflection values were multiplied by a gain factor of 1.20. These values, then, used to calculate the frictional force. The experimental frictional coefficient μ was obtained from μ=F_s/F_N formula. Several theories have been proposed in the past to account for the temperature rise at sliding contacts [17]. Unfortunately, the theories cannot be made use of in practical situations because the assumptions made in those theories are not fully valid. Measurement of the thermoelectric e.m.f. produced by the sliding pair, infrared techniques, physical and chemical changes associated with the temperature rise and the thermocouple technique are some of these. Because of its simplicity, the last technique is used in this work although there are some limitations. In this technique, temperature is measured away from the surface.
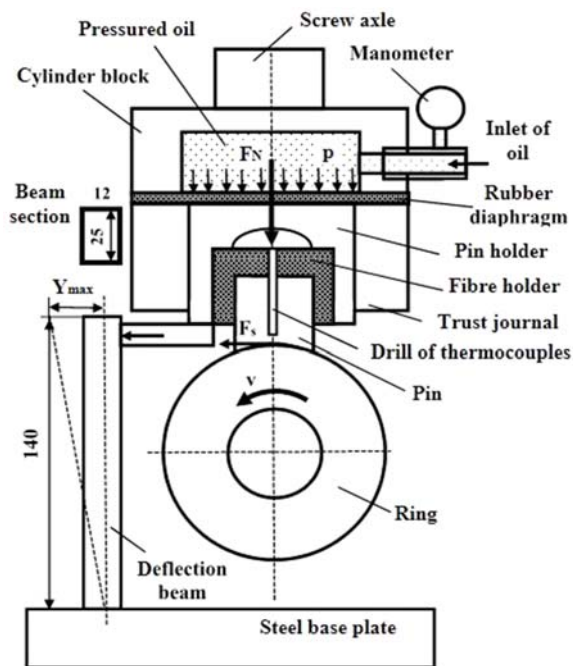
Figure 1. The hydrostatic loading and pin holder assembly.
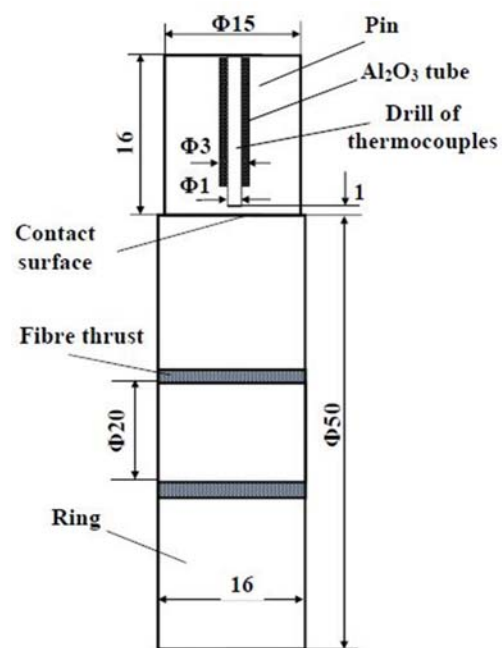

Figure 2. Test rig and the dimensions of samples assembly.

Figs 1 and 2 show the schematic arrangement of the ring, the pin and the thermocouples. As a result of frictional work, heat is generated at the interface and flows into the pin and the ring. The amount is dependent on the geometry and on the thermal, mechanical and tribological properties of both the pin and the ring. As shown in Figure 1, the amount of energy dissipated on sliding a distance L is given by μ.F_N.L. The rate of energy dissipation is therefore given by μ.F_N.L/dt=μ.F_N.v=F_s.v. Where F_s is friction force, v is the sliding speed at the interface and μ is the coefficient of friction. The factor of pv is the power per unit contact area [2]. The heat release intensity in the friction zone depends on friction power and is determined by relationship Q=μ.F_N.v. Where μ is the friction coefficient, F_N is the load per unit of length, v is the slip velocity [18]. The frictional heat per unit area generated in the sliding contact is given by q=μ.p.v. The combination of contact pressure (p) and sliding velocity (v), referred to as the pv factor is an important parameter in the field of mechanical wear. The energy dissipated (frictional heat) in the mechanical wear process is proportional to pv, which has a significant effect on the mechanical wear. The bulk temperature of the pin specimen was measured from the interface surface at a distance of 1 mm from the contact surface by using type K thermocouples (Ni-Cr-Ni). The type K is the most common type of thermocouple. It is inexpensive, accurate, reliable, and has a wide temperature range. The type K is commonly found in nuclear applications because of its relative radiation hardness. Maximum continuous temperature is around 1100 °C. Thermocouples were placed

in one hole drilled in the pin holder at a distance of 1 mm from the contact surface [15]. Each test was repeated with three sets of the pin and ring samples.
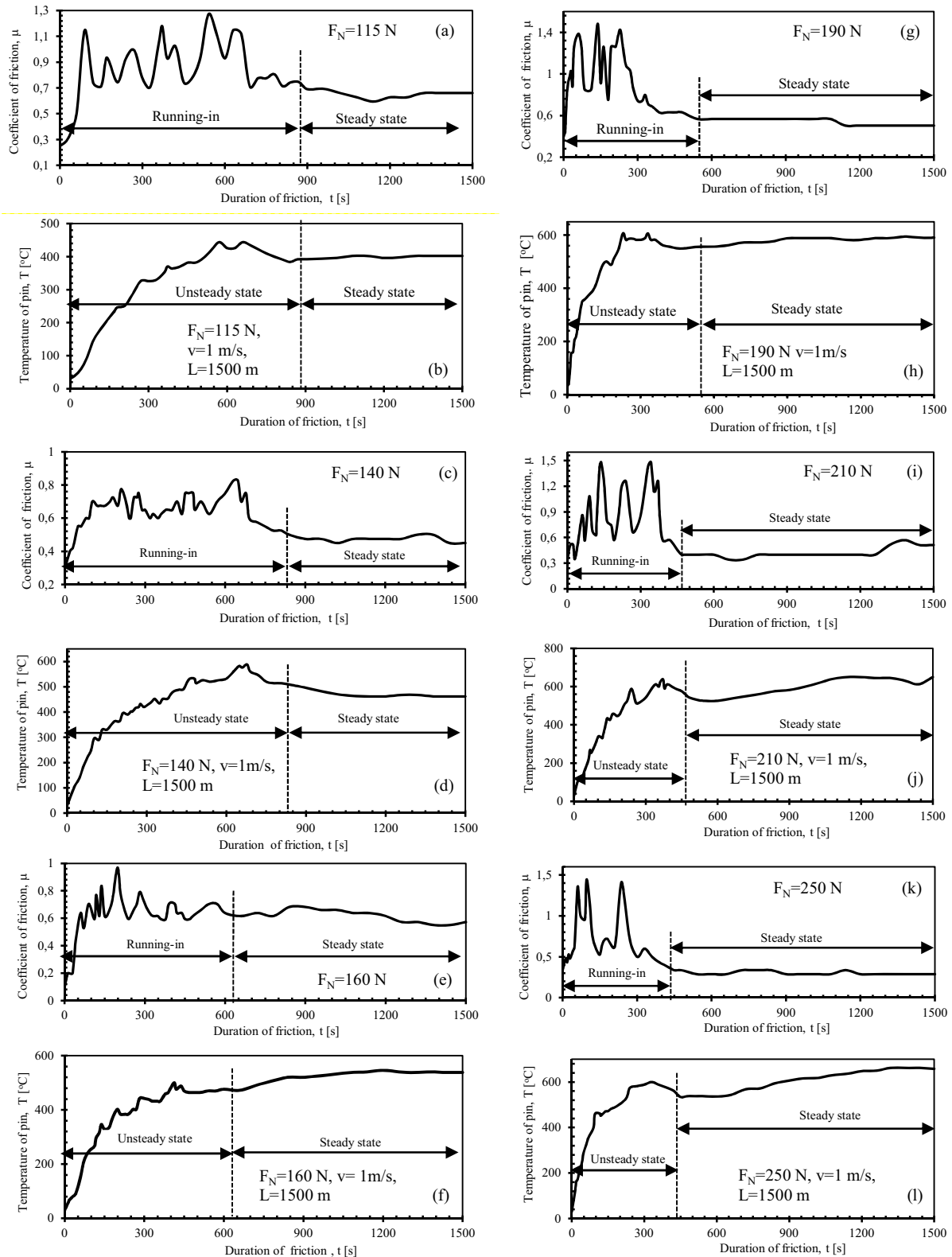
3.Results

3.1. The effects of sliding speed and load on the coefficient of friction and the temperature
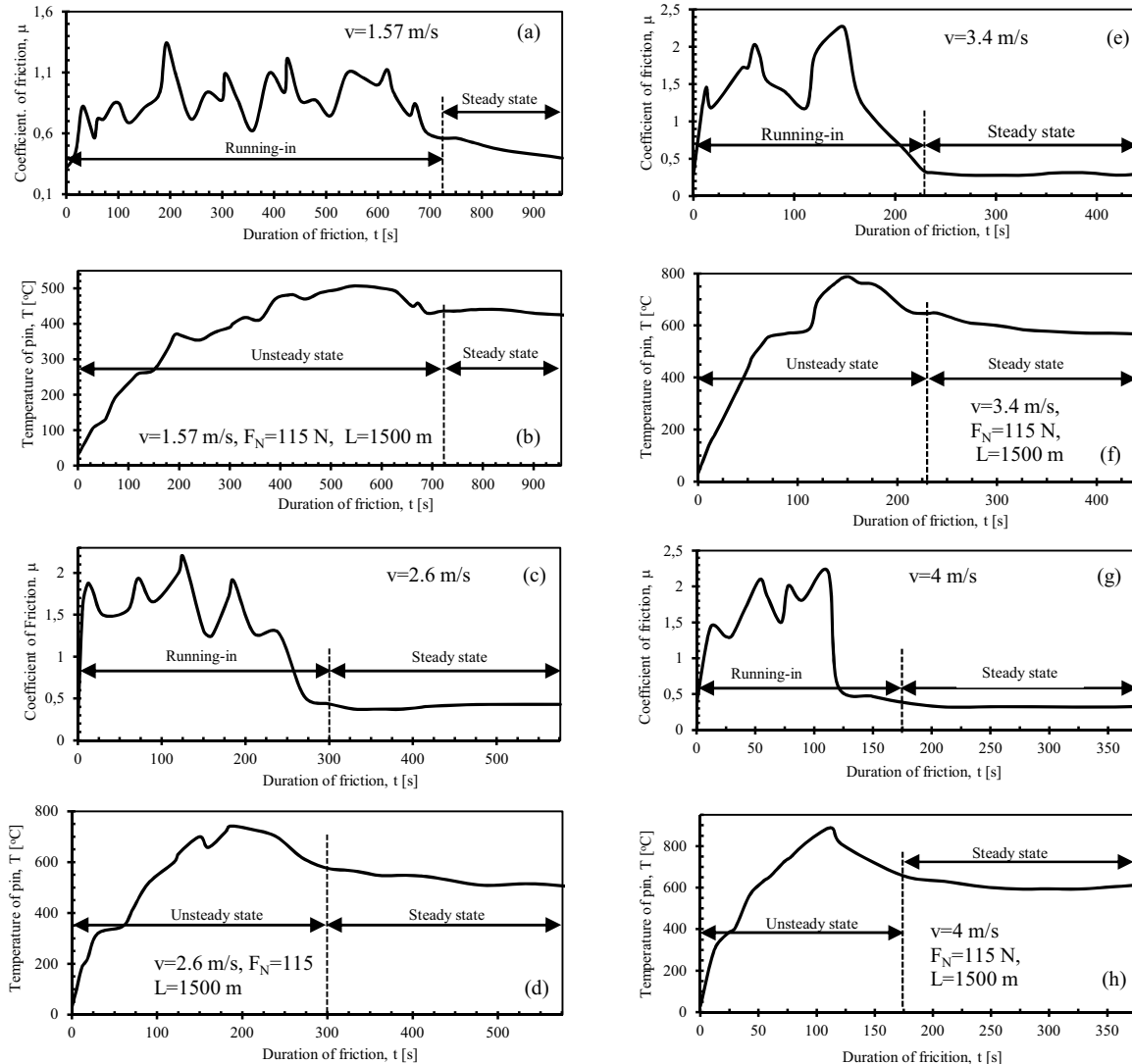
Figure 3. Comparison of the frictional coefficient and temperature of the pin.

In order to understand the variation in frictional coefficient and bulk temperature of pin with sliding speed, the tests were performed at a speed range 1-4 m/s, a load of 115 N and a sliding distance of 1500 m under dry friction conditions. During the tests, the friction coefficient and pin bulk temperature were continuously recorded throughout the test by a multichannel recorder as shown in Figure 3. The experimental results for general friction state were given in Table 1. Figures 3a, 3c, 3e, and 3g show the variation in coefficient of friction with duration of friction. It is possib1e to calculate three types of frictional coefficient for a sliding distance of 1500 m by using the recorded diagrams in these figures as follows : the minimum frictional coefficient (μ_{min}), the average frictional coefficient (μ_m) and the maximum frictional coefficient (μ_{max}). Figures 3b, 3d, 3f and 3h show the pin temperature recorded by the thermocouples placed at 1 mm distance from the sliding contact. It is possib1e to define three types of bulk temperature of pin for a sliding distance of 1500 m in these

figures as follows: the minimum temperature (T_{min}), the average temperature (T_m) and the maximum temperature (T_{max}). The general pattern of the graphs of frictional coefficient are similar to that for temperature of pin.

Figure 4. Comparison of the frictional coefficient and temperature of the pin.

Table 1. The influence of sliding speed on the coefficient of friction and the temperature of pin for cumulative friction.

Speed v (ms^{-1})	p (Nm^{-2}) $x10^{-4}$	pv factor $(Nm.m^{-2}.s^{-1})$ $x10^{-4}$	Time t (s)	Friction coefficient			Pin temperature			Friction heat q $(Nm.m^{-2}.s^{-1})$ $x10^{-4}$
				μ_{min}	μ_{max}	μ_m	T_{min} (^oC)	T_{max} (^oC)	T_m (^oC)	
1		64.97	1500	0.248	1.271	0.795	30	444	337	51.65
1.57		102	955	0.312	1.341	0.802	30	506	358	81.80
2.6	64.97	168.9	577	0.25	2.184	1.159	30	742	493	195.75
3.4		220.89	441	0.28	2.246	1.072	30	788	541	236.79
4		259.88	375	0.32	2.20	1.039	30	888	587	270.01

In order to compare the variation in the coefficient of friction and the bulk temperature with load, tests were carried out at a sliding distance of 1500 m, a speed of 1 m/s, and loads in the range 115-250 N under dry friction conditions. Figures 4a, 4c, 4e, 4g, 4i and 4k show the variation in coefficient of friction with duration of friction. The experimental results for general friction state were given in Table 2. Figures 4b, 4d, 4f, 4h, 4j, and 4k show the pin temperature recorded by the thermocouples placed at 1 mm distance from the sliding contact.
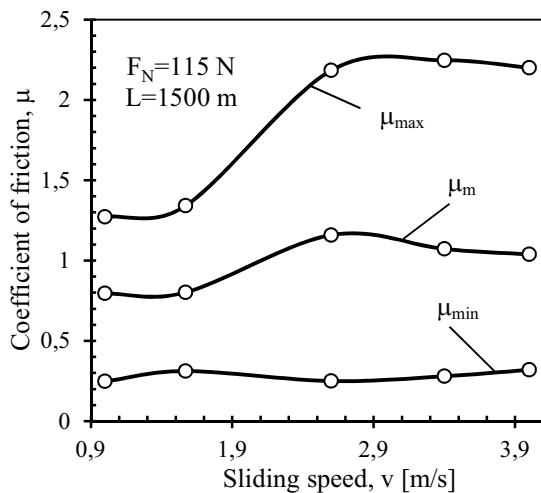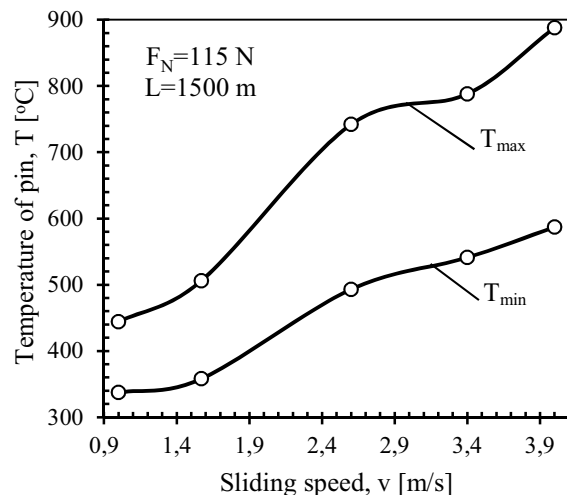

Figure 5. The variation in coefficient of friction with speed

Figure 6. The variation in temperature of pin with speed.

Figure 5 shows the dependence of frictional coefficient on the sliding speed for general friction. In general, the average frictional coefficients increase as the speed increases in range 1-4 m/s. According to the third law of friction, the frictional coefficient would be independent of the sliding velocity. The reason for this is that changes arising from strain rate and friction heating are expected with increasing speeds. However, the maximum frictional coefficient is directly proportional to the speed. The slope of the curves of average frictional and minimum frictional coefficient decreases with increasing speed. The average and minimum frictional coefficients increase slightly. The average maximum and minimum frictional coefficients belong to unsteady state sliding. Minimum frictional coefficient is defined as static friction coefficient at the beginning of sliding. So, the contact between pin and ring continues as metal-metal and the surfaces are roughed severely. The flakes of metallic debris produced between surfaces adhere to contacting surface as shown in Figure 7. Since plastic deformation and wear normally do occur, the general contact situation changes with time. Figure 8 shows the optical micrograph of subsurface for the worn surface of AISI 3315 steel. It can be seen that the subsurface is affected by frictional forces and heat generated during the friction. The thickness of the mechanically affected layer increases with an increase in load because the plastic deformation of the subsurface is increased with the temperature [15]. The plastic deformation occurred at the surface during the friction can be seen clearly from the Figure 8. The grains of the subsurface is deformed and elongated to the

rolling direction.
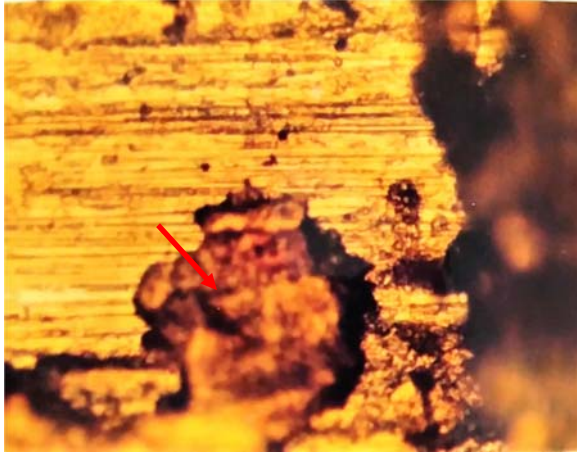
Figure 7. The flakes of metallic debris on surfaces of pins for 115 N and 3.4 m/s after 10 s. (x400)


Figure 8. Optical micrograph of subsurface for the worn surface of AISI3315 steel (x200, Sliding direction is from left to right)

Table 2. The influence of load on the coefficient of friction and the temperature of pin for general friction.

Load F_N (N)	p (Nm^{-2}) x10^{-4}	pv factor (Nm.m^{-2}.s^{-1}) x10^{-4}	Friction coefficient			Pin bulk temperature			Frictional heat q_s (Nm.m^{-2}.s^{-1}) x10^{-4}
			μ_{min}	μ_{max}	μ_m	T_{min} (^{o}C)	T_{max} (^{o}C)	T_m (^{o}C)	
115	64.97	64.97	0.248	1.271	0.797	30	444	342	51.78
140	79.09	79.09	0.30	0.825	0.613	30	426	388	48.48
160	90.39	90.39	0.10	0.969	0.614	30	546	402	55.49
190	107.34	107.34	0.399	1.482	0.795	30	606	481	85.33
210	118,64	118.64	0.342	1.482	0.695	30	650	484	82.45
250	141.24	141.24	0.564	1.440	0.288	30	662	489	40.67
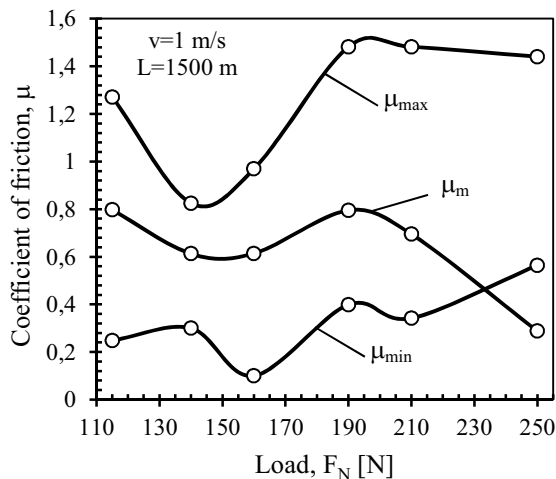
Figure 9. The variation in coefficient of friction with load for general friction.
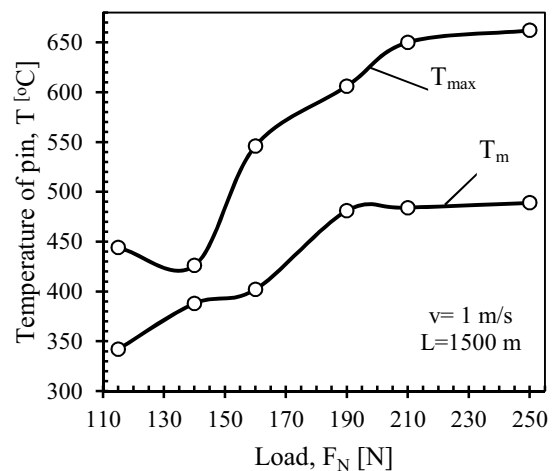
Figure 10. The variation in temperature of pin with load for general friction

Figure 9 shows the relationship between the frictional coefficients and the load for general friction. In general, the average frictional coefficient decreases slightly as the load increases in range 115-250 N because of the temperature rise the surface oxidizes. But, the average maximum and minimum frictional coefficients increase slightly as the load increases in range 115-250 N. Figure 10 shows the relationship between the temperature of pin and the load for general friction. The temperature
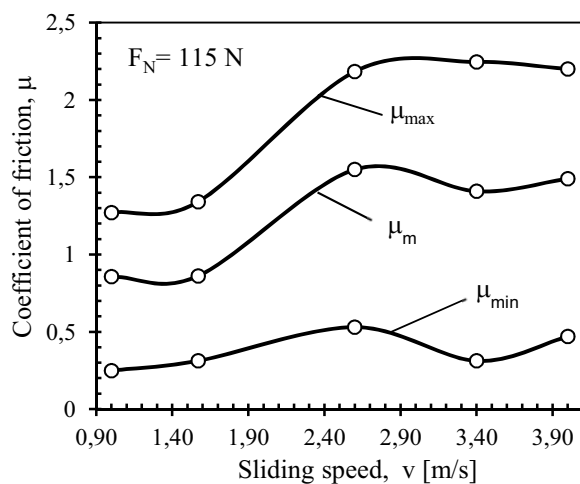
increases with an increase in the load as shown in this figure. The reason for this is that changes arising from strain rate and friction heating are expected with increasing loads. It is shown clearly in Figures 3 and 4 that the friction is occurred two stages between steel-steel pairs for pin-on ring test system as running-in (unsteady state) and steady state friction.

### 3.2. The effects of sliding speed on the unsteady (running-in) friction

As shown in Figures 3, the recorded temperature and frictional coefficient increase with time. At the beginning of sliding, till the first few minutes of test, the frictional coefficient usually fluctuates very much. This friction behaviour is defined as unsteady state sliding. However, steady state conditions are soon reached and remained constant thereafter. It is possible to define this friction behaviour as steady state friction. The unsteady state and steady state is limited by the vertical lines. The vertical lines represent the limit between the unsteady state and steady state as shown in these Figures. The experimental results of unsteady friction are given in Table 3.

Table 3. The influence of sliding speed on the coefficient of friction and the temperature of pin for unsteady friction.

| Speed v (ms^{-1})	pv factor ($Nm.m^{-2}.s^{-1}$) x10^{-4}	Time t (s)	Friction coefficient			Pin temperature			Friction heat q ($Nm.m^{-2}.s^{-1}$) x10^{-4}
			μ_{min}	μ_{max}	μ_m	T_{min} (^{o}C)	T_{max} (^{o}C)	T_m (^{o}C)	
1	64.97	900	0.248	1.271	0.857	30	444	304	55.67
1.57	102	700	0.312	1.341	0.861	30	506	340	87.82
2.6	168.9	270	0.53	2.184	1.55	30	742	474	261.79
3.4	220.89	200	0.312	2.246	1.409	30	788	527	311.23
4	259.88	125	0.468	2.20	1.49	30	888	572	387.22

Figure 11. The variation in unsteady friction coefficients with speed.
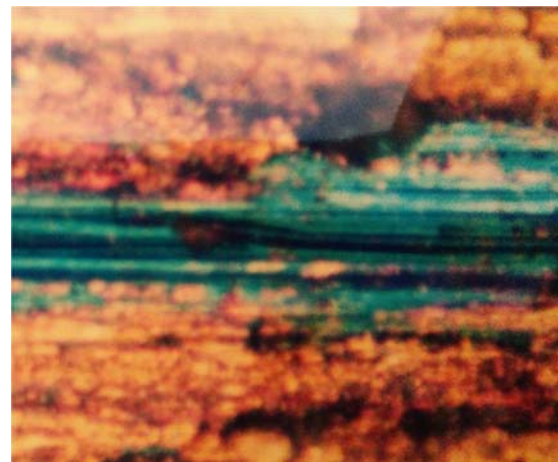

Figure 12. The flakes of metallic debris on surfaces of pins for 115 N and 3.4 m/s after 120 s. (x200)

Figures 11 shows the variation in unsteady friction coefficients with speed. Generally, in the unsteady state regime, the friction coefficient increases slightly with an increase in speed. In this regime, the contact between pin and ring continues as metal-metal and the surfaces are roughed severely. The flakes of metallic debris produced between surfaces adhere to contacting surface during unsteady state sliding as shown in Figure 13. Since plastic deformation and wear normally do occur, the general contact situation changes with time.
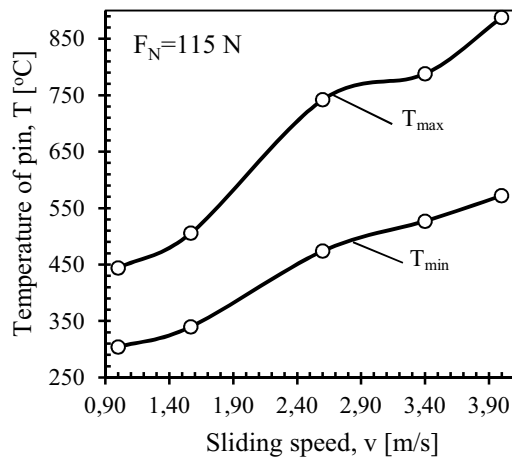
Figure 13. The variation in temperature of pin for unsteady friction with speed.
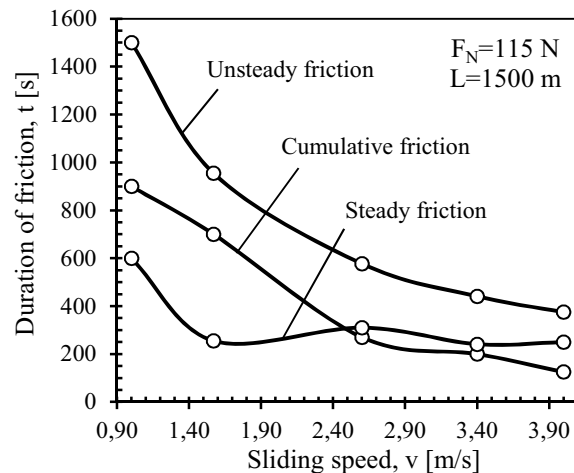
Figure 14. The variation in duration of friction with speed

Figures 13 show the variation in the temperature of pin with speed for unsteady friction. Generally, in the unsteady state regime, the temperature increase linearly with an increase in speed. The reason for this is that changes arising from strain rate and friction heating are expected with increasing speeds. Figure 14 shows the variation in the duration of unsteady friction steady friction and with speed for a distance of 1500 m. The duration of friction decreases with an increase in speed for three friction state. The reason of this can be explained as duration of test decreases with an increase in speed and the steady state sliding is reached earlier at because of formation of protective oxide film on surfaces.

3.3. The effects of sliding speed on the steady friction

As shown in Figures 18, after the first few minutes of test, steady state conditions are reached and frictional coefficient and temperature remain constant. It is possible to define this friction behaviour as steady state friction. The vertical lines represent the limit between the unsteady state and steady state. The experimental results of steady friction were given in Table 4.

Table 4. The influence of sliding speed on the coefficient of friction and the temperature of pin for steady friction.

Speed v (ms^{-1})	pv factor ($Nm.m^{-2}.s^{-1}$) x10^{-4}	Time t (s)	Friction coefficient			Pin temperature			Friction heat q ($Nm.m^{-2}.s^{-1}$) x10^{-4}
			μ_{min}	μ_{max}	μ_m	T_{min} (°C)	T_{max} (°C)	T_m (°C)	
1	64.97	600	0.594	0.806	0.690	384	422	399	44.82
1.57	102	255	0.330	0.842	0.456	425	458	436	46.51
2.6	168.9	310	0.374	0.495	0.425	495	566	512	71.78
3.4	220.89	241	0.280	0.363	0.315	542	612	561	69.58
4	259.88	250	0.320	0.495	0.401	594	648	617	104.21

Figure 15 shows the relationship between the steady frictional coefficient and the sliding speed. In general, the average and minimum frictional coefficients decrease slightly as the speed increases in range 1-3.4 m/s because of formation of protective oxide film on surfaces as shown in Figure 13. But, the maximum frictional coefficient decrease linearly to a minimum value as the speed increases in range 1-3.4 m/s. And then, the frictional coefficients increase maximum as at a speed of 4 m/s because of the oxide film with critical thickness is broken up and the contact of surfaces occurs metal-metal as shown in Figure 14. As shown in Figure 16, temperature of pin increase linearly as the speed increases. Figure 17 shows the variation of the average friction coefficients with speed for three friction states.
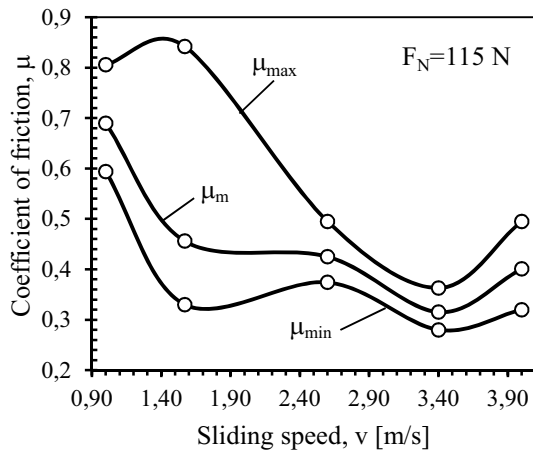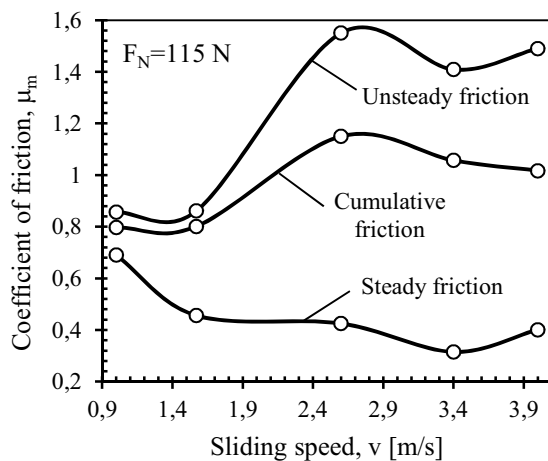
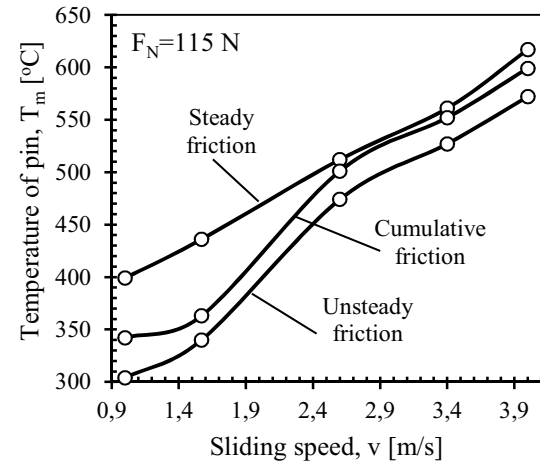**Figure 15.** The variation in steady friction coefficients with speed.
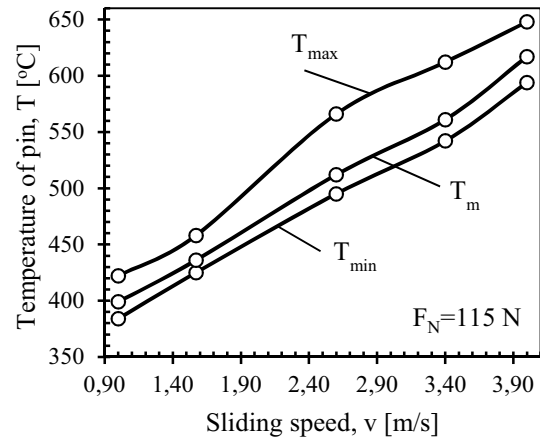
Figure 16. The variation in temperature of pin for steady friction with speed

As shown in Figure 17, the friction coefficient for unsteady state is higher than that for the other two friction state. It can be seen that the unsteady and cumulative friction coefficients increase linearly as the speed increases in range 1-2.6 m/s and then they decrease slightly in range 2.6-4 m/s. However, the average steady friction coefficient decreases slightly with an increase in speed to 4 m/s. Figure 18 shows the variation of the average temperature of pin with speed for three friction states. As shown in figure, the average temperature for unsteady state is lower than that for the other two friction state. It can be seen that the temperatures linearly increase with an increase in speed.


**Figure 17.** The variation in average friction coefficients with speed.

Figure 18. The variation in average temperature of pin with speed

Figure 19 shows the variation in frictional heat with speed in general friction state. As shown in this figure, frictional heat of unsteady and cumulative friction increases with increasing speed. However, the frictional heat for steady increases slightly with an increase in speed. Figure 20 shows the variation in frictional heat with load in general friction state. Friction is the process of conversion of energy. The conversion of external mechanical energy into the energy of internal processes occurs in the process of friction. As shown in Figure 20, frictional heat of unsteady and cumulative friction increases with increasing load and reaches a maximum at 190 N because of the average frictional coefficient increases with load and reaches a maximum at 190 N. After the load of 190 N, the cumulative frictional heat decreases with increasing load to a load of 250 N because the average frictional coefficient decreases with load to a load of 250 N.
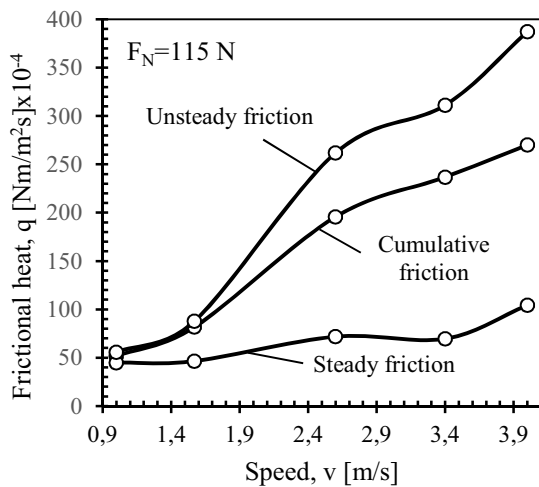
Figure 19. The variation in frictional heat with speed.
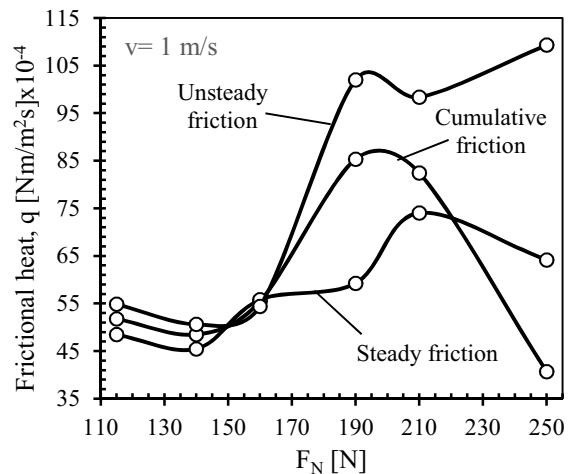
Figure 20. The variation in frictional heat with load for three friction state

4. Conclusions

The conclusion derived from the present study may be summarised as follows

1.In general, the frictional coefficient decreases slightly as the load and speed increases because of the temperature rise the surface oxidizes.

2.The thickness of the mechanically affected layer increases with an increase in load because the plastic deformation of the subsurface is increased with the temperature.

3.The friction is occurred two stages between steel-steel pairs for pin-on ring test system as running-in (unsteady state) and steady state friction. The duration of unsteady state friction decreases with an increase in load and speed.

4.The steady state coefficient of friction decreases with an increase in load and speed because of the formation of oxide film on the surfaces. In general, the average frictional coefficients increase as the speed increases.

5.The temperature increases with an increase in the speed. Generally, in the unsteady state regime, the friction coefficient increases slightly with an increase in speed.

6.Generally, in the unsteady state regime, the temperature increase linearly with an increase in speed. The duration of friction decreases with an increase in speed.

7.In general, the steady frictional coefficients decrease slightly as the speed increases because of formation of protective oxide film on surfaces.

8.The temperature of pin increase linearly as the speed increases for steady friction. The frictional heat increases with increasing speed.

References

1. Hutchings I.M., Leonardo da Vinci's studies of friction, Wear, 360-361, 51-66, 2016.

2. Halling J., Principles of Tribology, Macmillan, London,72-92, 1983.

3. Tabor D., Friction -the present state of our understanding, Trans. ASME,. Journal of lubrication technology, vol. 103, 169-179, 1981.

4. Hisakado T., On the mechanism of contact between solid surfaces, 4th report surface roughness on dry friction Bulletin of the JSME, vol.7, number 4, 223-226, 1984.

5. Do Z. and You-Dai X., Two-body micro cutting wear model Part IV: Theoretical analysis of friction, Wear, 129, 67-79, 1989.

6. Autay R., Kchaou M. and and Dammak F., Friction and wear behavior of steels under different reciprocating sliding conditions, Tribology Transactions, 55, 590-598, 2012.

7. Abouei, V., Saghafian, H., and Kheirandish, S., Effect of microstructure on the oxidative wear behavior of plain carbon steel, Wear, 262, 1225–1231, 2007.

8. Bahrami, A., Mousavi Anijdan, S. H., Golozar, M. A., Shamanian, M., and Varahram, N. , Effects of conventional heat treatment on wear resistance of AISI H13 tool steel, Wear, 258, 846–851, 2005.

9. Hardell, J., Kassfeldt, E., and Prakash, B., Friction and wear behaviour of high strength boron steel at elevated temperatures of up to 800 ∘C, Wear, 264,788–799, 2008.

10. Wei, M. X. Wang, S. Q., Cui, X. H., and Chen, K. M., Characteristics of extrusive wear and transition of wear mechanisms in elevated-temperature, Tribology Transactions, 53,888–896, 2010.

11. Kim, M. H., Rhee, K. Y., Paik, Y. N., Hong, J. S., and Ham, Y. S., Experimental investigation on the mechanical behavior of high-frequency induction-hardened mild carbon, SPS5 steel, Materials Science and Engineering A, 485, 31-38, 2008.

12. Z. Rymuza, Energy concept of the coefficient of friction, Wear 199, 87-96, 1996.

13. Quinn T. F. J., Review of oxidational wear, part I; the origins of oxidational wear, Tribology International, vol. l6, 257-271, 1983.

14. Chen Z. and Thomson P.F., Friction against superplastic aluminium alloys, Wear, 201, 227-232, 1997.

15. Odabaş D., Theoretical and experimental investigation of the effects of thermomechanical factors on the wear behaviour of AISI 3315 steel under dry sliding conditions, Ph. D. Thesis, Erciyes University, Engineering Faculty, Kayseri, Turkey (In Turkish), 1991.

16. Ling F. F. and Simkins T.E., Measurement of pointwise juncture condition of temperature at the interface of two bodies sliding contact, J. Basic Eng., 85, 481-487, 1963

17. Saka N., A, Eleiche M. and Suh N. P., Wear of metals at high sliding speeds, Wear, 23, 109-125, 1977.

18. Tareq M. A. A., Oksana O.M., Rudolph G. M., Temperature resistance of the boundary lubrication layers under rolling with slippage condition, International Journal of Mechanical Engineering and Applications, 5(2), 78-86, 2017.