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PREDICTION OF THE WEAR RATES OF EPOXY-BASED NANOCOMPOSITES USING ARTIFICIAL NEURAL NETWORK APPROACH

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ABSTRACT

The present investigation aims to use the artificial neural networks (ANN) approach to develop models that could be used to predict the wear rates of epoxy-based nanocomposites. The epoxy matrix was reinforced with different volume fractions (vol.-%) of boron carbide (BC) nanoparticles having average sizes of 50 nm. The BC nanoparticles were dispersed into the epoxy matrix using mechanical stirring technique. The wear tests were conducting under dry sliding conditions and several sliding speeds and applied loads. The developed ANN model was successfully used to predict the influence of the sliding speed, load, and BC nanoparticles volume fraction on wear rates of the epoxy/BC nanocomposites. The mean relative absolute error (MARE) of the developed ANN model was 4.27%.

KEYWORDS: Metal matrix Nanocomposites, Epoxy, Artificial Neural Network, Wear rate.

توقع معدل بري المواد المركبة النانومترية ذات الأساس من مادة الابوكسى باستخدام الشبكات العصبية الاصطناعية

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الملخص

يهدف البحث الحالي إلى استخدام نهج الشبكات العصبية الاصطناعية (ANN) لتطوير نماذج يمكن استخدامها للتنبؤ بمعدلات تآكل للمؤتلفات النانومترية ذات الأساس من مادة الإيبوكسي. تم تدعيم الايبوكسي بحبيبات نانومتريه (حجم٪) من كربيد البورون (BC) بمتوسط حجم 50 نانومتر باستخدام تقنية التقليب الميكانيكي. أجريت اختبارات التآكل في ظروف انزلاق جاف وعدة سرعات انزلاق وأحمال مختلفة. تم استخدام نموذج ANN المطور بنجاح للتنبؤ بتأثير سرعة الانزلاق والحمل والنسبة الحجمية للحبيبات (BC) النانومترية على معدلات تآكل للمؤتلفات النانومترية. كان متوسط الخطأ النسبي المطلق (MARE) لنموذج ANN المطور 4.27٪.

الكلمات المفتاحية: الشبكات العصبية الاصطناعية, الايبوكسى, المواد المؤتلفة النانومترية, معدل التآكل.

1. INTRODUCTION

Epoxy and its composites broadly are used in a wide rage of applications such as floor coatings and fuselages of aircraft [1]. Epoxy and its composites have excellent mechanical, thermal, chemical characteristics. It is also compatible with several types of reinforcement materials [2]. These excellent characteristics allowed the epoxy, and its composites to be the choice for many high-performance engineering applications.

It has been reported that the prediction of the mechanical and tribological behavior of epoxy-based nanocomposites [3-6]. Based on this, several modelling techniques were developed to predict the such behaviors of the epoxy-based nanocomposites. One of these modelling approaches is the artificial neural network (ANN) which can be used to model complex behaviors. It uses learning algorithms that can independently adjust (or learn) as they receive new input. This makes the ANN a very effective tool for non-linear statistical data modeling [7,8].

Several investigators developed ANN models to predict the tribological behaviour of epoxy-based nanocomposites [9,10]. For example, Sabarinathan et al. [9] developed ANN for predicting the dry sliding wear behavior of epoxy resins reinforced with multi-wall carbon nanotubes (MWCNTs). The results revealed that specific wear rate was successfully computed through using ANN. The general regression neural network (GRNN) network showed that the mean relative error is <1% and prediction quality 99% and it is quite suitable tool for prediction of wear in composites. Yusuf and Fatih [10] prepared basalt fabric filled epoxy composites (BFRCs) mixed with nano-Al2O3 particles. They developed multiple regression analysis (MRA) model for predicting the dry wears and compared it with the ANN model. The results revealed that both MRA and ANN approach offered an effective technique for prediction of dry wear of the nanocomposites, however, the ANN model exhibited more accurate results when compared with the MRA model.

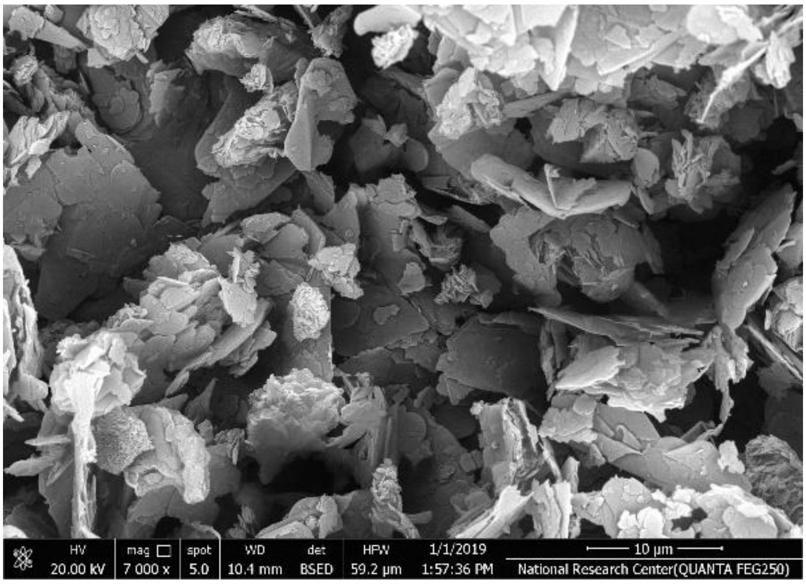
In the present investigation, an A`NN model was developed to predict the wear behaviour of epoxy resin reinforced with boron carbide (BC) nanoparticles. The prepared epoxy/BC nanocomposites have different volume fractions of BC nanoparticles up to 1 vol.-%. The wear tests were performed at dry sliding conditions using a pin-on-ring wear tester at different applied loads and sliding speeds.

2. EXPERIMENTAL PROCEDURES

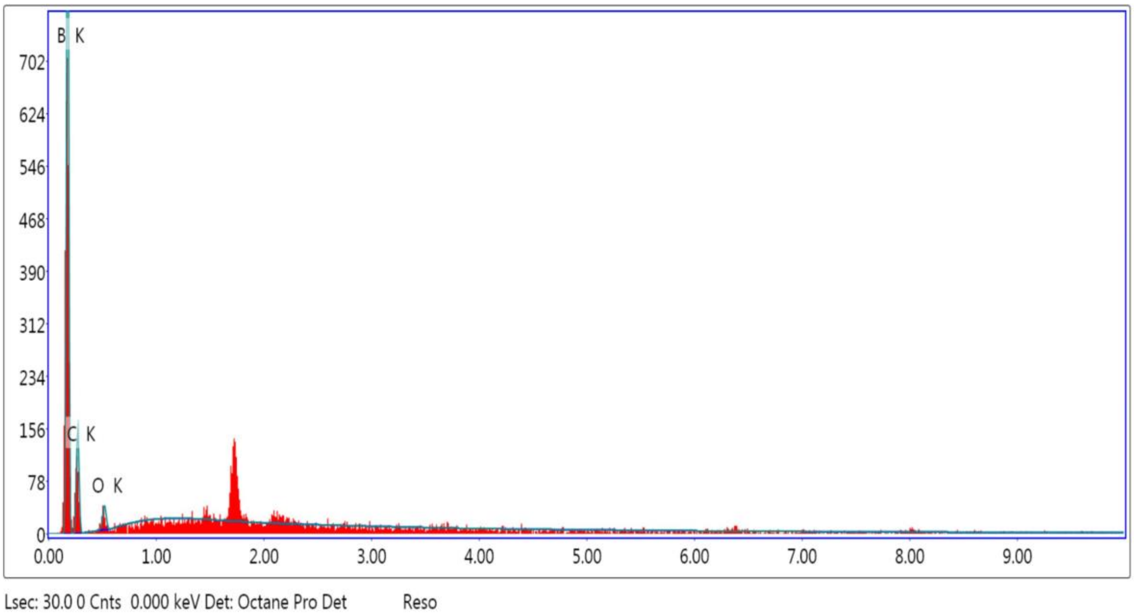
In the present investigation, the thermoset epoxy resins used as a matrix material. The BC nanoparticles have average size of 50 nm and were dispersed in the epoxy matrix with different volume fractions up to 1 vol.-%. Figure 1 shows scanning electron microscope (SEM) micrograph and energy dissipative x-ray (EDAX) analysis of the BC nanoparticles.

The epoxy-based nanocomposites were fabricated by using mechanical stirring technique as follows: first, the epoxy resin and the desired volume fraction of BC nanoparticles were mixed in plastic mold and stirred mechanically at about 200 rev/min for two minutes; then the hardener was added to the mixture (by the ratio 1:2 vol.-%) and stirred mechanically again for three minutes; finally, the epoxy/BC nanocomposites slurry was poured in a plastic cylindrical die having a diameter of 12 mm and allowed to fully harden at room temperature for 14 days.

Dry sliding wear tests were carried out using pin-on-ring machine. The counterface disc is made from heat treated H13 tool steel. The hardness of the counterface is about 55 HRC. The wear tests were performed under different sliding speeds of 0.5, 1 and 1.5 m/sec and different applied loads of 30, 50 and 70 N. The duration of the test was kept constant at 300 seconds. and it is controlled using a stopwatch. The wear rates were calculated by dividing the weight loss by the test duration. The weight loss was measured using a digital balance having an accuracy of 1×10-4 g. Before each test, the counterface disc is polished using SiC emery papers having fineness of 1000 grit.



(a)



(b)

Fig. 1: (a) SEM micrograph and (b) EDAX analysis of the BC nanoparticles.

3. ARTIFICIAL NEURAL NETWORK

In present investigation, Statistica commercial statistical package with ANN modelling capability was used for the construction of the ANN models. Several ANN models were constructed and examined to determine the best possible network architecture, activation function, and training algorithm. The mean absolute relative error (MARE) was used for comparison and selection of the trained ANN models.

The general structure of the ANN model is shown in Fig. 2. The ANN model has three layers, namely, (1) input layer, (2) hidden layer and (3) output layer. The input layer has three nodes, representing the BC vol.-%, sliding speed and the applied load. While the output layer has one node representing the wear rate of the epoxy/BC nanocomposites. The data entered to the model was collected based on the experimental work carried out in the present investigation.

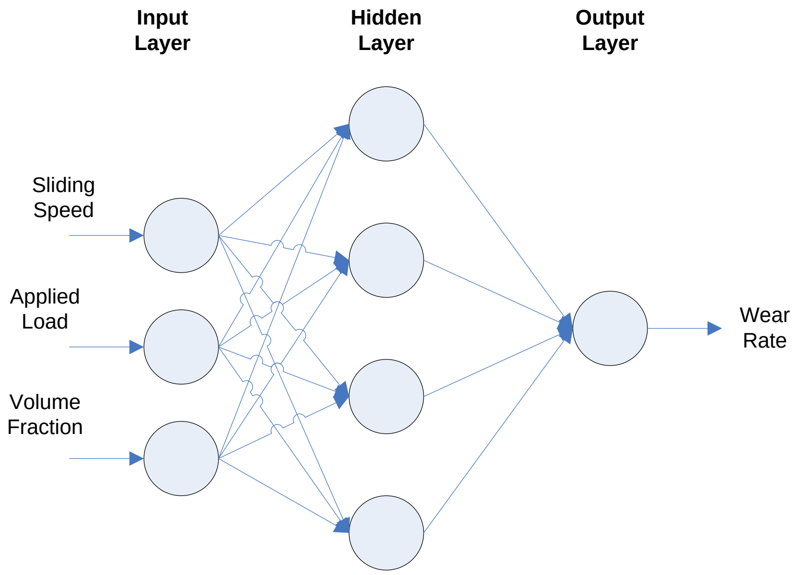


Fig. 2: The ANN structure.

4. RESULTS AND DISCUSSION

Table 1 lists the experimental as well as the predicted wear rates of the epoxy/BC nanocomposites obtained at different conditions of applied loads, sliding speed and volume fractions of the BC nanoparticles. The best neural network was found to be a multi-layer perceptron (MLP) network having a single hidden layer that consists of 10 neurons. Consequently, the ANN model having the structure of 3-10-1 was the most suitable model for predicting the wear rate of epoxy/BC nanocomposites. The model exhibited the lowest MARE of 4.27%. A comparison between the predicted (output) and experimental (target) wear rates of epoxy/BC nanocomposites resulted from the generated ANN model is shown in Fig. 3. An ideal prediction of the model is occurred when all the data points are located on the 45o line shown in Fig. 3. The accuracy of the ANN model is easily assessed by the proximity of the wear rate data points to this line. The results revealed that the predicted and experimental wear rates generated from the ANN model are close to each other.

Figure 4 shows the error graph of the predicted wear rates, by each case, relative to the experimental wear rates. The maximum error obtained from the model was about 17.36%. The regression coefficient (R) was about 0.9825 which is close to 1, representing a robust correlation between the experimental and the predicted outputs.

Figure 5 shows 3-D surfaces for the predicted wear rates, for the epoxy/BC nanocomposites as a function of sliding speed and load as well as the BC nanoparticles vol.-%, with experimental wear rates (represented by small circles). The results revealed that wear rate of the epoxy/BC nanocomposites increased with increasing the loads and the sliding speed but reduced with increasing the BC vol.-%. The increase of the wear rates of polymer-based nanocomposites with increasing the applied load and the sliding as well as the reduction of the wear rates due to the increase of the amount of nanofillers were reported by many workers [11-15]. The increase of the vol.-% of the hard BC nanoparticles increases the load carrying capacity of the nanocomposite surfaces due to the reduction of the spaces between BC nanoparticles. Increasing the sliding speed and/or the applied load tend(s) to break the interfaces between the nanoparticles and the matrix material which leads to the increase of the wear rates. Moreover, nanoparticles can easily detach from the specimen and act as abrasive particles which also increases the wear rates of the nanocomposites.

Table 1: The experimental and the predicted wear rates of the epoxy/BC nanocomposites.

Exp. #	BC Vol.-%	Applied Load (N)	Sliding Speed (m/s)	Wear Rate (Target) (g/sec.)	Wear Rate (Predicted) (g/sec.)
1	0.000000	30.00000	0.500000	0.000331	0.000349
2	0.000000	50.00000	0.500000	0.000645	0.000616
3	0.000000	70.00000	0.500000	0.000825	0.000842
4	0.000000	30.00000	1.000000	0.000533	0.000521
5	0.000000	50.00000	1.000000	0.000782	0.000803
6	0.000000	70.00000	1.000000	0.000984	0.000949
7	0.000000	30.00000	1.500000	0.000753	0.000764
8	0.000000	50.00000	1.500000	0.000972	0.000960
9	0.000000	70.00000	1.500000	0.000996	0.000981
10	0.500000	30.00000	0.500000	0.000210	0.000225
11	0.500000	50.00000	0.500000	0.000408	0.000387
12	0.500000	70.00000	0.500000	0.000522	0.000577
13	0.500000	30.00000	1.000000	0.000337	0.000315
14	0.500000	50.00000	1.000000	0.000495	0.000524
15	0.500000	70.00000	1.000000	0.000623	0.000633
16	0.500000	30.00000	1.500000	0.000476	0.000461
17	0.500000	50.00000	1.500000	0.000615	0.000592
18	0.500000	70.00000	1.500000	0.000630	0.000620
19	1.000000	30.00000	0.500000	0.000167	0.000196
20	1.000000	50.00000	0.500000	0.000326	0.000296
21	1.000000	70.00000	0.500000	0.000416	0.000419
22	1.000000	30.00000	1.000000	0.000269	0.000253
23	1.000000	50.00000	1.000000	0.000395	0.000397
24	1.000000	70.00000	1.000000	0.000497	0.000460
25	1.000000	30.00000	1.500000	0.000380	0.000378
26	1.000000	50.00000	1.500000	0.000491	0.000497
27	1.000000	70.00000	1.500000	0.000503	0.000491

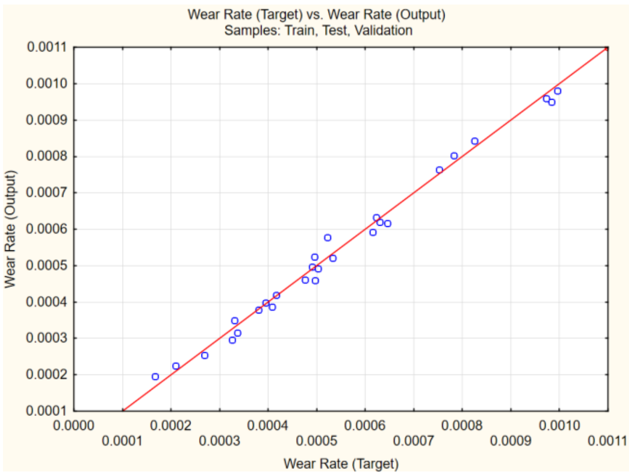


Fig. 3: Experimental versus predicted wear rates developed from the ANN model.

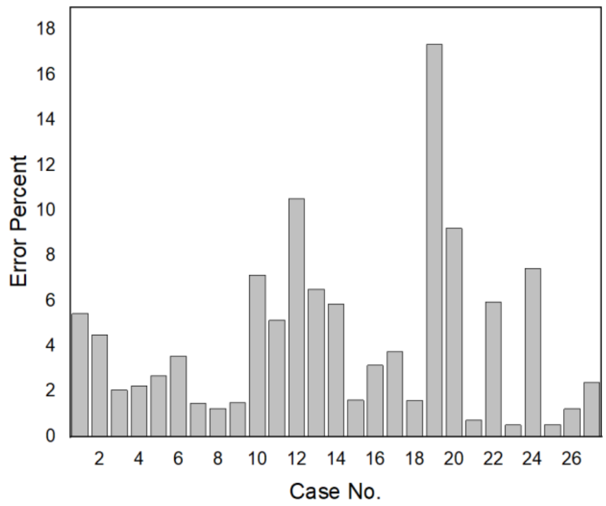


Fig. 4: The error graph of the predicted wear rates developed from the ANN model.

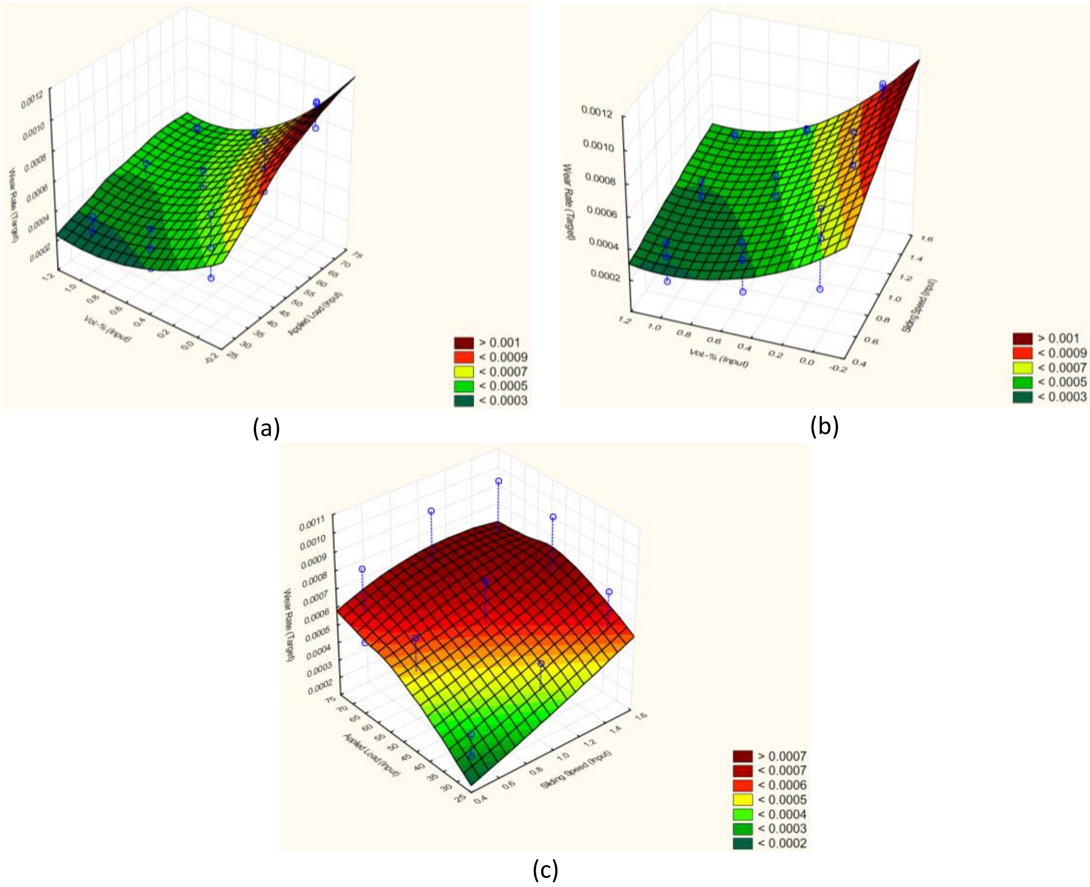


Fig. 5: Variation of wear rates with the (a) BC vol.-% and load, (b) BC vol.-% and sliding speed, and (c) load and sliding speed.

Figure 6 shows the relative sensitivity of wear test variables resulting from the developed ANN modelling. This analysis determines the influence of varying of a particular variable from its lowest to their highest values on the resulting ANN output (i.e., wear rate) when compared with the other factors. The results revealed that the BC nanoparticles vol.-% exhibited the highest relative sensitivity of 58.16.

This indicates that any variation in vol.-% of the BC nanoparticles vol.-% will exhibit a significant influence on the wear rates than that resulting from varying the levels of the sliding speed and the load. The applied load and the sliding speed exhibited lower relative sensitivities than the volume fraction of about 33.47 and 20.85, respectively.

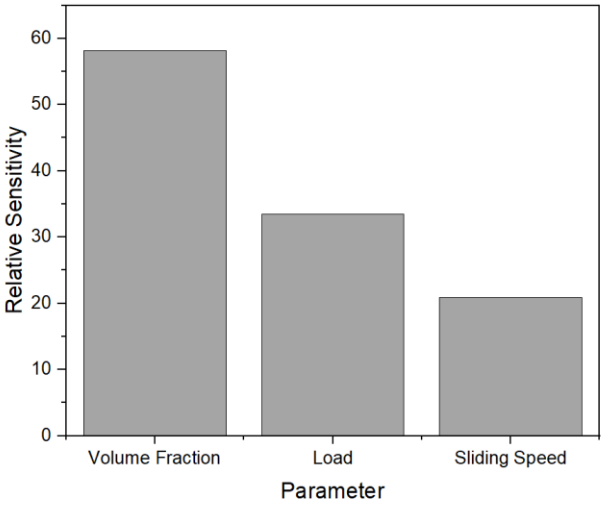


Fig. 6: Relative sensitivity values of the wear test parameters.

The ANN model constructed in the present work could be significantly beneficial especially from the viewpoint of the nanocomposites design. The ANN model might be used to predict the effect of the wear test variables, typically, the load and the sliding speed, along with the material variables, typically, the BC nanoparticles vol.-%, on the wear rates epoxy/BC nanocomposites. It is important to point out that the constructed ANN model might be used to predict the wear rates of epoxy/BC nanocomposites with an acceptable accuracy only in the range of experimental tests. The constructed ANN model cannot be used efficiently to predict the extrapolated wear rates accurately.

CONCLUSIONS

Based on the stated results, the following conclusions can be represented:

1) An artificial neural network (ANN) model was successfully developed to predict the wear rates of epoxy/BC nanocomposites under dry sliding conditions. The predicted wear rates developed from the ANN model showed good agreement with experimental wear rates. The mean relative absolute error (MARE) of the developed ANN model was 4.27%.
2) Significant savings in terms of cost and time can be achieved when using ANN modelling. It is a mathematical tool that can be used to predict the wear rates of nanocomposites successfully.
3) The sensitivity analysis showed that the volume fraction of the BC nanoparticles exhibited the highest influence on the wear rate of epoxy/BC nanocomposites followed by the applied load and sliding distance, respectively.

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