# Wear Measuring and Wear Modelling Based on Archard, ASTM, and Neural Network Models

A. Shebani, C. Pislaru

***Abstract*—** The wear measuring and wear modelling are a fundamental issue in the industrial field, mainly correlated to the economy and safety. Therefore, there is a need to study the wear measurements and wear estimation. Pin-on-disc test is the most common test which is used to study the wear behaviour. In this paper, the pin-on-disc (AEROTECH UNIDEX 11) is used for the investigation of the effects of normal load and hardness of material on the wear under dry and sliding conditions. In the pin-on-disc rig, two specimens were used; one, a pin which is made of steel with a tip, is positioned perpendicular to the disc, where the disc is made of aluminum. The pin wear and disc wear were measured by using the following instruments: The Talysurf instrument, a digital microscope, and the alicona instrument; where the Talysurf profilometer was used to measure the pin/disc wear scar depth, a digital microscope was used to measure the diameter and width of wear scar, and the alicona was used to measure the pin wear and disc wear. After that, the Archard model, American Society for Testing and Materials model (ASTM), and neural network model were used for pin/disc wear modelling. Simulation results are implemented by using the Matlab program. This paper focuses on how the alicona can be considered as a powerful tool for wear measurements and how the neural network is an effective algorithm for wear estimation.

***Keywords*—**Wear modelling, Archard Model, ASTM Model, Neural Networks Model, Pin-on-disc Test, Talysurf, Digital microscope, Alicona.

## I. INTRODUCTION

The wear can be defined as the removal of material from solid surfaces by mechanical action. Wear of materials is an everyday experience and has been observed and studied for a very long time. Several factors are effects on the wear mechanisms such as normal load, hardness of material, sliding distance, sliding velocity, and coefficient of sliding friction; this paper is focuses on effects of normal load and hardness of material on wear behaviour based on pin-on-disc test [1]-[6].

Artificial neural networks (ANNs) are often used for applications where it is difficult to state explicit rules. There is a wide range of application domains where ANNs are being used, including classification, optimization, prediction, and recognition. Neural networks with their remarkable ability to derive meaning from complicated or imprecise data can be used to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques.

Feed-forward layered neural networks have increasingly been used in many areas such as modeling of non-linear systems. One example of a feed forward neural network is the Backpropagation neural network (BPNN). This form of neural networks has been applied in different fields of research and satisfactory performance has been obtained. In practice, however, the BP has been found to perform poorly (e.g. slow convergence of weights in the non-linear updating procedure and difficulty in modeling). An alternative approach to overcome the limitations associated with the BP algorithm is to use the Radial Basis Function (RBF) network. The RBF network can be regarded as a special three layer network, including input, hidden and output layers. The performance of the RBF depends on the proper selection of three important parameters (centers, widths and weights) [7]-[10].

## II. EXPERIMENTAL SETUP

The pin-on-disc test (AEROTECH UNIDEX 11) which is shown in Fig. 1 is used in this paper for the investigation of the effects of the normal load and hardness of material on the pin/disc wear under dry and sliding conditions.

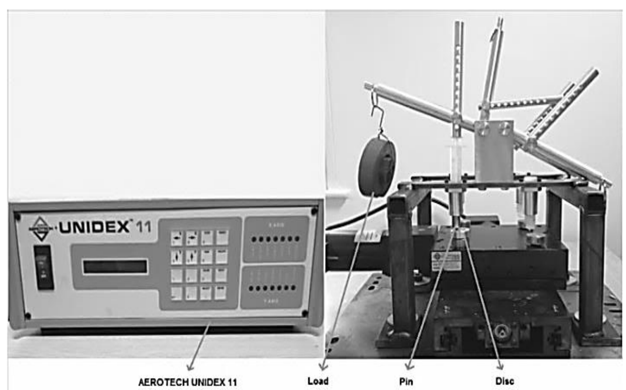


Fig. 1 Pin-on-disc (AEROTECH UNIDEX 11)

Experiments were conducted at normal load 6N, 10N, 16N, and 22N, with test time of one hour for each load, sliding speed of 500mm/min, and sliding distance of 5mm. The materials which were used in the test were, disc made of aluminium 6082 and pin made of mild carbon steel EN8.

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The wear test was started such as in the following steps:

1. Proper mass was added to the system lever in pin-on-disc tester. The first weight was equivalent to the first sample of the normal load (6N).
2. The motor started and the speed is adjusted to the desired value while holding the pin specimen out of contact with the disk; and then the motor was stopped.
3. The pin and disc were inserted into their holders.
4. The timer was adjusted to the desired time (one hour).
5. The test was started with the specimens in contact under load.
6. After one hour the test was stopped (when the desired time was achieved).
7. The pin and disc were removed, to commence in wear measurements.

## III. RESULTS AND DISCUSSION

### *A 2D wear measurements*

Taylor Hobson (Talysurf series 2), which is shown in Fig. 2 was used to measure the depth of the wear scar. The Taylor Hobson profilometer measures the wear scar depth by sliding the probe across the wear track and provides a wear profile, and then the Talysurf software package calculate the depth of the wear scar.


Fig. 2 Taylor Hobson (Talysurf)

The Talysurf profilometer was used to measure the wear scar depth. The surface is measured by moving the stylus across the pin/disc surface.

An example of the wear scar depth of disc surface can be seen in Fig. 3, which is shows the depth of the disc wear scar after (6N, 10N, 16N, and 22N) which is measured by using Talysurf.

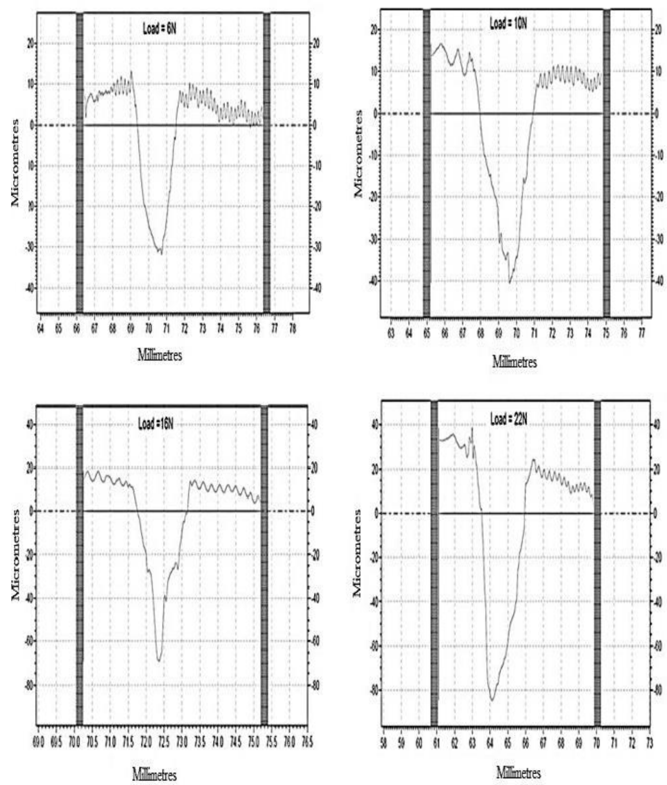


Fig. 3 Disc wear scar depth measured by using Talysurf

The disc wear scar depth can be estimated by using the following equations [3]:

$$h = k\,p\,s \tag{1}$$

The contact pressure p can be calculated by using following equation:

$$p = \frac{F}{A} \tag{2}$$

Where:

h is the wear depth (mm), k is the wear coefficient (-), p is the contact pressure (psi), F is the normal load (N), and A is the contact area ($mm^2$).

The contact area $A$ can be calculated by using the following equation:

$$A = \pi\,a\,b \tag{3}$$

Where: $a$ is the half length of disc wear track, and $b$ is half width of the disc wear track.

The disc wear depth measured and modelled is shown in Table I.

TABLE I
DISC WEAR DEPTH

| No | Normal load | Disc wear scar depth measured | Disc wear scar depth estimated |
|---|---|---|---|
| 1 | 6N | 31.9075 ($\mu m$) | 32.216 ($\mu m$) |
| 2 | 10N | 40.6689 ($\mu m$) | 41.1082 ($\mu m$) |
| 3 | 16N | 69.2192 ($\mu m$) | 68.9414 ($\mu m$) |
| 4 | 22N | 84.5123 ($\mu m$) | 85.1472 ($\mu m$) |

## *B ROUGHNESS PARAMETERS*

The center line average value $R_a$ is the one of most important roughness parameters; it is used to monitor a production process where gradual changes in the surface finish due to the wear. An instrument for measuring the center line average value $R_a$ should have a higher measuring repeatability [4].

The definition of roughness $R_a$ is shown in Fig. 4:

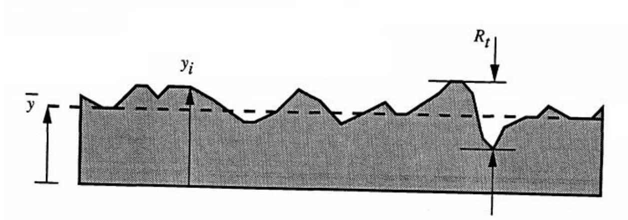


Fig. 4 Definition of roughness average [11]

The center line average value ($R_a$) also it called roughness average, it can be calculated by using the following equation:

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i - \bar{y}| \quad (4)$$

Where:

$\bar{y}$ is the height of the midline of the profile, $y_i$ is the height of an arbitrary point on the profile and $n$ is the number of data, and $R_t$ is the maximum vertical distance from the highest to the lowest point [11].

Fig. 5 shows the quantity $R_a$ is the average deviation of the profile from mean line.

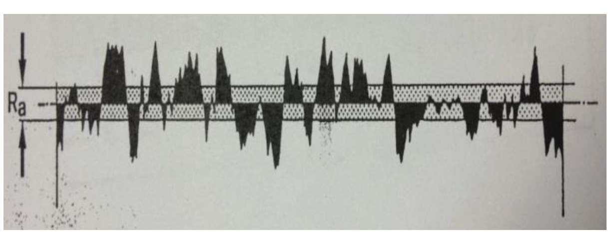


Fig. 4 Deviation of the parameter [12]

The value of the average deviation of the profile $R_a$ is calculated by using 2D Talysurf measurements, it was equal 1.0532 ($\mu m$) for 6N. This value can be taken directly from Talysurf instrument. The significant result at 6N, is that the value of skewness of roughness ($R_{sk}$) was negative ($-0.6846$), this indicates that the surface height distribution has a longer tail at the lower side of the mean plane.

For the next step, the digital microscope (VHX) which is shown in Fig. 6 was used to measure the pin wear scar diameter. The diameter of the pin wear scar and disc wear scar are appeared on the computer screen, such as in Fig. 7 and Fig. 8.

Fig. 6 Pin/disc wear scar measurements by using digital microscope (VHX)

The digital microscope (VHX) was used throughout the pin-on-disc experiments in this paper to measuring the pin/disc wear scar. Fig. 7 shows pin wear scar diameter, which was measured by using digital microscope at 6N.

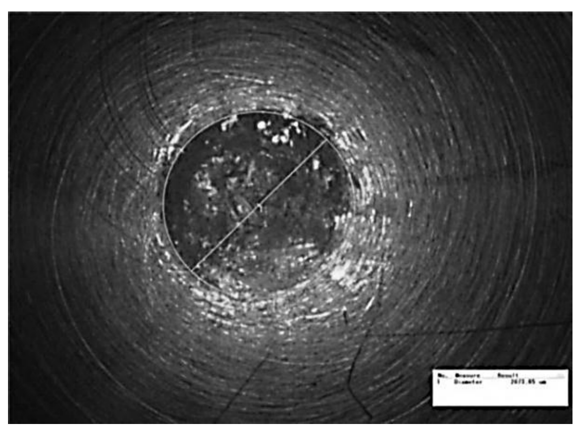

Fig. 7 Pin wear scar diameter using digital microscope

The pin wear scar diameter measurements by using digital microscope after load of 6N, 10N, 16N, and 22N are shown in Table II. These measurements will be used to wear modelling by using an ASTM model.

TABLE II
PIN WEAR SCAR DIAMETER

| No | Normal load | Pin wear scar diameter |
|---|---|---|
| 1 | 6N | 1885.35($\mu m$) |
| 2 | 10N | 2073.65 ($\mu m$) |
| 3 | 16N | 2267.00($\mu m$) |
| 4 | 22N | 2358.45($\mu m$) |

Table II shows that the pin wear scar diameter clearly was affected by changing the normal load, the increasing of wear scar diameter observed on the pin indicate that the pressure inside the contact area under 22N is bigger than the pressure inside the contact area under 6N. Fig. 8 shows disc wear scar length and width which were measured by using digital microscope under load of 6N. Four tests under load of 6N, 10N, 16N, and 22N were carried out by using a pin-on-disc test, and for each test the width and length of the disc wear scar were measured by using digital micoscope. Some thin, regular and radial scratches are seen on the surface which result abrasive wear and deformation of the disc worn surface.

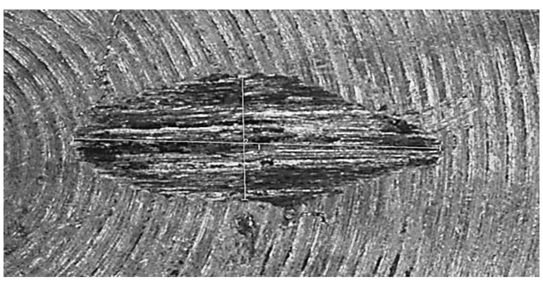

Fig. 8 Disc wear track section measured by using digital microscope

The disc wear scar length and width measurements by using digital microscope after load of 6N, 10N, 16N, and 22N are shown in Table III. These measurements will be used to wear modelling by using the ASTM model.

TABLE III
DISC WEAR SCAR LENGTH AND DEPTH

| No | Normal load | Disc wear scar length | Disc wear scar width |
|---|---|---|---|
| 1 | 6N | 3825.88($\mu m$) | 1545.27($\mu m$) |
| 2 | 10N | 3886.73 ($\mu m$) | 1616.79 ($\mu m$) |
| 3 | 16N | 4126.28($\mu m$) | 1744.94($\mu m$) |
| 4 | 22N | 4190.11($\mu m$) | 2195.17($\mu m$) |

C 3D SURFACE MEASUREMENTS

Fig. 9 shows the 3D contact analysis of pin-on-disc, where ***F*** is the normal load, and ***R*** is the pin radius.

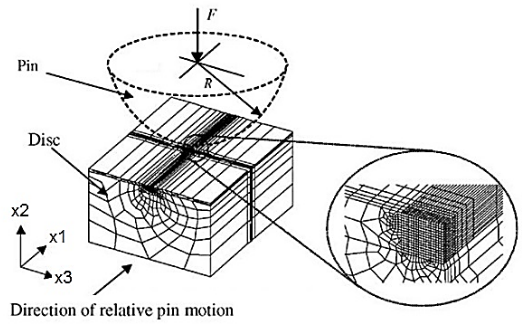


Fig. 9 3D pin/disc contact analysis [13]

In the next step for pin-on-disc test is measure the pin wear and disc wear by using the alicona (INFINTE FOCUS) which is shown in Fig. 10.

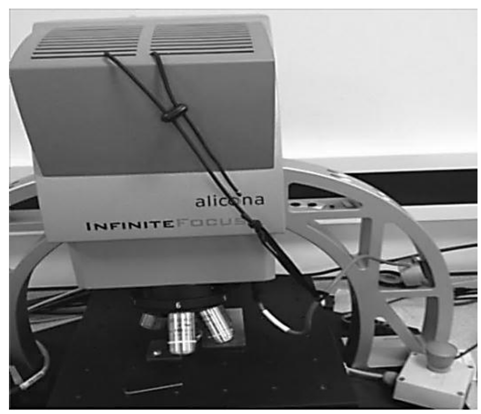


Fig. 10 3D wear measurements using alicona (INFINTE FOCUS)

In this paper, the volume loss for the disc/pin were measured by using alicona, that by taking a digital image of the pin/disc surface before the test and save it as a reference 1, and then take another image of the pin/disc surface after test and save it as a reference 2, and then the software of alicona compared this image by reference image and automatically calculate the pin/disc wear in ($\mu m^3$).

Fig. 11 show the disc wear scar depth which is measured by using alicona after load of (6N, 10N, 16N, and 22N); this figure shows the disc surface before the test and after four tests.

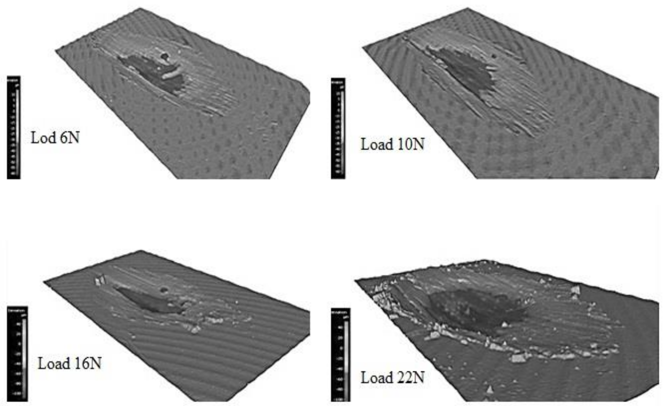


Fig. 11 Disc wear scar measured using alicona

For pin wear scar, equation (5) and equation (6) are used to estimate the pin wear:

$$V = \frac{\pi h^2}{3} [3R + h] (mm^3) \quad (5)$$

$$h = R - \sqrt{(R^2 - \frac{D^2}{4})} (\mu m) \quad (6)$$

Where V is the disc wear in ($mm^3$), R is the radius of the pin in (μm) , and D is the wear scar diameter in (μm). The equation (5) and equation (6) are modified in order to calculate the disc wear; equation (7) and equation (8) are used to estimate the disc wear:

$$V = \frac{a \pi h^2}{3 b} [3R - h] (mm^3) \quad (7)$$

$$h = R - \sqrt{(R^2 - b^2)} (\mu m) \quad (8)$$

Where V is the disc wear in ($mm^3$), R is the radius of the pin in (μm), and (a , b ) are the half-length and the width of the disc wear scar respectively in (μm) [14].

Fig. 12 show the pin wear scar depth which is measured by using alicona after load of (6N, 10N, 16N, and 22N); this figure shows the pin surface before the test and after four tests.

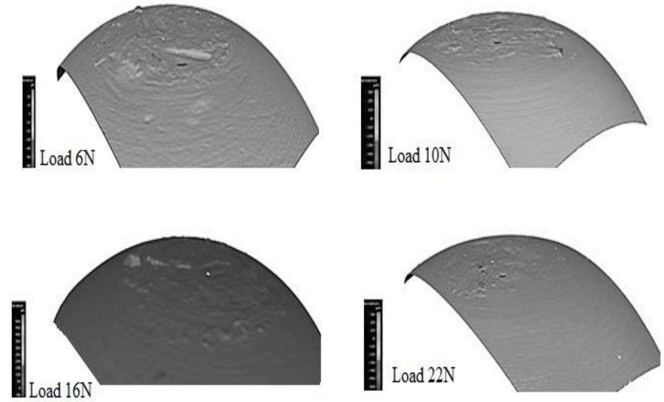


Fig. 12 Pin wear scar measured by using alicona

Table IV shows the disc wear measured by using alicona and estimated by using the equation (7) and equation (8).

TABLE IV
DISC WEAR MEASURED AND ESTIMATED

| No | Normal load | Disc wear measured | Disc wear estimated |
|---|---|---|---|
| 1 | 6N | 0.0786 $\mu m^3$ | 0.0736 $\mu m^3$ |
| 2 | 10N | 0.0798 $\mu m^3$ | 0.0801 $\mu m^3$ |
| 3 | 16N | 0.1226 $\mu m^3$ | 0.1272 $\mu m^3$ |
| 4 | 22N | 0.2301 $\mu m^3$ | 0.2431 $\mu m^3$ |

Table 1 Disc wear measured and estimated

Table IV shows the pin wear measured by using alicona and estimated by using the equation (5) and equation (6).

TABLE V
PIN WEAR MEASURED AND ESTIMATED

| No | Normal load | Pin wear measured | Pin wear estimated |
|---|---|---|---|
| 1 | 6N | $2.522 . 10^{-3} \mu m^3$ | $2.582 . 10^{-3} \mu m^3$ |
| 2 | 10N | $2.604 . 10^{-3} \mu m^3$ | $2.674 . 10^{-3} \mu m^3$ |
| 3 | 16N | $2.963 . 10^{-3} \mu m^3$ | $2.931 . 10^{-3} \mu m^3$ |
| 4 | 22N | $3.196 . 10^{-3} \mu m^3$ | $3.227 . 10^{-3} \mu m^3$ |

As we notice from Table IV and Table V, that the equations (5) to (8) can be used to pin/disc wear estimation.

Fig. 11 and Fig. 12 show that there are significant changes in pin/disc wear scar depth under changing the normal load, where the wear scar depth gradually increased; these depths are caused by effects many factors such normal force. Table (4) and Table (5) show that the disc wear was greater than the pin wear, that because the pin was made of strong material (steel) and the disc was made of aluminium, therefore the hardness of the material has a significant effect on the wear behavior.

## IV. PIN/DISC WEAR MODELLING

The Archard, ASTM, and Neural Network models were used in the following section to predict the pin/disc in ($mm^3$). The pin wear and disc wear were calculated by using the Archard model [15]:

$$V = k \, \frac{N\,S}{H} \quad (mm^3) \tag{9}$$

Where: $K$ is the non-dimensional wear coefficient, $V$ is the measured wear volume ($mm^3$), $H$ is the hardness of material (N/ $mm^2$), $F_N$ is the normal load (N) and $L$ is the sliding distance ($mm$).

The pin wear and disc wear were calculated by using the ASTM model [16, 17]:

$$\text{Pin Wear} = \frac{\pi\,h}{6}\left[\frac{3\,d^2}{4} + h^2\right](mm^3) \tag{10}$$

$$h = r - \left[r^2 - \frac{d^2}{4}\right]^{0.5} \quad (mm) \tag{11}$$

$$\text{Disc Wear} = 2\,\pi\,R\left[r^2 \sin^{-1}\left(\frac{d}{2r}\right) - \left(\frac{D}{4}\right)(4\,r^2 - D^2)^{0.5}\right](mm^3) \tag{12}$$

Where:
h is the height of material removed from the pin in mm, d is the pin wear scar diameter in µm, r is the pin radius in µm, R is the disc wear track radius in µm, and D is the disc wear track width in µm.

In this paper, the normal load was changed such as 6N, 10N, 16N, and 22N, and the wear coefficient $k$ was calculated by using:

$$K = \frac{V\,H}{L\,F_N} \tag{13}$$

Where: $K$ is the non-dimensional wear coefficient, $V$ is the measured wear volume ($mm^3$), $H$ is the hardness of material (N/ $mm^2$), $F_N$ is the normal load (N) and $L$ is the sliding distance ($mm$).

In our pin-on-disc tests, the disc was made of aluminium 6082, the hardness of aluminium 6082 is 95(HB), and the pin was made of mild carbon steel EN8, the harness of this type of steel is 255(HB); these values were taken from standard hardness tables [18, 19].

The radial basis function neural network is used in this paper for pin/disc wear modelling, where the centers of the RBFNN was selected by using K-Means clustering algorithm and the width of Gaussian function was measured by using Euclidean algorithm, and the weights of output layer were adaptive by using least mean squares algorithm [20]-[23].
Then the K means algorithm will do the following three steps until convergence such as [20]-[23]:

1) Determine the centroid coordinate.
2) Determine the distance of each object to the centroids.
3) Group the object based on minimum distance.

Euclidean distance is calculated by using the following equation [20]-[23]:

$$E_{dist} = \sqrt{\sum_{i=1}^{n} (Xi - cj)^2} \tag{14}$$

Where $n$ the vector dimension, and Edist is the Euclidean distance.

The weight adaptation can be performing using the least square algorithm, such as in the following equation [20]-[23]:

$$W_i(t+1)new = W_i(t)old + \mu\left(y_d(t) - y(t)\right)X_i(t) \tag{15}$$

Where $0 < \eta \leq 1$ is a positive gain factor term that controls the adaptation rate of the algorithm, $y(t)$ and $y_d(t)$ are the actual output and the desired output respectively and t is the current time.
This algorithm adjusts the weights to reduce the error until ideally $\left(y_d(t) - y(t)\right) = 0$, which means no modification to the weight would be necessary.

The first purpose of this test is to investigate effects of normal load and hardness of material on wear. The second purpose of this test is to use the Archard wear model, ASTM model, and neural network model to wear prediction, and compassion between wear measured and wear modelled (for pin and disc). The pin wear and disc wear were measured at normal load (6N, 10N, 16N, and 22N), and then, the Archard, ASTM, network models were used for wear prediction at the same values of normal load. After that, the results were plotted using a Matlab program such as in Fig.13 and Fig. 14.

Simulation results for pin wear measured and pin wear modeled based on Archard, ASTM and neural network models are illustrated in Fig. 13.

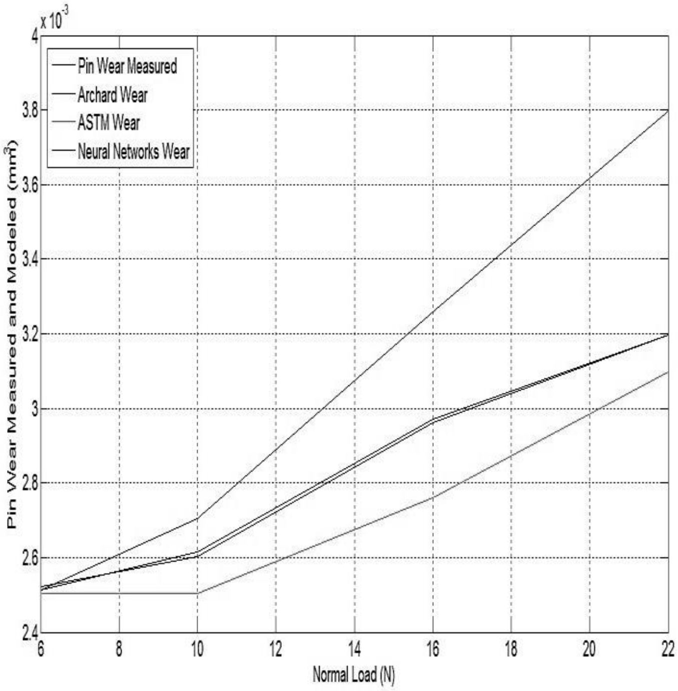


Fig. 13 Pin wear measured, Archard, ASTM, and Neural Network wear

Variations of pin wear with normal load are presented in Fig. 13; it shows the wear test results together with the wear results obtained from two models (Archard, ASTM, and Neural Network models). The normal load was changed such as 6N, 10N, 16N, and 22N. It is observed that the pin wear increases with the increase of normal load, this is due to the fact that as, the normal load increases frictional heat is generated at the contact surface and hence the strength of the material decreases. On the other hand, when the load on pin is increased, the actual area of contact would increase, resulting in increased frictional force and real surface area in contact causing higher wear.

Simulation results for disc wear measured and disc wear modeled based on Archard, ASTM and neural network models are illustrated in Fig. 14.

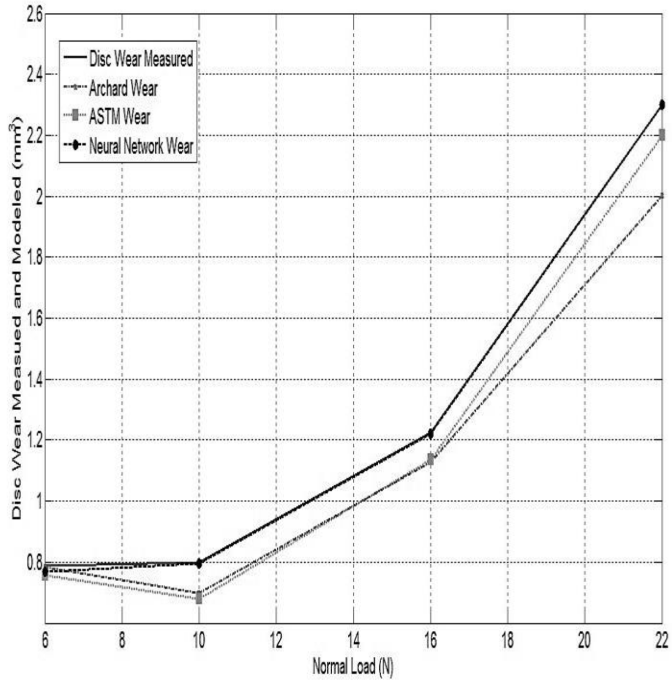


Fig. 14 Disc wear measured, Archard, ASTM, and Neural Network wear

Variations of disc wear with normal load are presented in Fig. 14; it shows the wear test results together with the wear results obtained from two models (Archard, ASTM, and Neural Network models). The normal load was changed such as 6N, 10N, 16N, and 22N; as a result, the disc wear increased with the increase of normal load. Therefore, the wear was influenced by the normal load; the wear is proportional to the normal load.

## V. Conclusion

Simulation results show that the pin/disc wear is proportional to the normal load; and the disc wear was bigger than the pin wear, because the disc is made of aluminium and the pin is made of steel, where the hardness of steel is greater than the hardness of aluminium, and the wear is decreased when the hardness is increased. The difference between the results of Archard model, ASTM model, and neural network model can be simply due to the components of the three models, where the Archard model depends on normal load, wear coefficient, sliding distance, and hardness of material; the ASTM model depend on pin wear scar diameter, pin radius, wear track radius, and wear track width; and neural network model depends on the training of network. We can consider the neural network model is an effective model which can be used for wear prediction and study of wear behaviour.

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