Investigations of Microstructures and Tribological Behavior of $AA7075/Al_2O_3$ Particulate Composite as a Function of Volume Fraction by Applying Artificial Neural Network

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Abstract - *The present research aims at investigating the Tribological parameters of AA 7075/ Al2O3 particulate composite by experimental and artificial neural network (ANN) techniques. AA 7075/ Al2O3 composite with (0-20 vol %) of Alumina (Al2O3) were fabricated by stir casting process. Microstructure analysis was carried out by optical micrograph, SEM, XRD and EDS analysis. Density and hardness of the developed composites are measured experimentally. 270 wear tests on Pin on disc wear testing machine were carried out as per ASTM G99 standards at various loads and speed. Wear behavior of composite are investigated by calculating wear rate and coefficient of friction at all the load and speed conditions for all the developed composites. 13 Input parameters are considered in the input layer of ANN model out of which 10 parameters are obtained from experiments and 3 parameter was estimated by empirical relations. The output of ANN was consisting of eight parameter related to wear behavior. ANN containing Levenberg Marquardt (LM) and Bayesian Regularizations (BR) algorithm with 10 hidden neurons in single hidden layer configuration was modeled. Results of the microstructure analysis indicates good dispersion of Al2O3 particles, Strong bond strength, lower interface products and improved grain refinements in the composite. Density and Hardness was found to increases with increase in volume fraction of Al2O3. Wear rate and coefficient of friction of the composite reduces with increase in volume fraction of Al2O3. Levenberg Marquardt algorithm with 10 hidden neuron gave good prediction of wear properties with Mean Square Error of 2.8253e-6 at 49 epoch for wear rate and 0.002046 at 25 epoch for coefficient of friction. The regression value R as 0.9978 for wear rate and 0.9997 for coefficient of friction as compared to Bayesian Regularization algorithm. Developed model can be used for prediction of wear behavior to reduce the cost and time involved in experimental work.*

Key Words: Wear Rate, AA 7075, Artificial Neural Network, Levenberg Marquardt, Particulate composites.

1. INTRODUCTION

Particulate composites are research topics in the domain of commercialization and mass production for automobile related applications. AA 7075 aluminum alloy is high strength alloy among all the aluminium alloy series and good response to heat treatment [1]. The reinforcement alumina (Al2O3) possesses high hardness and is a low cost ceramic material easily available, stable with aluminum [2] [3]. Particulate composites are developed for increases in strength, wear resistance, isotropic properties and lower cost. The Aluminum bases composites are attractive for automobile applications due to light weight and fuel efficient [4]. The cost of particulate composite is lower, suitable for production in large quantities and good response to secondary process [5]. Particulate composites with various reinforcements are developed by stir casting process to achieve uniform distribution of particles [6]. Due to various strengthening mechanisms during solidification both hardness and strength of the composite increases [7]. Apart from mechanical properties the wear behaviour also found to improve in composites. Wear is a common cause in all the interacting surfaces which reduces the life of the parts. Wear accounts for 1% to 4% of gross national products of developed countries [8]. More than 100 parameters are estimated to affect the wear behaviour of composite materials [9]. This indicates the nonlinear nature of the wear behaviour of composite materials which has to be studied over wide range of speeds, loads and volume fractions apart from the material properties, manufacturing route, secondary process etc. Artificial neural network is good prediction tool, fast processing, learning and adaptive system as compared to other statistical models for the estimation of wear behaviour [10]. The selection of number of hidden layer, transfer function, number of neurons, training algorithms and input parameters will influence the prediction capability of ANN [10]. ANN developed with Levenberg Marquardt Algorithm was found to have good prediction capability for wear and mechanical properties. In the present work AA 7075/Al2O3 composite was developed by stir casting process and wear behavior was investigated by pin on disc wear test and prediction of wear rate was carried out by Artificial neural network Model.

2. MATERIALS AND EXPERIMENTAL METHODS

The material used in the development of composite material is high strength AA 7075 T6 as matrix and

Alumina (Al_2O_3) supplied by Carborandum Universal as the reinforcement. The presence of Zn at more than 5.6 % and Mg 2.1% forming $MgZn_2$ having monoclinic structure improves the strength of the alloy [1]. Alumina available in particulate form at 50 microns to 150 microns are selected for the composite.The reinforcements in the volume fractions of 5%, 10%, 1% and 20% are used. Stir casting furnace with bottom pouring arrangement was used for the fabrication of the composite material. The melting temperature of 700°C and reinforcement pre heating temperature of 450°C was used. The AA 7075 alloy was melted in the furnace and pre heated Al_2O_3 was added in to the molten metal with stirring speed of 400rpm of stirrer. The stirring was carried out for 10 minutes and the mixture was poured in to metal mould by bottom tapping arrangements.

Microstructural analysis was carried out by optical microscope (METZER 100) for determining grain structure, particle distribution and grain boundary segregations. Polished and etched specimens are prepared for the optical micrographs. The particle composition and interface reactions are analyzed by XRD and EDS analysis. The secondary phases, interface products, particle compositions are studied by XRD spectrum. Density was determined by Archimedes principle and hardness was found by Vicker's Hardness test (FIE Make).

Pin on Disc wear test was carried out by wear testing machine (Ducom TR-20) as per ASTM G99 standards on all the composites. Dry sliding Wear test are carried out at various disc speeds and applied loads. The duration of the test was fixed at 10 minutes and test conducted in dry sliding condition at room temperature. The wear was found in terms of weight loss of the composite pin with electronic balance of 0.1mg accuracy. The specimen was weighed before and after the test and the weight loss is converted to volume loss by dividing with density. The wear rate, wear coefficient are calculated by Archards wear equations. A total of 270 wear test at loads of 1kg to 16 kg and speed of 200 rpm to 1200 rpm are carried out.

3. ARTIFICIAL NEURAL NETWORK MODELING AND PREDICTIONS

Simulation of Tribological process and prediction of wear rate are carried out with different numerical approach like FEM analysis, Statistical methods, Taguchi methods, genetic algorithms, Artificial Neural Network etc. the most comprehensive tool for prediction with best accuracy is the Artificial Neural Network Tool. ANN resembles the biological neurons which are trained by past experience and input data [10]. The architecture of ANN is shown in figure 1 which has input layer through input data is provided and the weight adjustments and computations occurs in the hidden layer. In this layer the neurons are connected with input as well output layers. The hidden layer may be single layer or multiple layers with different set of neurons.

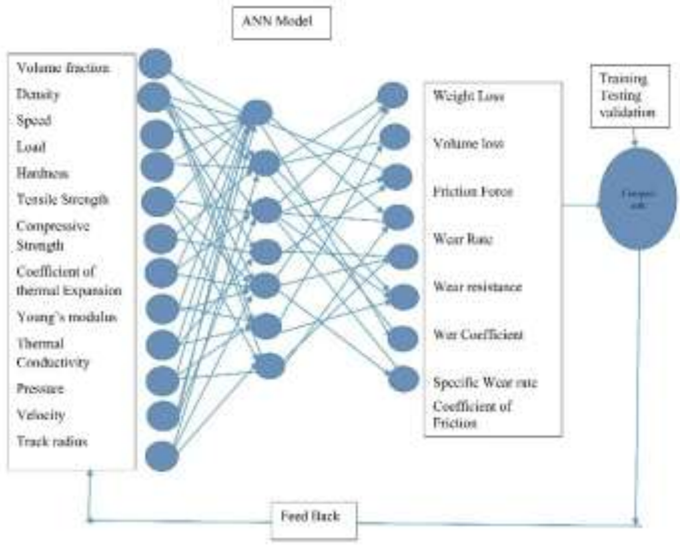


Fig -1: Structure of Artificial Neural Network

In the present work ANN model was developed by considering feed forward back propagation algorithm with single hidden layer. Two types of algorithms are considered are Levenberg Marquardt and Bayesian Regularization algorithm. 13 input parameters are used in input and eight output of wear behavior are determined by ANN. Table 1 shows the input and output parameters of ANN.

Table -1: Input and Output parameters of ANN

Sl No	Input Parameters	Output Results
1	Speed	Weight Loss
2	Load	Volume Loss
3	Sliding Distance	Wear rate
4	Pressure	Specific wear rate
5	Density	Wear resistance
6	Track radius	Wear coefficient
7	Hardness	Coefficient of friction
8	Tensile stress	Friction force
9	Compressive stress	
10	Young's modulus	
11	CTE	
12	Thermal Conductivity	
13	Elongation	

10 neurons are used for both the algorithms and the training, testing and validations of the developed ANN was carried out by MATLAB 2015. The trials are carried out with number of iterations till the lower MSE value are obtained. The training was carried out with 80% of the total available data and 20% for the testing and validation.

The LM are used in ANN for faster convergence and suitable for Back propagation networks. The training of ANN was continued till its Mean Square Error value is minimum and the Training of ANN with BR algorithms are carried for minimum Mean Square Error. After training and optimizing the ANN prediction of wear rate and coefficient of friction was carried out for AA7075 alloy, 5 vol %, 10vol %, 15% vol, 20 vol % and 25 vol % Al2O3 composite at 1kg to 25 kg load, 100 rpm to 1400 rpm speed. The results of ANN are compared with Experimental results.3D plots of wear rate and coefficient of friction are plotted against load and speed for ANN predicted results.

4. RESULTS AND DISCUSSIONS

Stir casting process used for the development of composite material was successful. The stir casting process has improved the distribution of the Al2O3 particle in the matrix as compared to conventional castings. The particles size used for the composite is in the range of 50µm to 150 µm dose not form agglomeration in the castings. Melting temperature of the AA7075 was kept at 700°C makes it viscous enough such that the Al2O3 particles will neither be sink to the bottom and nor float over the melt surface. The stirring speed at 400 rpm and the stirrer position at the middle of the melt height provides uniform spreading of the Al2O3 particles in the 3D space of the crucible. The bottom pouring techniques will allow the particles to be in the distributed position with providing no time for the agglomeration during the process of pouring. The melting temperature, particle pre heating and use of metal moulds develops high quality castings.

Optical microstructures of the composites are shown in figure2 at 50X and 200X magnifications. The primary requirements of any particulate composites are uniform dispersion of the reinforcement. In the figure 2 it is observed that at all volume fractions uniform dispersion can be observed and the inter particle distances are fairly uniform. The size of the Al2O3 selected has influenced the distribution to be uniform. The dark irregular shape indicates the Al2O3 particles and the matrix material at the background. Figure 3 shows the grain refinement in the composite due to addition of the reinforcement. The grain size reduceses with increases in volume fraction of the reinforcement. The metal mould used for the casing facilitates rapid cooling of the melt which aids grain refinement of the composite. The SEM micrograph of all the composite and alloy is shown in figure 4 a to 4 e indicating the regions of reinforcement particles and secondary phases.

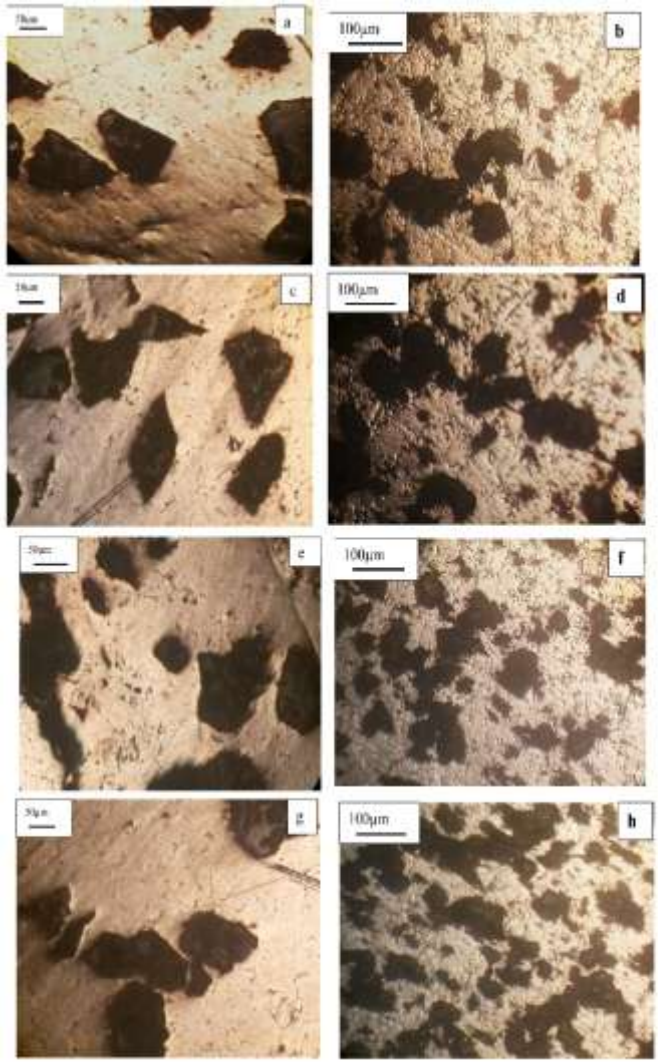


Fig -2: optical microstructure of composite: (a) AA 7075/ Al2O3 5vol% at 200x, (b) AA 7075/ Al2O3 5vol% at 50x, (c) AA 7075/ Al2O3 10vol% at 200x, (d) AA 7075/ Al2O3 10vol% at 50x, (e) AA 7075/ Al2O3 15vol% at 200x, (f) AA 7075/ Al2O3 15vol% at 50x, (g) AA 7075/ Al2O3 20vol% at 200x, (h) AA 7075/ Al2O3 20vol% at 50x.

Secondary phases consisting of $MgZn_2$ are identified in the grain boundary of all the composite which improves the strength. The EDS spectrum of the figure 4f gives the elemental composition of the composite containing Mg, Zn and Si as the elements in AA 7075 alloy. The XRD analysis shown in figure4g indicates the secondary phase composition and the interface reactions product Spinel ($MgAl_2O_4$). The spinal identified in the composite is the reaction product of aluminum with Al_2O_3 at high temperature which reduces the strength of the composite. The spinel formed is at lower percentage which indicates reduction in interface reactions. The XRD spectrum also indicates the Mg_4Zn_7, a secondary phase on the alloy AA7075 which has monoclinic structure which increases the strength

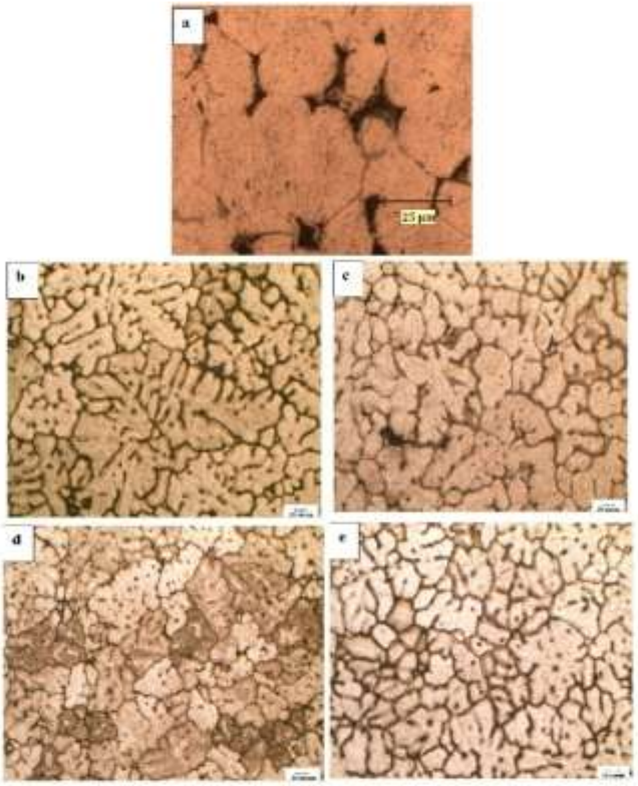


Fig-3: optical microstructure of composite indicating grain size: (a) AA 7075 alloy, (b) AA 7075/ Al_2O_3 5vol% at 200x, (c) AA 7075/ Al_2O_3 10vol% at 200x, (d) AA 7075/ Al_2O_3 15vol% at 200x, (e) AA 7075/ Al_2O_3 20vol% at 200x.

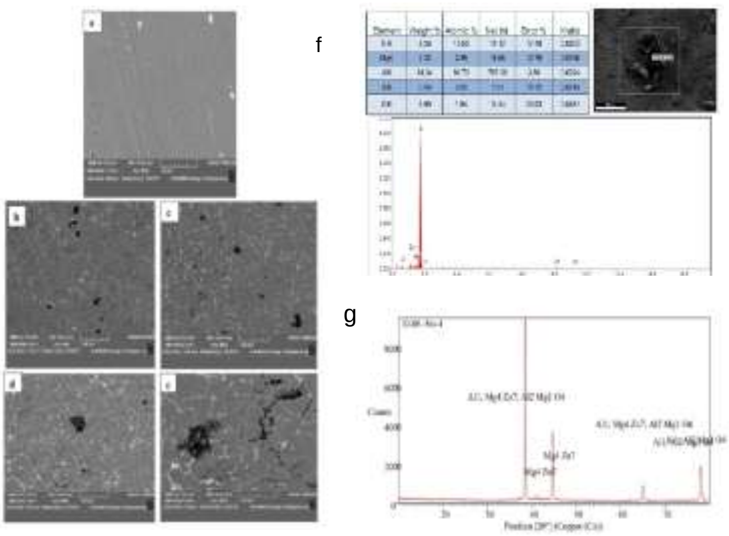


Fig -4: SEM images of composites: (a) AA 7075 alloy at 10.0Kx , (b) AA 7075/ Al2O3 5vol% at 10.0Kx, (c) AA 7075/ Al2O3 10vol% at 10.0Kx, (d) AA 7075/ Al2O3 15vol% at 10.0Kx, (e) AA 7075/ Al2O3 20vol% at 10.0Kx, (f) EDS Spectrum for AA 7075/ Al2O3 20vol% at 10.0Kx (g) XRD Spectrum AA 7075/Al2O3 20vol% at 10.0Kx.

The developed composite indicates the density values of 2.73g/cm3 for 5 vol % and 2.93 g/cm3 for 20 vol % of reinforcement. The light weight required for automobile applications are achieved due to lower density as compared to steel material. The increases in hardness of the composite is due to presence of hard particles which resists the deformation with increases in volume fraction. Due the presence of Al2O3 grain refinement occurs and it strengthens the composite. The restriction to the movement of dislocations in the composite makes the composite harder and increases the hardness.

To improve the life of interacting parts it is necessary to enhance the wear resistance at various load and speed. Pin on disc test which simulate the behavior of the interacting parts are studied and the wear rate, wear coefficient are calculated. The wear rate reduces with increases in reinforcement volume fraction as harder particles will be in contact with the counter body. The mechanisms of wear changes with speed and load. The wear rate also increases with increases in speed and load. The unreinforced AA7075 alloy was reported with high wear rate compared to composite materials. The wear mechanisms noticed in unreinforced AA7075 alloy was oxidative wear at lower load and speed referred as mild wear. Adhesive wear at medium load and speed refereed as severe and delamination with metal adhesion at high speed and load termed as seizure wear. In case of composite material with Al2O3 at different volume fraction mild wear region was noticed at lower load and speed in addition to above mentioned three wear regions. The coefficient of friction reduces with increases in volume fraction of reinforcements and also with increases in load.

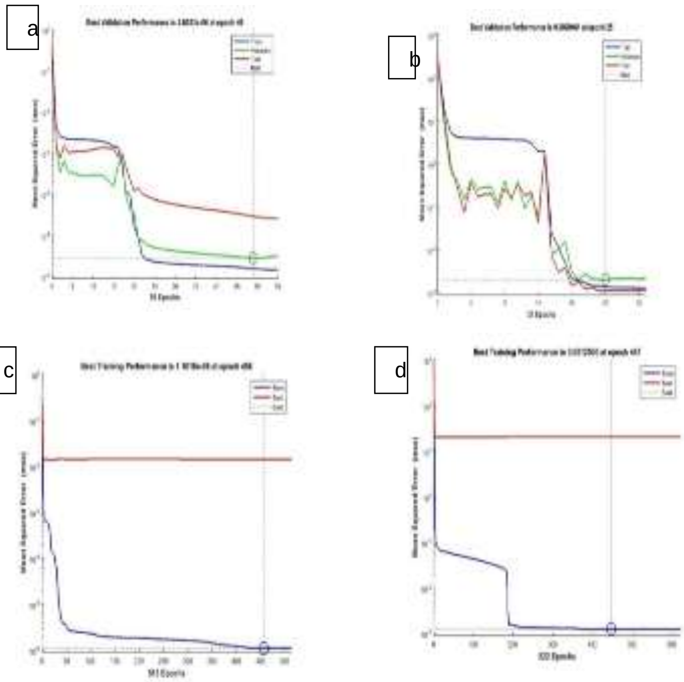


Chart -1: Mean Square Error Plots of ANN training: (a) Levenberg Marquardt algorithm for wear rate, (b) Levenberg Marquardt algorithm for Coefficient of friction, (c) Bayesian Regularization algorithm for wear rate, (d) Bayesian Regularization algorithm for Coefficient of friction wear rate.

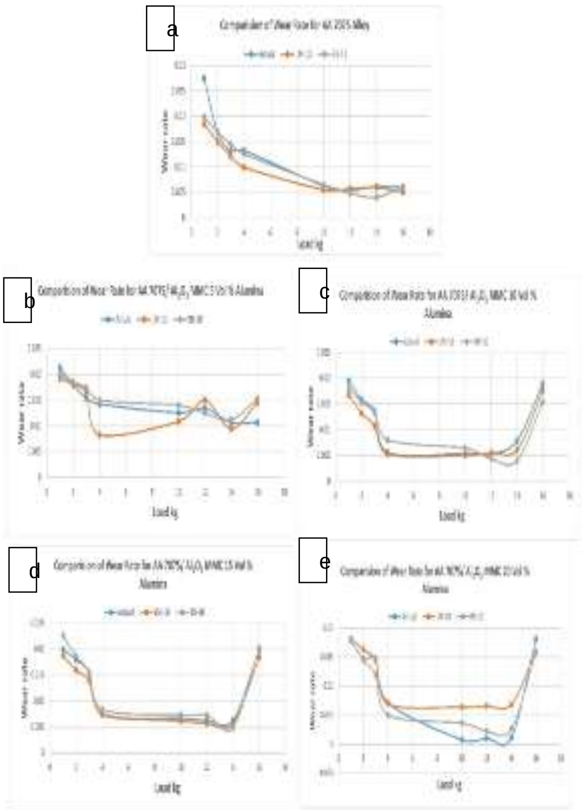
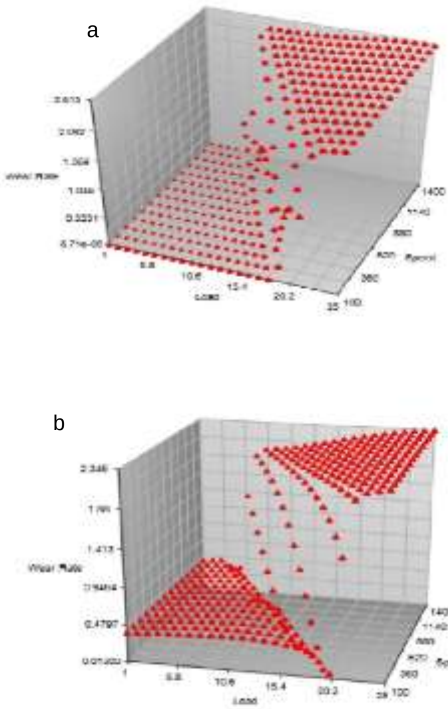


Chart-2: comparison of Experimental and ANN predictions of wear rate: (a) AA 7075 alloy, (b) AA 7075/ Al2O3 5vol%, (c) AA 7075/ Al2O3 10vol%, (d) AA 7075/ Al2O3 15vol%, (e) AA 7075/ Al2O3 20vol%.



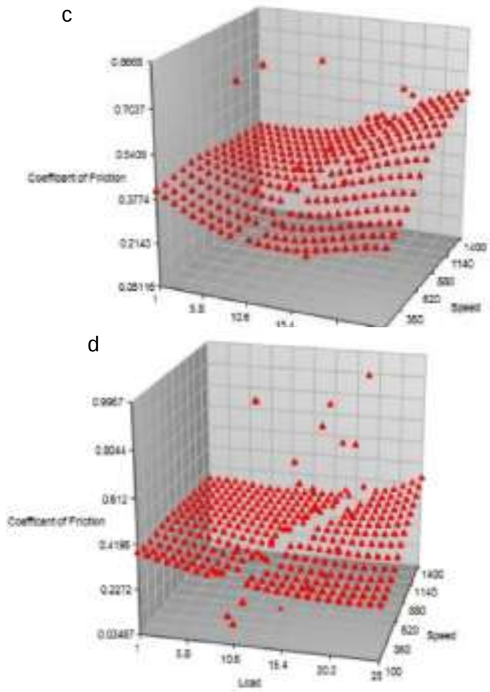


Fig -5: ANN predictions of Tribological parameters: (a) wear rate for AA7075 (b) wear rate for AA7075/Al2O3 with 25 vol %,, (c) Coefficient of friction for AA7075 Alloy,(d) Coefficient of friction for AA7075/Al2O3 with 25 vol %

CONCLUSIONS

Particulate composite material with Al2O3 as reinforcement and AA7075 aluminum alloy as matrix material was developed by stir casting process Microstructure and SEM analysis indicate uniform distribution of reinforcement. The increases in Hardness were found to be 30% compared to AA7075 alloy. Hardness increases with high interface bond strength and grain refinement.

Wear test carried out on the composite indicates improved wear behavior as compared to AA 7075 alloy. The presence of Al2O3 particles resists the wear of composite at the surface of interaction at higher load and speed. The coefficient of friction marginally decreases with increases in load and speed for composites.

ANN model developed with LM algorithm has better prediction capability of wear rate and coefficient of friction for the composite as compared to BR algorithm. The developed ANN can be extended to any combination of speed and load for prediction of wear behavior of composite and also can be extended to higher volume fraction of reinforcement. The developed ANN model reduces the time and cost involved in experimental work and predicts reliable results of wear behavior.

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BIOGRAPHIES

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