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EXPERIMENTAL EVALUATION OF TRIBOLOGICAL PERFORMANCE OF BORON STEEL PLOUGHSHARE UNDER DRY SLIDING CONTACT

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Abstract

Experimental evaluation of the tribological performance of boron steel ploughshare used for soil tillage operation has been studied under dry sliding contact. A ball-on-disc dry sliding tribological properties test was performed following ASTM standards. Surface morphology examination of the ploughshare sample was performed using optical microscopy. The effect of applied load, sliding speed, and sliding time on the tribological properties of the ploughshare sample was analyzed. Results showed that with increasing applied load from 2 to 10N, friction performance of the ploughshare material operated within the boundaries of $0.232 \leq \mu \leq 0.325$, $0.283 \leq \mu \leq 0.378$, $0.308 \leq \mu \leq 0.381$, $0.338 \leq \mu \leq 0.405$ at constant sliding speed and time of (5cm/s, 360s), (10cm/s, 540s), (15cm/s, 720s) and (20cm/s, 900s) respectively showing that friction increased as sliding speed and time increased with percentage increase of 22%, 8.8%, 9.7% and 16.3%, 0.8%, 6.3% for minimum and maximum friction respectively. Wear performance of the ploughshare material operated within the boundaries of $44.44 \leq WR \leq 94.44$ x 10-6g/m, $16.67 \leq WR \leq 64.81$ x 10-6g/m, $12.96 \leq WR \leq 53.70$ x 10-6g/m, $18.89 \leq WR \leq 42.22$ x 10-6g/m at constant sliding speed and time of (5cm/s, 360s), (10cm/s, 540s), (15cm/s, 720s) and (20cm/s, 900s) respectively showing that wear rate decreased as sliding speed and time increased with percentage decrease of 31.4%, 17.1%, 21.4% for maximum wear rate.

Keywords: *Boron Steel Ploughshare, Soil Tillage, Tribological Property, Dry Sliding Contact*

1. Introduction

Soil tillage machinery is farm machines used to prepare the soil for planting or sowing by breaking up the clods and surface crusts, thus improving soil granulation and destroying the weeds. These operations often result in high friction and wear rates, leading to loss of energy, mechanical efficiency, and reduction in the operational life of the tillage tool. The plough disc performs the soil tillage operation by means of a set or several sets of rotating discs, each set being mounted on a common shaft. Ploughshares are found to be very suitable for primary tillage operations. The disc is the main part of a plough, which cuts and pulverizes the soil. Tribology is the study of friction, wear, and lubrication of interacting surfaces in relative motion. The study of friction and wear of agricultural machine components cannot be overemphasized. The events that occur on the surface, such as wear, corrosion or stress concentration, create regions prone to crack nucleation, which under static or dynamic loading will eventually lead to most components and structures failures (Gandra et al., 2013). Wear refers to surface degradation due to continuous loss of material when two contacting surfaces are in relative motion with each other. Wear is the main reason for the loss of performance of components of agricultural machinery. For soil tillage machinery, it leads to the degradation of the soil's working quality. Wear is a major problem in industry, and its direct cost is estimated to vary between 1 and 4% of gross national product (Philip, 1989). Wear constitutes a major problem in the excavation, earth moving, mining, automobiles and mineral processing industries and occurs in a wide variety of components, such as bulldozer blades, excavator teeth, drill bits, crushers, slusher, ball and roll mills, chutes, slurry pumps and cyclones (Hawk et al., 1999). The wear behaviour of the material is related to parameters such as shape, size of component, composition, and distribution of micro constituents in addition to the service conditions such as load, sliding speed, environment, and temperature (Sarkar and Clarke, 1980). The wear of component depends on its surface characteristics like roughness, microstructure, and

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hardness. The complex nature of wear has delayed its investigations and has resulted in isolated studies towards specific wear mechanisms. Friction and wear of materials are generally considered essential properties in engineering practice (Ma et al., 2010). Friction and wear are the main reasons for the reduction in the operational life of soil tillage machinery. During the action of working parts of ploughing machinery (WPPM) on the soil, the stress deformation changes and the initial structure of the soil is disturbed (Viktor and Warouma, 2013; Borak, 2013). Reducing friction and wear are significant concerns in many tribological applications.

The process by which agricultural tools are worn includes impact, abrasion, fretting, and chemical action. However, abrasion is the predominant factor in the wear of tillage tools. The extent of abrasive wear on tillage tools is a function of the normal dynamic pressure of soil on the tool-engaging surface, the relative sliding velocity of soil particles, the shape of the tool, the hardness of the metal, and the characteristics of the soil. Most soil-engaging parts in an agricultural machine are subjected to dynamic loads, abrasive wear, or chemical ac¬tion during their operation. The rapid wear of soil-engaging machine parts is responsible for most of the idle time for maintenance, as well as expenditures for repairs and the manufacture of spare parts (Foley et al., 1984). Increasing machines' service life has become a critical challenge of technological progress. The problems of increasing durability are inseparably linked with a study of the friction and wear patterns of machine parts in operation and the development of the basis of the durability rating of parts and machines. This work investigates the effect of applied load, sliding speed and sliding time on the tribological performance of ploughshare manufactured using boron steel.

2. Materials and Method

2.1 Material

The OEM boron steel ploughshare studied in this research was manufactured in India and procured from a commercial agricultural machinery company based in Lagos State, Nigeria. The ploughshare was meant to be used for soil tillage operations in Nigeria. The ploughshare sample and its specifications are shown in Figure 1 and Table 1.

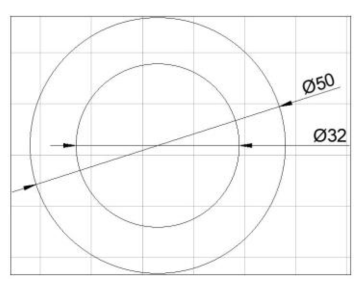
Fig. 1 Boron steel ploughshare.

Table 1 The specifications of boron steel ploughshare

Steel type	Boron steel (BS)
Weight (Kg)	16.5
Disc blade diameter (mm)	660, (26 Inches)
Disc blade thickness (mm)	6
Sharp length (mm)	12
Sharp (tip) thickness (mm)	1.7
Country of manufacture	India

2.2 AutoCAD models of circular disc sample of boron steel ploughshare

The sample boron steel ploughshare for friction and wear test was cut and machined into circular discs with a diameter of 50mm and maintained the thickness of the disc blades (6mm). The disc blade was cut into a circular disc of 5 pieces and machined to the required dimensions. Automated computer-aided design (AutoCAD) software was used to produce the 2D drawing, 3D wireframe and 3D solid models of the circular disc, as presented in Figures 2 to 4, respectively.



All Dimensions in mm

Fig. 2 2D drawing of circular disc machined from ploughshares

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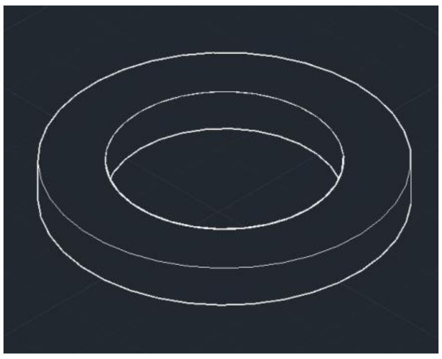

Fig. 3 3D wireframe of circular disc machined from ploughshare

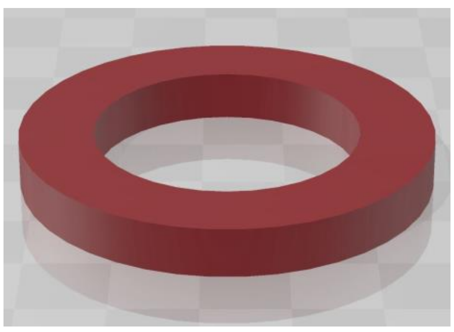

Fig. 4 3D solid model of circular disc machined from ploughshare

2.3 Tribological experimentation

To determine the ploughshare sample's wear rate and coefficient of friction, friction and wear tests were performed on a ball-on-disc tribometer under dry sliding contact. A typical ball-on-disc setup where F is the normal force applied on the ball, r is the ball diameter, R is the wear track's radius and S and the disc's rotational speed is shown in Figure 5. The ploughshare sample was designated as the rotating disc sliding against a stationary ruby ball under dry sliding contact. Sample preparation and procedures followed ASTM D99-95a standard. All tests were carried out at LNG Material Laboratory, Ahmadu Bello University (ABU) Zaria, Kaduna State, Nigeria.

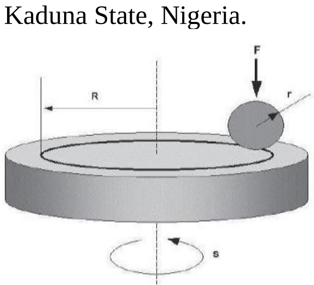

Fig. 5 Typical ball-on-disc setup

2.3.1 Sample preparation

Prior to measuring or weighing and testing, the samples were prepared by first milling to smoothen rough edges along the circumference of the discs, and then all the samples were cleaned with non-chlorinated, non-film-forming cleaning agents and solvents. The samples were then allowed to dry. Care was taken to ensure that no dirt and foreign material occupied the dimples for the dimpled samples. All samples were in dry conditions before the commencement of experimentations. The initial mass (m1) of all samples was taken to the nearest 0.0001g using a digital weighing balance with a precision of 0.0001g or 0.1mg (Ohaus digital balance, model AR2140, Ohaus Corp. USA) (Fig. 7).

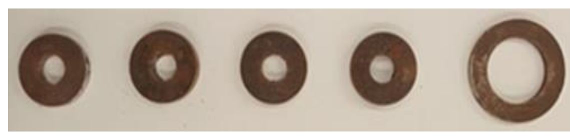

Fig. 6 Tribological test samples of boron steel ploughshare material

Fig. 7 Digital weighing balance

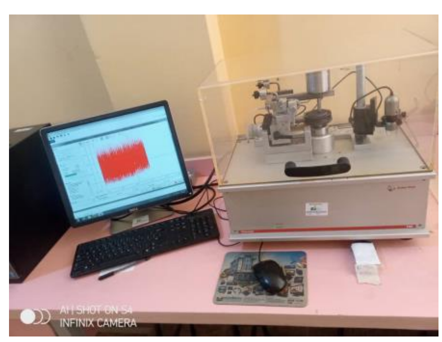

Fig. 8 Tribometer: Anton Paar GmbH, TRB3. CSM Instrument, Austria

2.3.2 Dry sliding ball-on-disc wear test

Dry sliding wear tests were conducted using a ball-on-disc tribometer (Anton Paar GmbH, TRB3, Version 6.1.19, CSM Instrument, a company of Anton Paar, 8054 Graz Austria) (Figure 8). This tribometer is equipped with an automatic calibration procedure for friction force, rotating speed, and measurement radius with integrated temperature and humidity sensors for real-time environmental monitoring and automatic generation of reports for measurements. With the ploughshare sample kept constant, the applied load, sliding speed, and time were varied. Tables 2 to 4 show loading conditions, environmental conditions, and ball properties for the tribological experiment, respectively.

Table 2 Loading conditions for the tribological experiment

Sliding condition	Dry sliding contact
Load (N)	2, 4, 6, 8, 10
Sliding speed (cm/s)	5, 10, 15, 20
Time (s)	360, 540, 720, 900
Wear track diameter (mm)	varied
Frequency (Hz)	10
Cycles sampled (cycles)	1/1

Table 3 Environmental conditions of the tribological experiment

Humidity (%)	55
Ambient temperature (°C)	27 - 29
Atmosphere	Air

Table 4 Ball properties used for the tribological experiment

Material	Ruby
Composition (wt.%)	99%Al_2O_3
Diameter (mm)	6
HV- Hardness Vicker (Kg/mm^2)	2200 - 2400
Bending strength (MPa)	390
Compression strength (MPa)	2100
Thermal conductivity (W/mK)	36

2.3.3 Calculation for wear and friction

Friction and wear behaviours of the samples measured on a ball-on-disc tribometer under dry sliding conditions were calculated and reported as mass loss, wear rate and coefficient of friction for all samples.

Mass loss

The mass loss was calculated by taking the mass difference of the sample before and after each test. The mass loss was calculated using Equation (1).

$$\Delta m=(m1-m2) \quad (1)$$

where Δm is the mass loss in grams (g), m1 is the mass of the sample before the wear abrasion test in grams (g), and m2 is the mass of the sample after the wear abrasion test in grams (g).

Wear rate

Wear rate is the amount of material removed per unit of time. It can also be defined as the amount of material removed per unit distance. This study calculated the wear rate using Equation (2).

$$W=\Delta m/SD \quad (2)$$

where W is the sample wear rate in (g/m), Δm is the mass loss in grams (g), and SD is the sliding distance in (m).

Coefficient of friction

The coefficient of friction was calculated using Equation (3).

$$\mu= Ff/Fn \quad (3)$$

where μ is the coefficient of friction (dimensionless), Ff is the frictional force in Newton (N), and Fn is the applied load in Newton (N).

2.4 Surface morphology investigation

The morphology of the sample prepared from boron steel ploughshare was investigated using the Keyence Optical Microscope (VH-Z450 BY Keyence Corporation, USA) shown in Figure 9. Sample preparation and procedures followed ASTM F410 standards.

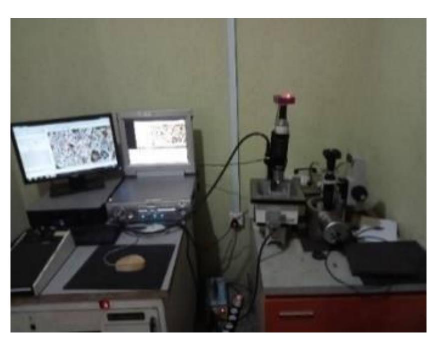

Fig. 9 Keyence Optical Microscope

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3. Results and Discussions

3.1 Tribological characterization

The tribological characteristics of boron steel ploughshare were evaluated under dry sliding contact at varying loads, sliding speed and time. Mass loss, wear rate and friction coefficient were determined. Results of the friction coefficient and wear rate behaviour of the ploughshare are presented in Table 5.

3.1.1 Friction characterization

Friction characterization of boron steel ploughshare for soil tillage application was performed to evaluate the effect of applied load, sliding speed and time on its friction property.

Friction history

Representative friction histories of the boron steel ploughshare sample are presented in Figures 10 to 14 at varying applied loads of 2 to 10N, respectively, at a constant sliding speed of 5cm/s and time of 360s. Figure 10 shows that at 2N load, the friction coefficient increased rapidly at the start of the test with a minimum of 0.061, about 0.23 and then followed a transient state, reaching a maximum value of about 0.256, reporting a mean friction coefficient value of 0.232 and a standard deviation of 0.015. Figure 11 shows that at 4N load, the friction coefficient increased rapidly at the start of the test to a value of about 0.280, followed by a transient state reaching a maximum of 0.292, mean friction coefficient of 0.277 and standard deviation of 0.014. Figure 12 shows that at 6N load, the friction coefficient increased rapidly at the start of the test to a value of about 0.320, then slightly decreased, followed by a transient state reaching a maximum of 0.314, the mean friction coefficient of 0.297 and standard deviation of 0.013. Figure 13 shows that at 8N load, the friction coefficient increased rapidly at the start of the test to a value of about 0.260, then slightly decreased, followed by a transient state reaching a maximum of 0.286, mean friction coefficient of 0.279 and standard deviation of 0.011. Figure 14 shows that at 10N load, the friction coefficient increased rapidly at the start of the test to a value of about 0.30 and then slightly decreased and increased, maintaining a transient state with a maximum of 0.341 recorded, mean friction coefficient and standard deviation were observed to be 0.325 and 0.015 respectively. A similar pattern of friction histories of boron steel ploughshare was observed at varying applied loads of 2 to 10N with constant sliding speeds of 10cm/s and time of 540s, sliding speed of 15cm/s and time of 720s, and sliding speed of 20cm/s and time of 900s.

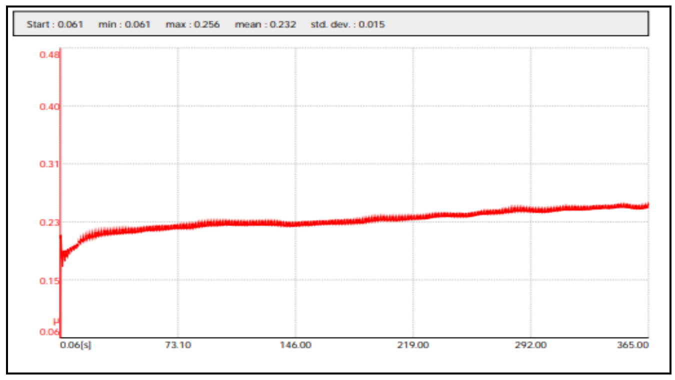

Fig. 10 Friction trend of boron steel ploughshare at applied load = 2N, sliding speed = 5cm/s, time = 360s

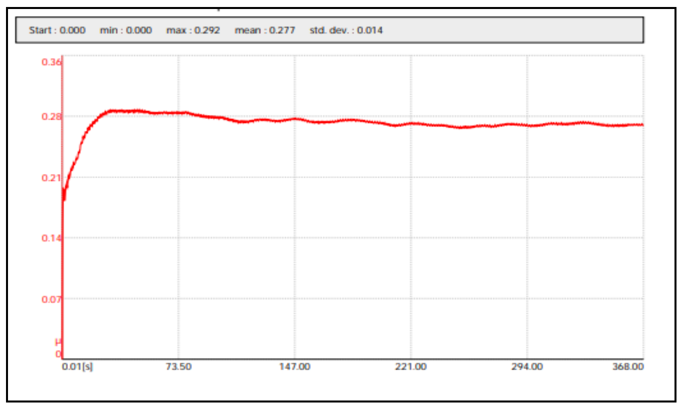

Fig. 11 Friction trend of boron steel ploughshare at applied load = 4N, sliding speed = 5cm/s, time = 360s

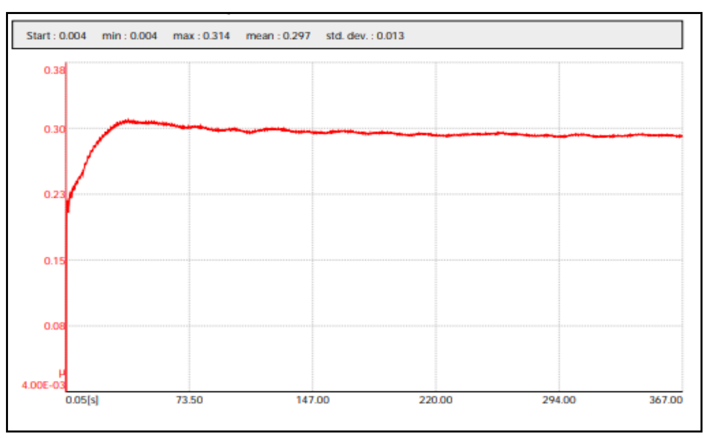

Fig. 12 Friction trend of boron steel ploughshare at applied load = 6N, sliding speed = 5cm/s, time = 360s

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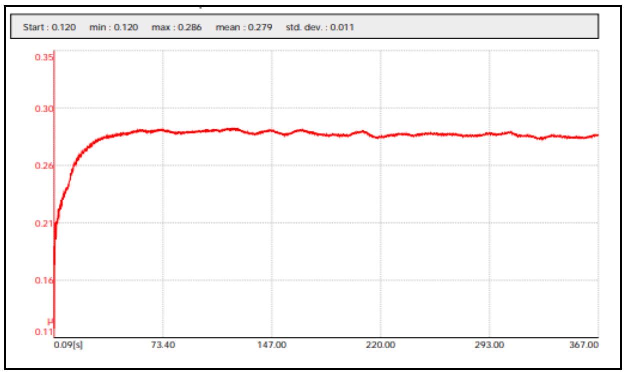

Fig. 13 Friction trend of boron steel ploughshare at applied load = 8N, sliding speed = 5cm/s, time = 360s

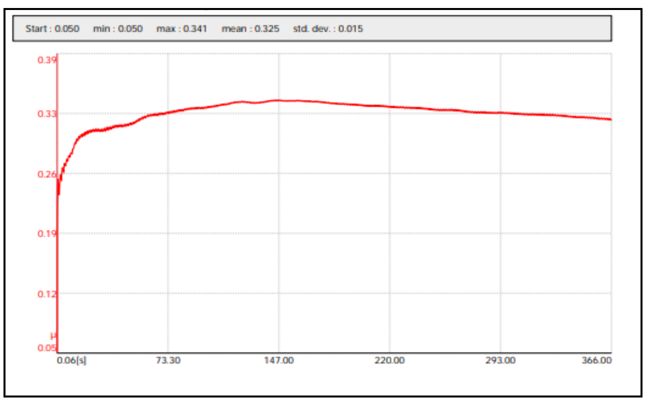

Fig. 14 Friction trend of boron steel ploughshare at applied load = 10N, sliding speed = 5cm/s, time = 360s

Effects of applied load on coefficient of kinetic friction

Friction coefficients of the boron steel ploughshare sample are presented in Figures 15 to 18. Figure 15 shows the variation of friction with normal load on boron steel ploughshare at a constant speed of 5cm/s and time of 360s with normal load increasing from 2 to 10N. On dry sliding contact, friction increased as the normal load increased, with the maximum value obtained at 10N being 0.325. Figure 16 shows the variation of friction with normal load at a constant speed of 10cm/s and time of 540s with normal load increasing from 2 to 10N. Also, in dry conditions, friction decreased as the normal load increased, with the maximum value obtained at 2N being 0.378. Figure 17 shows the variation of friction with normal load at a constant speed of 15cm/s and time of 720s with normal load increasing from 2 to 10N. Friction initially increased up to a normal load of 4N and then decreased as the normal load increased, with the maximum value obtained at 4N being 0.381. Figure 18 shows the variation of friction with normal load at a constant speed of 20cm/s and time of 900s with normal load increasing from 2 to 10N. Friction decreased as the normal load increased, with the maximum value obtained at 6N at 0.405.

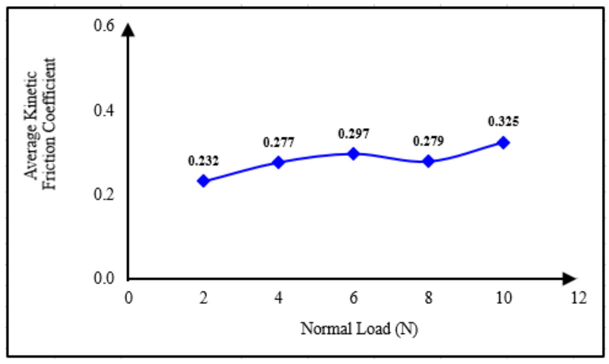

Fig. 15 Variation of friction with normal load on boron steel ploughshare sample @ speed = 5cm/s, time = 360s

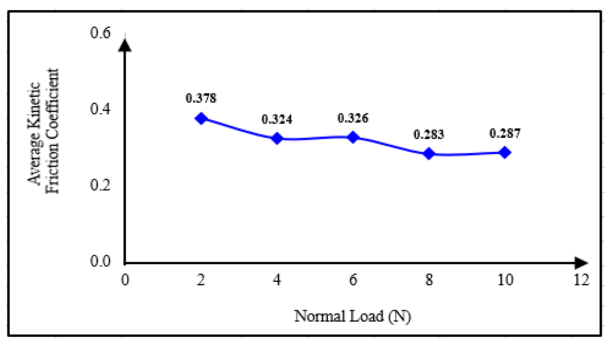

Fig. 16 Variation of friction with a normal load on boron steel ploughshare sample @ speed = 10cm/s, time = 540s

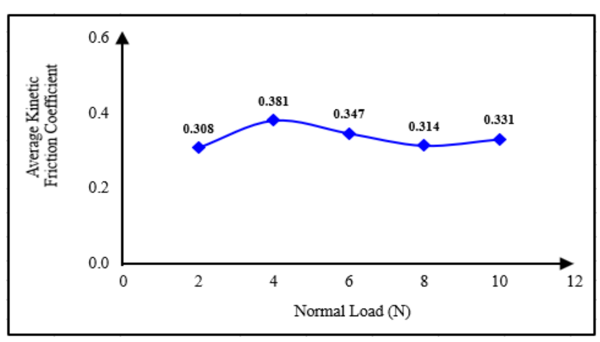

Fig. 17 Variation of friction with a normal load on boron steel ploughshare sample @ speed = 15cm/s, time = 720s

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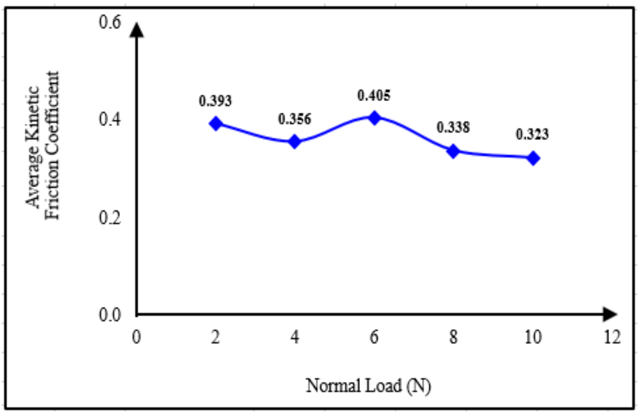

Fig. 18 Variation of friction with a normal load on boron steel ploughshare sample @ speed = 20cm/s, time = 900s

Effects of sliding speed on coefficient of kinetic friction

Figure 19 shows the friction variation with sliding speed on the boron steel ploughshare sample. At a constant load of 2N, friction exhibited a sinusoidal pattern as sliding speed increased. In contrast, at a normal load of 4N, friction increased as sliding speed increased. Similar patterns of variation of coefficient of friction versus sliding speed were observed at constant normal loads of 6, 8 and 10N.

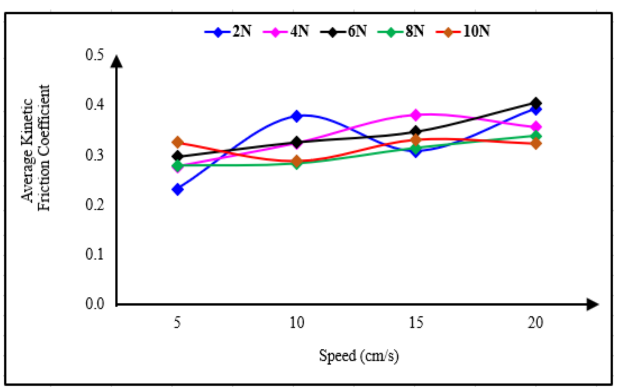

Fig. 19 Variation of friction with sliding speed on boron steel ploughshare

3.1.2 Wear characterization

Wear characterization of boron steel ploughshare used for soil tillage was performed to evaluate the effect of applied load, sliding speed and time on wear rate.

Effects of applied load on wear rate

The wear rate of the boron steel ploughshare sample is presented in Figures 20 to 23. Figure 20 shows the variation of wear rate with normal load at a constant speed of 5cm/s and time of 360s with normal load increasing from 2 to 10N. On dry contact, the wear rate increased as the normal load increased, with the maximum value obtained at 8N being 94.44 x 10-6 g/m and then dropped slightly at 10N. Similar patterns of variation of wear rate versus normal load were observed at constant sliding speeds of 10 and 15cm/s (Figures 21 to 22), with maximum values obtained at 8N being 64.81 x 10-6 g/m and 53.70x 10-6 g/m respectively. Figure 23 shows the variation of wear rate with normal load at a constant speed of 20cm/s and time of 900s with normal load increasing from 2 to 10N. On dry contact, the wear rate increased as the normal load increased but dropped at 8N and then increased, with the maximum value obtained at 10N being 42.22 x 10-6 g/m.

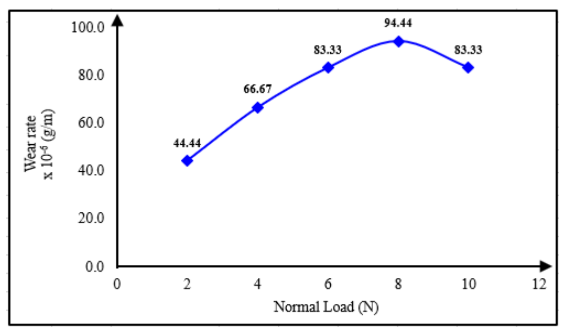

Fig. 20 Variation of wear rate with normal load on boron steel ploughshare sample @ speed = 5cm/s, time = 360s

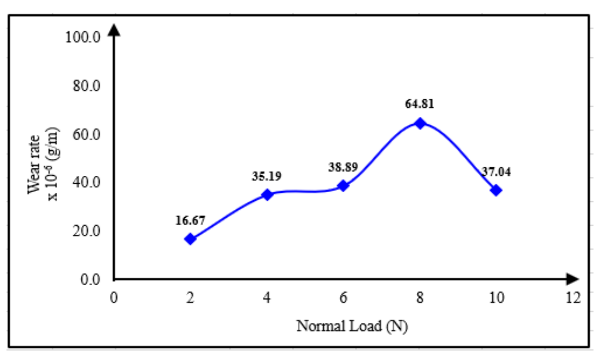

Fig. 21 Variation of wear rate with normal load on boron steel ploughshare sample @ speed = 10cm/s, time = 540s

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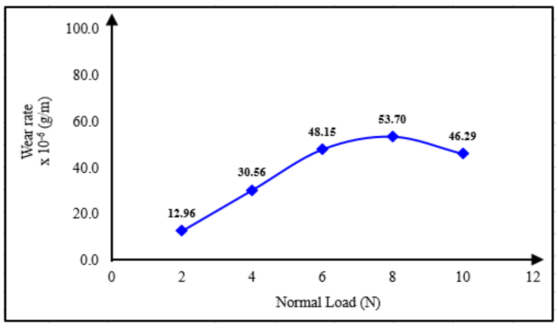

Fig. 22 Variation of wear rate with a normal load on boron steel ploughshare sample @ speed = 15cm/s, time = 720s

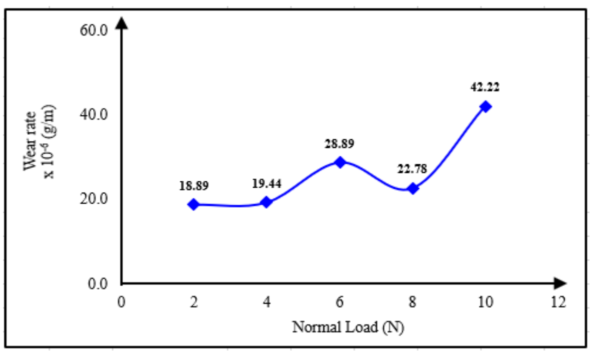

Fig. 23 Variation of wear rate with a normal load on boron steel ploughshare sample @ speed = 20cm/s, time = 900s

Effects of sliding speed on wear rate

Figure 24 shows the variation of wear rate with sliding speed on the boron steel ploughshare sample. At a constant load of 2N, the wear rate decreased as the sliding speed increased. Similar patterns of variation of wear rate versus sliding speed were observed at constant normal loads of 4, 6, 8 and 10N, respectively. This agrees with the report of Hardell et al. (2008).

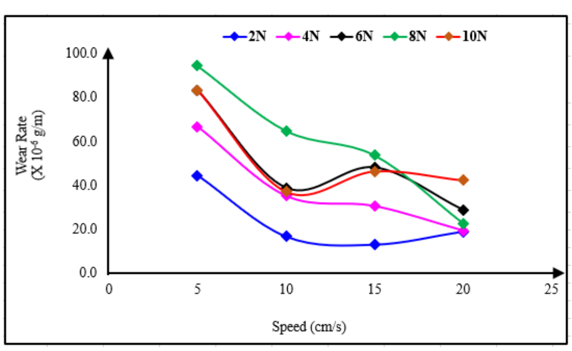

Fig. 24 Variation of wear rate with sliding speed of boron steel ploughshare

Table 5 Friction and wear test results of boron steel ploughshare

Load (N)	Speed (cm/s)	Time (s)	Wear Rate X 10^{-6} (g/m)	Average Coefficient of Kinetic Friction (μ)
2	5	360	44.44	0.232
4	5	360	66.67	0.277
6	5	360	83.33	0.297
8	5	360	94.44	0.279
10	5	360	83.33	0.325
2	10	540	16.67	0.378
4	10	540	35.19	0.324
6	10	540	38.89	0.326
8	10	540	64.81	0.283
10	10	540	37.04	0.287
2	15	720	12.96	0.308
4	15	720	30.56	0.381
6	15	720	48.15	0.347
8	15	720	53.70	0.314
10	15	720	46.29	0.331
2	20	900	18.89	0.393
4	20	900	19.44	0.356
6	20	900	28.89	0.405
8	20	900	22.78	0.338
10	20	900	42.22	0.323

3.2 Surface morphology analysis

The morphology of boron steel ploughshare was investigated and analyzed in relation to the results of the Rockwell hardness test using the Keyence Optical Microscope, model VH-Z450 BY Keyence Corporation, USA. Figure 25 shows the micrographs of the boron steel ploughshare sample obtained through optical microscopy with 2500X magnification and 86 microns of resolution. The micrograph revealed a smaller grain size distribution.

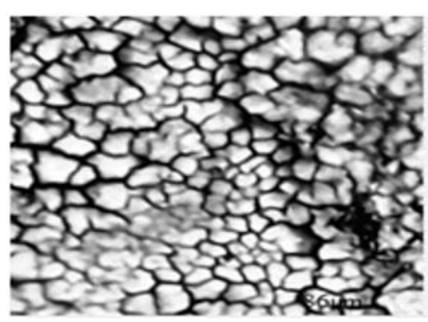

Fig. 25 Optical microscopy image of boron steel ploughshare sample with 2500X magnification and 86μ resolution

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3.3 Wear track investigation

Figure 26 shows the representative image of the wear track resulting from the ball-on-disc sliding contact of the boron steel ploughshare sample. The intensity of the wear rate of the ploughshare surface increased, showing a wear rate of 37.04 x 10-6 (g/m) obtained from boron steel ploughshare, which is evident by its wear track width of 1.0mm as in Figure 26.

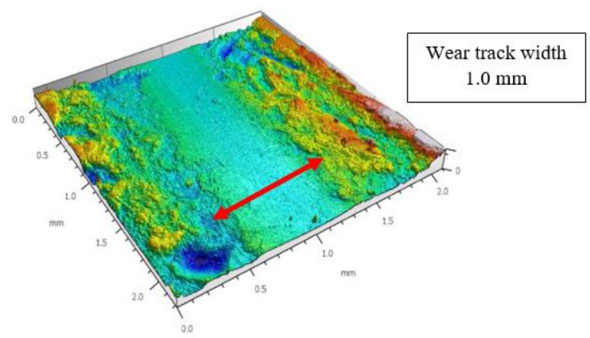

Fig. 26 Image of wear track of boron steel ploughshare at applied load = 10N, speed = 10cm/s, time = 540s

4. Conclusions

From this study, the variation of friction with normal load at constant speed and time of 5cm/s and 360s showed that friction increased as normal load increased but decreased as normal load increased when the sliding speed and time increased to 10cm/s and 540s. At 15cm/s and 720s, friction initially increased up to a normal load of 4N and then decreased as the normal load increased. At 20cm/s and 900s, friction decreased as the normal load increased. It can be concluded that the higher the normal load, the greater the resistance to the relative motion between the two sliding bodies. This study concluded that at 2N, friction exhibited a sinusoidal pattern as sliding speed increased.

In contrast, at 4N, friction increased as sliding speed increased. Similar patterns of variation of friction with sliding speed were observed at constant loads of 6, 8 and 10N as sliding speed increased. The study found that the wear rate increased as the normal load increased with the maximum value obtained at 8N and then dropped slightly at 10N with 5cm/s and 360s.

Similar patterns of variation of wear rate versus normal load were observed at ten and 15cm/s, with maximum values obtained at 8N. At 20cm/s and 900s, the wear rate increased as the normal load increased but dropped at 8N, increasing with the maximum value obtained at 10N. It was revealed that the variation of wear rate with sliding speed at a constant load of 2N showed an inverse relationship with wear rate decreasing as sliding speed increased. Similar patterns of variation of wear rate with sliding speed were observed at 4, 6, 8 and 10N, respectively.

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