

# Effects of Load and Speed on Wear Rate of Abrasive Wear for 2014 Al Alloy

**Odabas D.**

*Erciyes University, Department of Mechanical Engineering, 38039, Kayseri, Turkey  
odabasd@erciyes.edu.tr*

**Abstract:** In this paper, the effects of the normal load and sliding speed on wear rate of two-body abrasive wear for 2014 Al Alloy were investigated in detail. In order to understand the variation in wear behaviour with load and speed, wear tests were carried out at a sliding distance of 11 m, a speed of 0.36 m/s, a duration of 30 s and loads in the range 3-11 N using 220 grit abrasive paper, and at a speed range 0.09-0.90 m/s, a load of 5 N and an average sliding distance of 11 m using abrasive papers of 150 grit size under dry friction conditions. Before the wear tests, solution treatment of the 2014 Al alloy was carried out at temperatures of 505 and 520 °C for 1 h in a muffle furnace and then quenched in cold water at 15 °C. Later, the ageing treatment was carried out at 185 °C for 8 h in the furnace. Generally, wear rate due to time increased linearly and linear wear resistance decreased with increasing loads. However, the wear rate was directly proportional to the load up to a critical load of 7 N. After this load, the slope of the curves decreased because the excessive deformation of the worn surface and the instability of the abrasive grains began to increase. When the load on an abrasive grain reaches a critical value, the groove width is about 0.17 of the abrasive grain diameter, and the abrasive grains begin to fail. The wear rate due to time increased slightly as the sliding speed increased in the range 0.09-0.90 m/s. The reason for this is that changes arising from strain rate and friction heating are expected with increasing sliding speeds.

**Keywords:** Abrasive wear, solution treatment, wear rate.

## 1.Introduction

Wear occurs in many different situations, e.g. on earth-moving equipment, agricultural ploughs, slurry pumps, crushers, ball bearings, plain bearings, piston rings, seals, gears, brakes or in daily life at knives, shoes, clothes, furniture, stairways or human joints at the hip, knee or elbow. Materials are worn most of all by abrasive wear mechanism. Abrasive wear is the displacement of material caused by the presence of hard particles, between or embedded in one or both of two surfaces, in relatively motion, or by the presence of hard asperities on one or both of the relatively moving surfaces. Therefore, abrasive wear is classified as two-body and three-body abrasive wear mechanism [1]. It has been estimated that 50 % of all wear problems in industry are due to abrasion, and as such, much laboratory work has examined and sought to rationalise the abrasive wear behaviour of a wide range of materials [2]. Abrasive wear is experienced such as in feeders, belt conveyors, vibratory conveyors and screen conveyors. Any mechanical devices that involve the motion of bulk solids relative to surfaces will experience wear. The abrasive damage is occurred in aluminium alloy sheet used in truck's buckets under the action of sand friction resulting when transporting the sand in these trucks [3]. Aluminium alloys are known for their suitable mechanical properties, mainly due to their high strength-to-weight ratio [4]. Therefore, multiple experimental studies on abrasive wear of aluminium alloys have been conducted in recent decades due to the interest in the ever increasing use of light



aluminium alloys and composites in engineering applications [5]. Aluminium is the most accepted matrix for metal matrix composites because of its low density, ability to be strengthened by precipitation hardening, very good corrosion resistance, high thermal conductivity and electrical conductivity, and its high damping capacity [6]. With hard particles dispersed in a relatively ductile matrix, aluminium-alloy matrix composites possess an ideal structure for wear-resistant materials; recent studies have revealed this concept. Wang et al. [7] reported that both SiC particulate and whisker-reinforced composites exhibited greater wear resistance than the unreinforced aluminium alloy. The whisker reinforcement was more effective than the particulate reinforcement in improving the wear resistance of the matrix alloy. Song et al. [8] studied changes in the abrasive wear resistance of aluminium-based composites heat treated for different ageing conditions. They found that the hardness and abrasive wear resistance increase with increasing the ageing temperature to 200 °C, but at 250 °C decrease due to the coarsening of the intermetallic precipitates. The composites with 20 µm SiC particles were slightly more wear resistant than those with 3 µm SiC. In another study, it was shown that most composites exhibit better abrasive wear resistance than the unreinforced matrix alloys, and the impact-abrasive resistance increases with decreasing particle size and increasing volume fraction [9]. In all the investigations discussed, abrasive wear behaviour of aluminium alloys has been carried out using pin-on disc or pin-on drum test machines under continuous sliding motion. Previous investigations were mostly focused on a single factor (Sliding distance, load or speed etc), and combined multiple factors have rarely been studied. In order to have a better understanding of the wear mechanism, studies on multiple factors need emphasis, for there may be synergistic effect among these factors, which was often neglected in previous studies. In this paper, the effect of the pv factor (product of contact pressure and sliding speed) on the abrasive wear of solution-treated and age-hardened 2014 Al alloy was investigated under dry frictional conditions during continuous wear in detail. The pv factor is a well-known index in the field of mechanical wear. It can be used to characterize the service life and wear rate of machine elements [10].

## 2. Determination of wear rate as a function of time

In a mechanical friction contact, where two-body abrasive wear occurs, the worn volume  $V$  ( $\text{m}^3$ ) is proportional to the load  $F_N$  (N) and the sliding distance  $L$  (m), but inversely proportional to the hardness  $H$  ( $\text{Nm}^{-2}$ ) of the softer surface. Thus leads to the well-known expression for abrasive wear volume [11-15]

$$V = \frac{k_a F_N L}{H_s} = \frac{G}{\gamma} \quad (1)$$

where  $G$  (kg) is weight loss and  $\gamma$  ( $\text{kgm}^{-3}$ ) is the density of material.  $V/L$  ( $\text{m}^3\text{m}^{-1}$ ) is defined as the volumetric wear intensity. The wear resistance  $\varepsilon$  is calculated as  $\varepsilon=L/G$  ( $\text{m/kg}$ ) or  $\varepsilon=L/V$  ( $\text{m/m}^3$ ). The ratio  $k_a/H$  of the wear coefficient  $k_a$  and the hardness  $H_s$  ( $\text{Nm}^{-2}$ ), of the softer contact surface is used here as a constant and the worn volume is related to the softer of the two material surfaces. Where  $k_a$  is called the wear coefficient for abrasive wear. The wear coefficient  $k_a$  is dimensionless. It is a principal value for a friction pair to describe its wear rate. The physical meaning of  $k_a$  is the wear volume fraction at the plastic contact zone, and it is strongly affected by the material properties and the geometry of the zone in compression and shearing. Where there is a frictional contact between a very hard and a much softer surface, the harder surface is always subject to wear, but the worn volume cannot be predicted quantitatively. For all possible tribo-conditions the ratio  $k_a/H_s$  gives no more practical information to describe wear than the simple  $K$  value which is more frequently used.  $K$  ( $\text{m}^2\text{N}^{-1}$ ) is called the wear factor or specific wear rate. From equation (1), the wear factor of materials can be written as

$$K = \frac{k_a}{H_s} = \frac{V}{F_N L} \quad (2)$$

Since the normal contact pressure with plastic deformation is almost equal to the hardness value  $H_s$  of the wearing material, the total real contact area can be expressed by

$$A_r = \frac{F_N}{H_s} \quad (3)$$

From equation (1) and equation (3), the abrasive wear volume of materials can be written as

$$V = k_a A_r L \quad (4)$$

The sliding distance is expressed as  $L = vxt$ . Where  $v$  ( $\text{m s}^{-1}$ ) is sliding velocity and  $t$  (s) is duration of the wear process. The normal load  $F_N$  on the contact surface is expressed as  $F_N = pxA$ . Where  $p$  ( $\text{Nm}^{-2}$ ) is the average contact pressure and  $A$  ( $\text{m}^2$ ) is the nominal (apparent) contact area.

Equation (1) becomes

$$V = \frac{k_a F_N L}{H_s} = \frac{k_a (vt) F_N}{H_s} = \frac{k_a (vt) pA}{H_s} = \frac{k_a (pA) tv}{H_s} \quad (5)$$

The thickness  $h$  (m) of the wear linear amount can be expressed as

$$h = \frac{V}{A} = \frac{k_a (pv)t}{H_s} = \frac{G}{A\gamma} \quad (6)$$

$h/L$  ( $\text{mm}^{-1}$ ) is defined as the linear wear rate (intensity). If the wear depth  $h$  is taken as the basis upon which wear rate is defined, the variation in wear with the time can be expressed as  $\lambda = dh/dt$  [16]. In most calculations it is possible to assume a linear relationship between wear time  $t$  and the amount of wear  $h$ . In other word, it can be assumed that during the normal operating period, the wear rate remains constant. The variation in wear with the time can be expressed as  $\lambda = h/t$ . Thus, wear rate due to time can be expressed as

$$\lambda = \frac{h}{t} = \frac{k_a (pv)}{H_s} \quad (7)$$

where  $pv$  ( $\text{Nmm}^{-2}\text{s}^{-1}$ ) is referred to a factor.

### 3. Experimental details

#### 3.1. Material

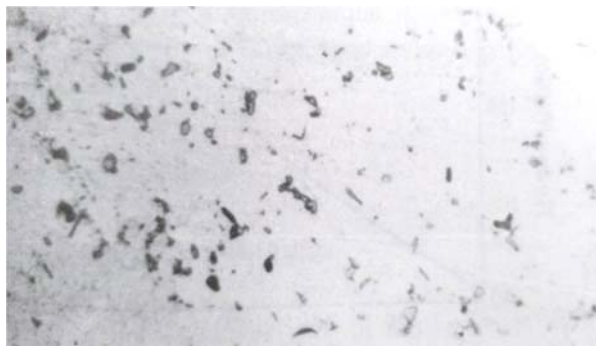
In this study, 2014 Al alloy with higher Cu content was chosen as a test material. For this test material, chemical analysis (wt.%) was: Cu 4.18; Mn 0.67; Mg 0.72; Si 0.81; Fe 0.26; Zn 0.02 and Ti 0.019 [5]. In general, this alloy is used for heavy-duty forgings, aircraft fittings and truck frames. 2014 Al alloy was fabricated by casting in a metal mould at Seydişehir Aluminium Co. in Konya, Turkey. After casting, the homogenization heat treatment was applied to the alloy at 500 °C for 2 h and the hot-pressed billets with a 45 mm diameter were extruded at 450 °C into rods with a 16 mm diameter with an extruded ratio of 3:1. After the rods were left for cooling at the room temperature, they were straightened by a 3 % plastic deformation. The specimens were prepared from the rods for the hardness and abrasive wear tests. The specimens to be used for the wear tests were cylinders with a 16 mm diameter and a length of 20 mm while those for the hardness tests were blocks 2.5x8x5 mm in size. Before the wear tests, the specimens were solution treated in a muffle furnace and then quenched in cold water at 15 °C. Later, the ageing treatment was carried out at 185 °C for 8 h in the furnace. T6 heat-treatment conditions (solution heat treated, artificially aged) and the hardness values are given in Table 1. Figure 1 shows microstructure of solution treated 2014 Al alloy after ageing treatment.

**Table 1.** Solution heat treatment of 2014 Al alloy and final hardness values.

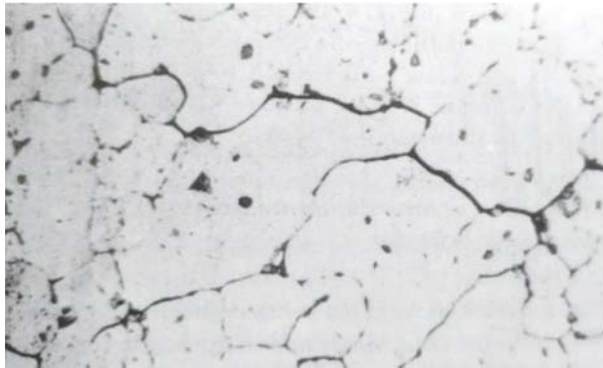
Solution heat treatment		Ageing treatment		After age hardening
Temperature (°C)	Time (h)	Temperature (°C)	Time (h)	Final hardness HB <sub>30</sub> (Kg.mm <sup>-2</sup> )
505	1	185	8	150
520	1	185	8	161

### 3.2. Test methods

Abrasive wear tests in continuous motion were carried out using a grinding-polishing machine with the pin-on disc configuration under dry sliding conditions [Fig.2]. The disc with 200 mm diameter was driven by an electric motor. The speed of the electric motor is changed by means of an A.C. speed-control converter. The waterproof SiC papers on the rotating disc were used as abrasive materials. The pin specimen (stationary) was mounted in a holder so that it could be removed for measurement and was rubbed against the surface of a SiC paper fixed to the flat surface of a revolving disc. Friction occurred continuously along a single track over which the abrasive ability gradually deteriorated. The radius of a single track was 35 mm. Thus, the average periphery of this track is equal to  $2\pi r = 2\pi 35 = 220$  mm and nominal contact area is equal to  $2.01 \times 10^{-4} \text{ m}^2$ . Wear was determined over a friction path of 11 m during the wear test.

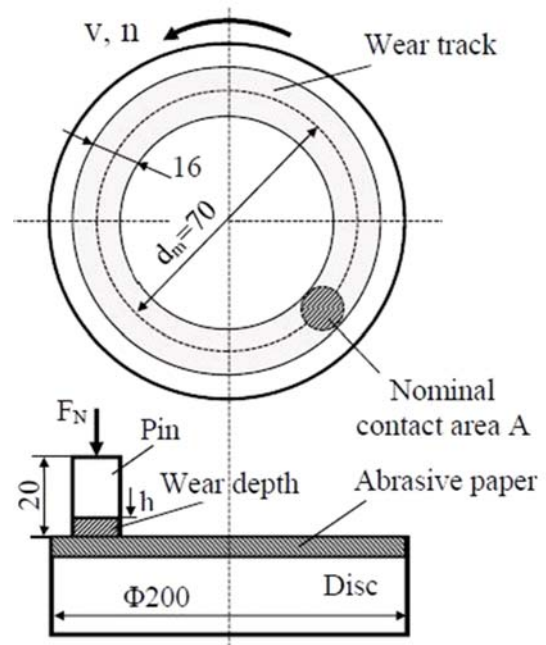


(a) Solution-treating temperature of 505 °C (x500)



(b) Solution-treating temperature of 520 °C (x500)

**Figure 1.** Microstructure of solution treated 2014 Al alloy after ageing treatment (Etched in Keller's reagent)



**Figure 2.** Schematic test rig of pin-on disc

Before the wear tests, the contact surfaces of the pins were polished with 500 grit size SiC paper and the initial average roughness was approximately  $R_a = 0.06 \text{ μm}$ . Prior to testing, all the specimens were cleaned by rinsing in ethanol and dried in hot air. During the tests, the pin specimens were loaded with dead weights and tests were conducted dry, at room temperature and room humidity. The wear loss was measured by means of an analytical balance with an accuracy of 0.1 mg. The wear surfaces, wear debris and subsurface deformation were also studied in optical and scanning electron microscopes. The density  $\gamma$  of test material for a 2014 Al alloy is  $2800 \text{ kgm}^{-3}$ .

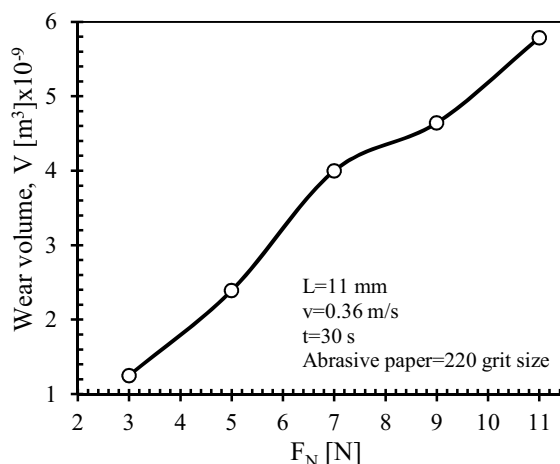
## 4. Results

### 4.1. The effects of load on the abrasive wear behaviour of 2014 Al alloy

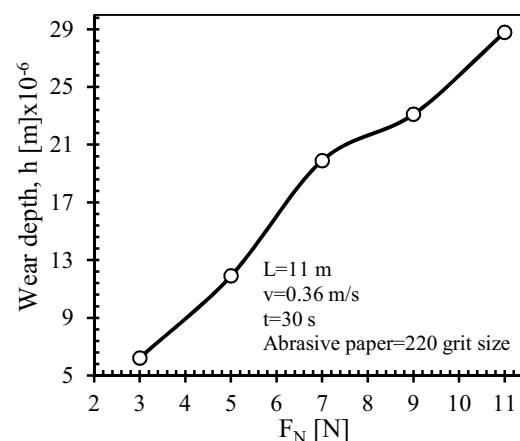
In order to understand the variation in wear behaviour with load for the continuous motion, wear tests were carried out at a sliding distance of 11 m, a speed of 0.36 m/s, a duration of 30 s and loads in the range 3-11 N using 220 grit abrasive paper under dry friction conditions. The specimen solution treated at 520 °C for 1 h were tested. The results were given in Table 2.

**Table 2.** The influence of the load on abrasive wear of 2014 Al alloy.

Load $F_N$ (N)	$p$ ( $\text{Nm}^{-2}$ ) $\times 10^{-4}$	$p v$ ( $\text{N}\cdot\text{m}^{-1}\text{s}^{-1}$ ) $\times 10^{-5}$	Weight loss $G$ (kg) $\times 10^{-6}$	Wear volume $V$ ( $\text{m}^3$ ) $\times 10^{-9}$	Wear depth $h$ (m) $\times 10^{-6}$	Wear rate $\lambda$ ( $\text{ms}^{-1}$ ) $\times 10^{-7}$	Linear wear rate $h/L$ ( $\text{mm}^{-1}$ ) $\times 10^{-7}$	Wear resistance $\varepsilon$ ( $\text{mm}^{-1}$ ) $\times 10^9$
3	1.492	5.371	3.5	1.25	6.218	2.072	5.652	17.692
5	2.487	8.953	6.7	2.392	11.90	3.966	10.818	9.243
7	3.482	12.535	11.2	4.00	19.90	6.633	18.090	5.527
9	4.477	16.117	13	4.642	23.094	7.698	20.994	4.763
11	5.472	19.699	16.2	5.785	28.781	9.593	26.164	3.822



**Figure 3.** The variation in wear volume of 2014 Al alloy with load.



**Figure 4.** The variation in wear depth with load.

Figure 3 shows the relationship between the wear volume and the load. The wear volume increases linearly with an increase in load. The polynomial function can be used to propose the relationships between wear volume and load. The rough regression formula can be expressed as wear volume  $V = (0.0172(F_N)^2 + 0.807F_N - 1.054) \times 10^{-9} \text{ m}^3$ . The correlation coefficient is defined as  $R = 99\%$ . Generally, wear depth increases linearly with increasing loads as shown in Figure 4. The regression formula of wear depth can be expressed as  $h = [(0.085(F_N)^2 + 4.0157F_N - 5.244)] \times 10^{-6} \text{ (m)}$ . This polynomial function has a correlation coefficient  $R$  of  $99\%$ . However, the wear volume and wear depth was directly proportional to the load up to a critical load of 7 N. After this load, the slope of the curves decreases because the excessive deformation of the worn surface and the instability of the abrasive grains began to increase. When the load on an abrasive grain reaches a critical value, the groove width is about 0.17 of the abrasive grain diameter, and the abrasive grains begin to fail. Thus, groove widths are fairly constant with load but the number of contact points increases linearly with load. If grit wear can be eliminated, the wear volume may be directly proportional to the applied load.

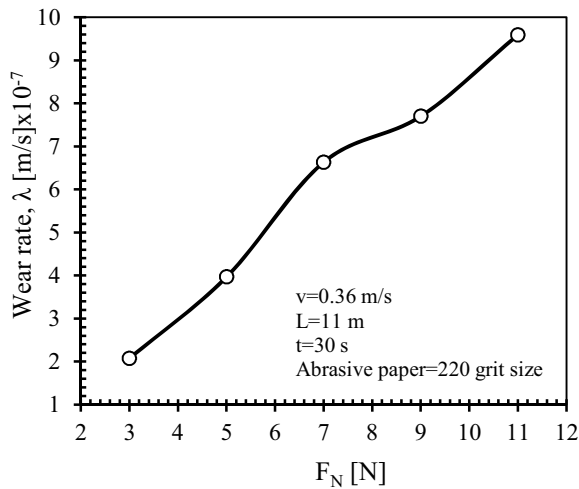
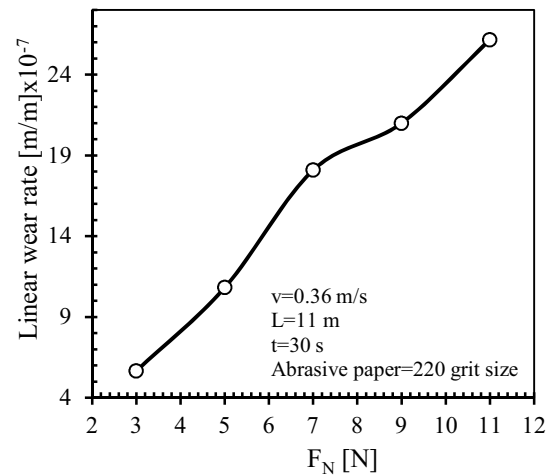
**Figure 5.** The variation in wear rate with load**Figure 6.** The variation in linear wear rate with load.

Figure 5 and 6 show the dependence of wear rate due to time and linear wear rate on the load. Generally, wear rate due to time and linear wear rate increase linearly with increasing loads as shown in these figures. The polynomial function can be used to propose the relationships between wear rate due to time and load. The regression formula of wear rate due time is expressed as  $\lambda = (0.028(F_N)^2 + 1.338F_N - 1.749) \times 10^{-7} \text{ (ms}^{-1}\text{)}$ . This function has a correlation coefficient  $R$  of % 99. The polynomial function can be used to propose the relationships between linear wear rate and load. The regression formula of linear wear rate is expressed as  $h/L = (-0.077(F_N)^2 + 3.65F_N - 4.768) \times 10^{-7} \text{ (mm}^{-1}\text{)}$ . This function has a correlation coefficient  $R$  of % 99.

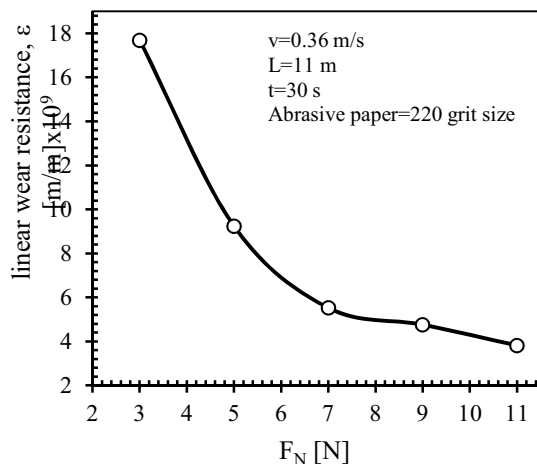
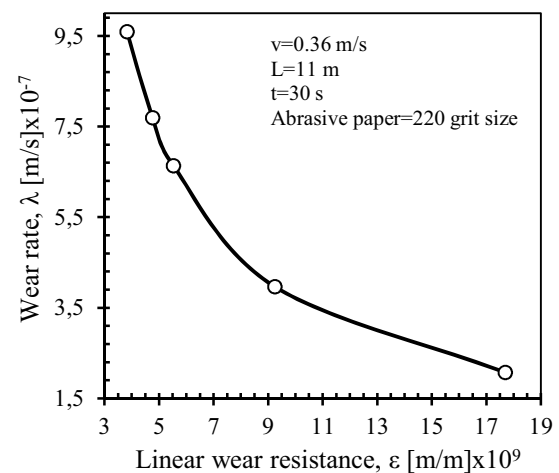
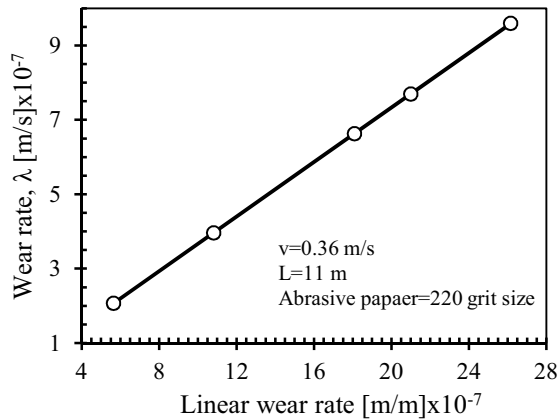
**Figure 7.** The variation in linear wear resistance with load.**Figure 8.** The variation in linear wear rate with linear wear resistance.

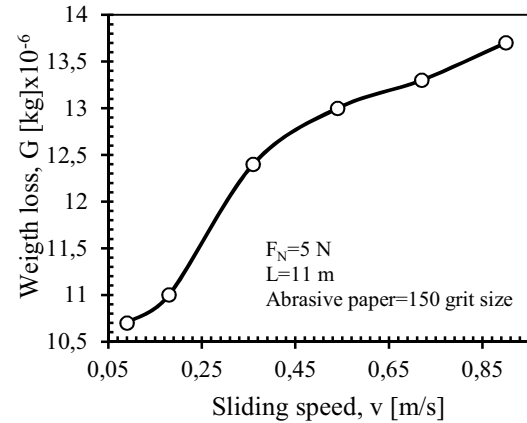
Figure 7 shows the relationship between the linear wear resistance and the load. The linear wear resistance decreases with an increase in load. The exponential function can be used to propose the relationships between linear wear resistance and load. The regression formula of linear wear resistance rate is expressed as  $\epsilon = (62.88F_N^{-1.189}) \times 10^9 \text{ mm}^{-1}$ . This function has a correlation coefficient  $R$  of % 98. Figure 8 shows the relationship between the wear rate due time and the load. The wear rate due to time decreases with an increase in linear wear resistance. The regression formula of wear rate due time is expressed as  $\lambda = [36.67\epsilon^{-1}] \times 10^{-7} \text{ ms}^{-1}$ . This exponential function has a correlation coefficient  $R$



of % 100. Figure 9 shows the relationship between the wear rate due time and linear wear rate. The wear rate due to time increases linearly with an increase in linear wear rate. The regression formula of wear rate due time is expressed as  $\lambda = [0.366(h/L)0.0005] \times 10^{-7} \text{ ms}^{-1}$ . This linear function has a correlation coefficient R of % 98.



**Figure 9.** The variation in wear rate with linear wear rate.



**Figure 10.** The variation in weight loss with speed.

#### 4.2. The effect of the sliding speed on the abrasive wear behaviour of 2014 Al alloy

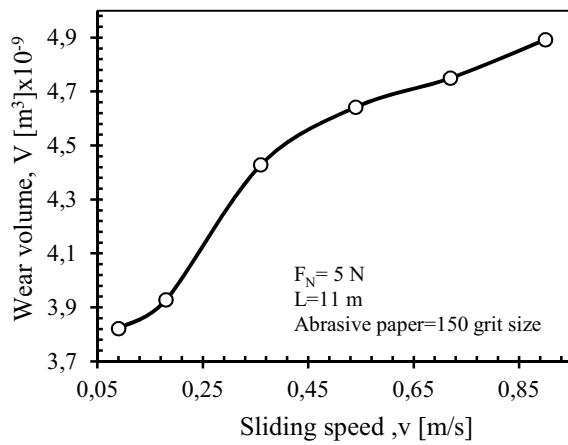
In this section, in order to compare the variation in the wear depth of the 2014 Al alloy with sliding speed for the continuous motions, and the abrasive wear tests were performed at a speed range 0.09-0.90 m/s, a load of 5 N and an average sliding distance of 11 m using abrasive papers of 150 grit size. A test material solution treated at 505 °C for 1 h was used during the wear tests. The results are given in Table 3.

**Table 3.** The influence of the speed on abrasive wear of 2014 Al alloy.

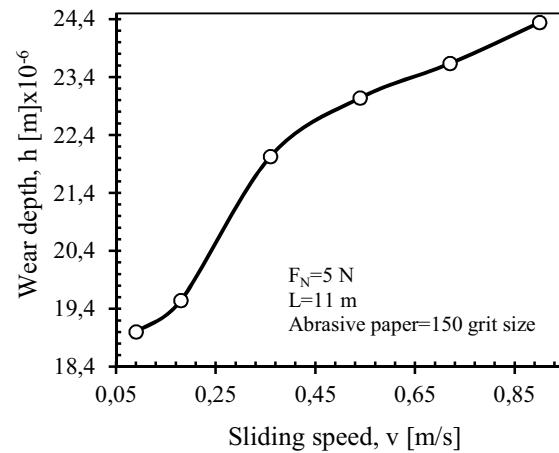
Speed $v$ ( $\text{ms}^{-1}$ )	Time $t$ (s)	$pv$ [ $\text{Nm/m}^2 \text{ s}$ ] $\times 10^{-5}$	Weight loss $G$ (kg) $\times 10^{-6}$	Wear volume $V$ ( $\text{m}^3$ ) $\times 10^{-9}$	Wear depth $h$ (m) $\times 10^{-6}$	Wear rate $\lambda$ ( $\text{ms}^{-1}$ ) $\times 10^{-7}$	Linear wear rate $h/L$ ( $\text{mm}^{-1}$ ) $\times 10^{-7}$	Wear resistance $\epsilon$ ( $\text{mm}^{-1}$ ) $\times 10^9$
0.09	122	2.238	10.7	3.821	19	1.557	17.272	5.789
0.18	61	4.476	11	3.928	19.542	3.203	17.765	5.629
0.36	30	8.953	12.4	4.428	22.029	7.343	20.026	4.993
0.54	20	13.429	13	4.642	23.039	11.519	20.944	4.774
0.72	15	17.906	13.3	4.750	23.631	15.519	21.482	4.655
0.90	12	22.383	13.7	4.892	24.338	20.281	22.125	4.519

Figure 10 shows the relationship between the weight loss and the speed. The weight loss volume increases slightly with an increase in speed. The reason for this is that changes arising from strain rate and friction heating are expected with increasing sliding speeds. The polynomial function can be used to propose the relationships between weight loss and speed. The rough regression formula can be expressed as wear volume  $G = (-4.188x^2 + 7.893x + 9.929) \times 10^{-6}$  (kg). The correlation coefficient is defined as R % 98. The wear volume increases slightly with an increase in speed as shown in Figure 11. The polynomial function can be used to propose the relationships between wear volume and speed. The regression formula is expressed as wear volume  $V = (-1.496x^2 + 2.819x + 3.545) \times 10^{-9}$  ( $\text{m}^3$ ). This polynomial function has a correlation coefficient R of % 98. Generally, wear depth increases linearly with increasing speeds as shown in Figure 12. The regression formula of wear depth can be expressed as  $h = [-7.295x^2 + 13.879x + 17.653] \times 10^{-6}$  (m). This polynomial function has a correlation coefficient R of % 98. In addition, the general pattern of the variation graphs in Figures 10, 11, 12 and 14 are

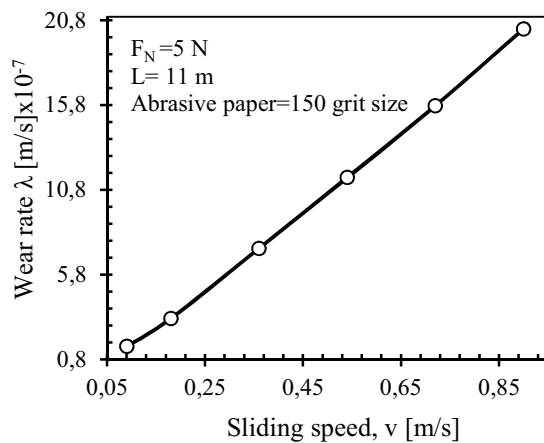
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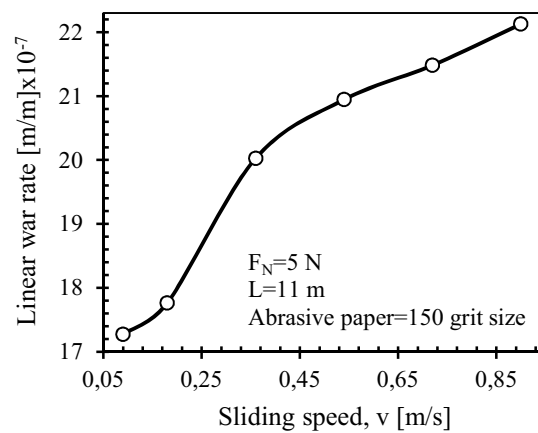
**Figure 11.** The variation in wear volume loss with speed.



**Figure 12.** The variation in wear depth with speed.



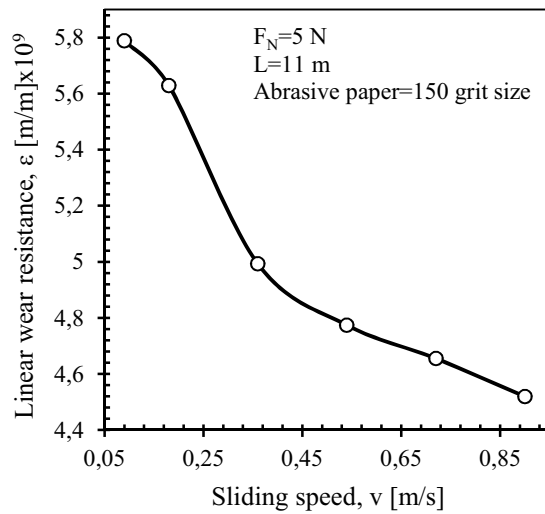
**Figure 13.** The variation in wear rate with speed.



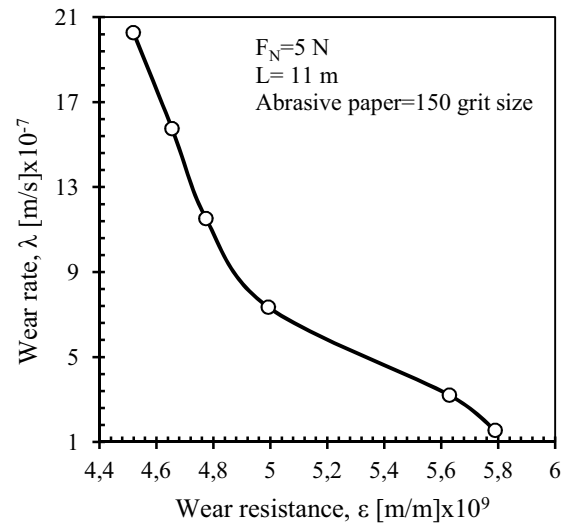
**Figure 14.** The variation in linear wear rate with speed

Figure 13 and 14 show the dependence of wear rate due to time and linear wear rate on the speed. Generally, wear rate due to time and linear wear rate increase linearly with increasing speeds as shown in these figures. The linear function can be used to propose the relationships between wear rate due to time and speed. The regression formula of wear rate due time is expressed as  $\lambda = (23.208v^2 - 0.848) \times 10^7$  ( $\text{ms}^{-1}$ ). This function has a correlation coefficient  $R$  of % 99. The polynomial function can be used to propose the relationships between linear wear rate and speed. The regression formula of linear wear rate is expressed as  $h/L = (-6.632(v)^2 + 12.618v + 16.047) \times 10^{-7}$  ( $\text{mm}^1$ ). This function has a correlation coefficient  $R$  of % 98. Figure 15 shows the relationship between the linear wear resistance and the speed. The linear wear resistance decreases with an increase in speed. The polynomial function can be used to propose the relationships between linear wear resistance and speed. The regression formula of linear wear resistance rate is expressed as  $\epsilon = (2.129xv^2 - 3.676v + 6.134) \times 10^9$  ( $\text{mm}^{-1}$ ). This function has a correlation coefficient  $R$  of % 98. Figure 16 shows the relationship between the wear rate due time and the wear resistance. The wear rate due to time decreases with an increase in linear wear resistance. The regression formula of wear rate due time is expressed as  $\lambda = [84331xe^{-1.853\epsilon}] \times 10^{-7}$  ( $\text{ms}^{-1}$ ). This exponential function has a correlation coefficient  $R$  of % 97. The general pattern of the variation graphs in Figures 15 and 16 are similar.

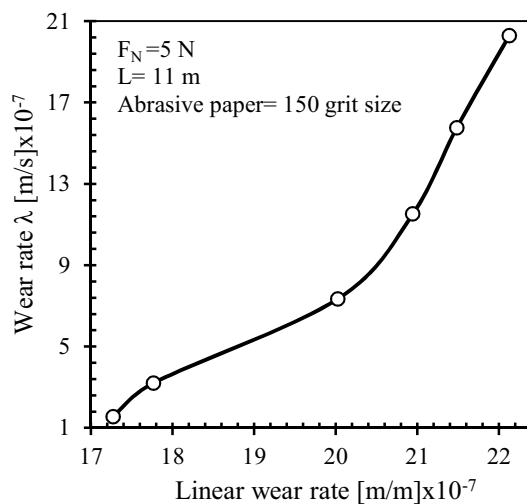




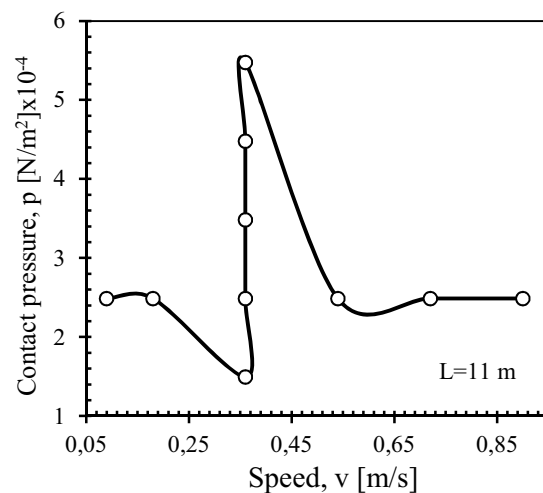
**Figure 15.** The variation in linear wear resistance with speed.



**Figure 16.** The variation in wear rate with wear resistance.



**Figure 17.** The variation in wear rate with linear wear rate.



**Figure 18.** The relationships between contact pressure and speed during tests.

Figure 17 shows the relationship between the wear rate due time and the linear wear rate. The wear rate due to time decreases with an increase in linear wear rate. The regression formula of wear rate due time is expressed as  $\lambda = [0.866(h/L)^2 - 30.448(h/L) + 269] \times 10^{-7} \text{ (ms}^{-1}\text{)}$ . This polynomial function has a correlation coefficient  $R$  of % 99.

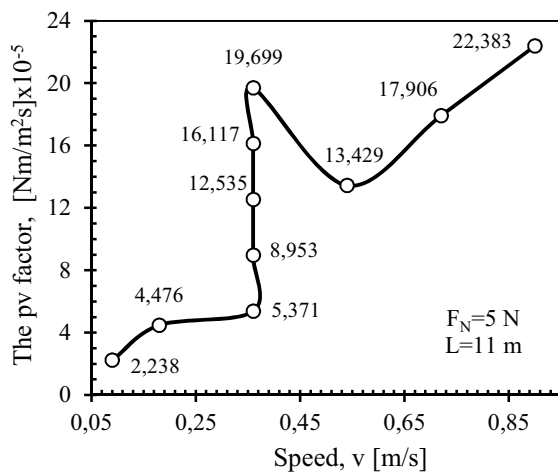
#### 4.3. The effects of the $p_v$ factor on the abrasive wear behaviour of 2014 Al alloy

The factor of  $p_v$  is a well-known index in the field of mechanical wear. It can be used to characterize the service life and wear rate of machine. Hence, further study on it will be helpful to understand the wear mechanism of material. The rate of wear of materials is obviously a function of load and speed and the  $p_v$  factor can be used as a design criterion [16]. The derivation of the  $p_v$  factor is based on the reasonable assumption that the rate of wear will be proportional to the rate of energy dissipation at the sliding interface [15]. Starting from this assumption, it can be derived the relationship between wear rate and the  $p_v$  factor for the pin-on disc configuration as shown in Figure 1. The amount of energy dissipated on a sliding distance  $L$  is given by  $F_f L = \mu F_N L$ . The rate of energy dissipation or frictional

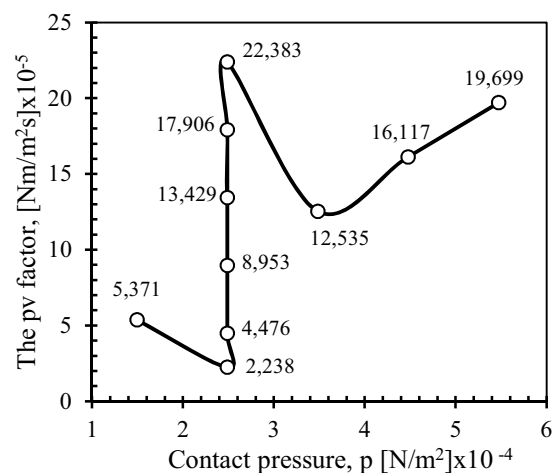
heat power is therefore given by  $q = \mu F_N L / t = \mu p v$  ( $\text{Nm} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ). Where  $F_N$  is normal load,  $v$  is the sliding speed at the interface and  $\mu$  is the coefficient of sliding friction. With increasing  $p v$  factor, the frictional heat increases accordingly, if the friction coefficient may be fairly assumed to be constant, then  $p v$  factor can be a direct indicator of the frictional power dissipated at the interface, that is to say, frictional heat will be directly proportional to the  $p v$  factor.

**Table 3.** The influence of the  $p v$  on abrasive wear of 2014 Al alloy.

$p v$ ( $\text{Nmm}^{-2} \cdot \text{s}^{-1}$ ) $\times 10^{-5}$	Wear depth $h$ (m) $\times 10^{-6}$	Wear rate $\lambda$ ( $\text{ms}^{-1}$ ) $\times 10^{-7}$	Linear wear rate $h/L$ ( $\text{mm}^{-1}$ ) $\times 10^{-7}$	Wear resistance $\epsilon = L/h$ ( $\text{mm}^{-1}$ ) $\times 10^9$
2.238	19.00	1.557	17.272	5.789
4.476	19.542	3.203	17.765	5.629
5.371	6.218	2.072	5.652	17.692
8.953	11.90	3.966	10.818	9.243
8.953	22.542	7.443	20.026	4.993
12.535	19.90	6.633	18.090	5.527
13.429	23.039	11.519	20.944	4.774
16.117	23.094	7.698	20.994	4.763
17.906	23.631	15.754	21.482	4.655
19.699	28.781	9.593	26.164	3.822
22.383	24.338	20.281	22.125	4.519

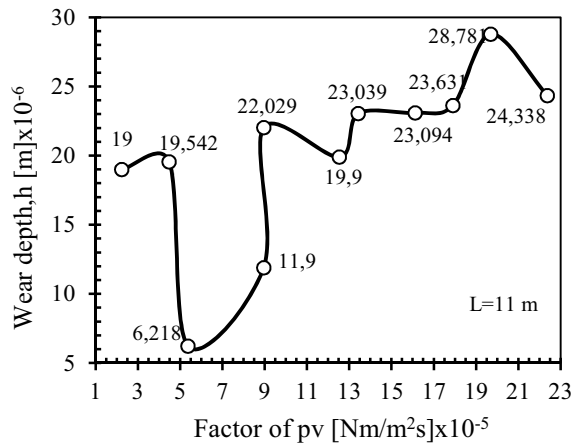


**Figure 19.** The variation in with the  $p v$  factor with speed.

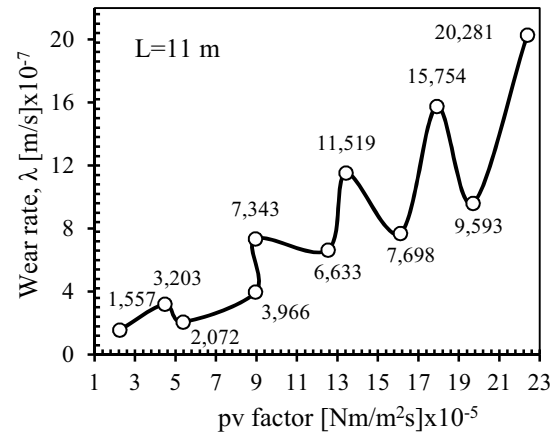


**Figure 20.** The variation in with the  $p v$  factor with contact pressure.

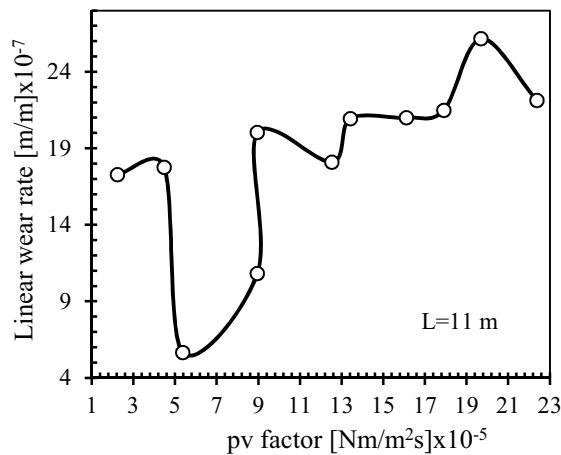
Figure 21 shows the variation in wear depth with the  $p v$  factor. In generally, the wear depth increases roughly with the  $p v$  factor as shown in this figure. But the wear depth reaches a minimum of  $6.218 \times 10^{-6}$  m at a  $p v$  of  $5.371 \text{ Nmm}^{-2} \cdot \text{s}^{-1}$  because the contact pressure is a minimum of  $1.492 \text{ Nm}^{-2}$  as shown in Figure 19. 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 22, wear rate due to time increases roughly with increasing  $p v$  factor. The wear rate values of (1.557, 3.203, 7.343, 11.519, 15.519) and 20.281  $\times 10^{-7} \text{ ms}^{-1}$  belong to a contact pressure of 2.487 speeds in the range 0.09-0.90  $\text{ms}^{-1}$ . The wear rate values of (2.072, 3.966, 6.633, 7.698 and 9.593)  $\times 10^{-7} \text{ ms}^{-1}$  belong to a speed of 0.36 contact pressures in the range (1.492-5.472)  $\times 10^{-4} \text{ Nm}^{-2}$ . It is evident that the wear rate values for a contact pressure of 2.487 and speeds in the range 0.09-0.90  $\text{ms}^{-1}$  are smaller than for a speed of 0.36 contact pressures in the range (1.492-5.472)  $\times 10^{-4} \text{ Nm}^{-2}$ . Because of the conversion of external mechanical energy into the energy of internal processes occurs in the process of friction. Thus, the effects of contact pressure on wear rate is higher than the effect of sliding speed.



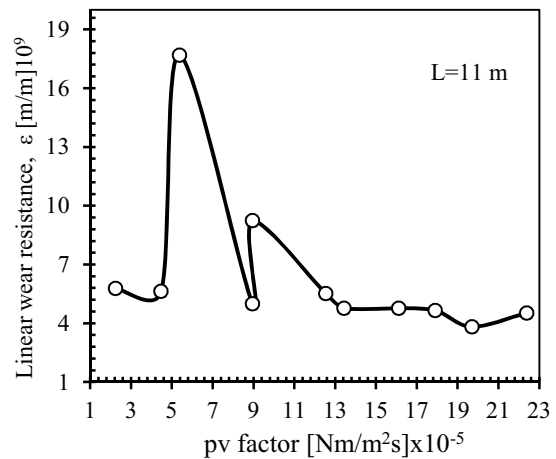
**Figure 21.** The variation in wear depth with the pv factor.



**Figure 22.** The variation in wear rate with the pv factor.



**Figure 23.** The variation in linear wear rate with the pv.



**Figure 24.** The variation in linear wear resistance with the factor of pv.

Figure 23 shows the variation in linear wear rate with the pv factor. In generally, the wear depth increases roughly with the pv factor as shown in this figure. But the wear depth reaches a minimum of  $6.218 \times 10^{-6}$  m at a pv of  $5.371 \text{ Nmm}^{-2}\text{s}^{-1}$  because the contact pressure is a minimum of  $1.492 \text{ Nm}^{-2}$  as shown in Figure 19. 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. Figure 24 shows the relationship between the linear wear resistance and the pv factor. The linear wear resistance decreases roughly in the range  $(2.238-12.535) \times 10^{-5} \text{ Nmm}^{-2}\text{s}^{-1}$  of pv and then it decreases linearly in the range  $(13.429-22.383) \times 10^{-5} \text{ Nmm}^{-2}\text{s}^{-1}$  of pv. But the linear wear resistance reaches a maximum of  $17.692 \times 10^9 \text{ mm}^{-1}$  at a pv of  $5.371 \text{ Nmm}^{-2}\text{s}^{-1}$  because the contact pressure is a minimum of  $1.492 \text{ Nm}^{-2}$  as shown in Figure 19. 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.

## 5. Conclusions

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

- 1) Generally, the wear volume and wear depth increase linearly with an increase in load.
- 2) Generally, wear rate due to time and linear wear rate increase linearly with increasing loads. The linear wear resistance decreases with an increase in load and the wear rate due to time decreases with

an increase in linear wear resistance.

3) The wear rate due to time increases linearly with an increase in linear wear rate. The wear volume increases slightly with an increase in speed. Generally, wear rate due to time and linear wear rate increase linearly with increasing speeds.

4) The linear wear resistance decreases with an increase in speed. The wear rate due to time decreases with an increase in linear wear resistance. The wear rate due to time decreases with an increase in linear wear rate.

5) In generally, the wear depth increases roughly with the  $p_v$  factor. Wear rate due to time increases roughly with increasing  $p_v$  factor. Thus, the effects of contact pressure on wear rate is higher than the effect of sliding speed. In generally, the wear depth increases roughly with the  $p_v$  factor. The linear wear resistance decreases roughly with increasing  $p_v$  factor.

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