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Predictive Modelling of the Effect of H_3BO_3 (nm) and TiO_2 (µm) Mixture on Minimum Quantity Lubrication Machining of the EN24 Steel

Penta Shreenivasa Rao[1*], Parvataneni Venkata Jagan Mohan Rao[2] and Ravi Kant Avvari[3]

[1]Department of Mechanical Engineering, Raghu Institute of Technology, Visakhapatnam, India– 531162
[2]Department of Marine Engineering, College of Engineering, Andhra University (A), Visakhapatnam, India– 530003
[3]Department of Electrical and Electronics Engineering, Sasi Institute of Technology and Engineering, Tadepalligudem, India – 534101
[2]pshreenivasarao@gmail.com, [3]ravikant0123@gmail.com

Abstract

In manufacturing industries, the metal removal is one of the processes where efficiency is determined by the cutting forces and temperature. Lubrication is a strategy adopted to reduce the cutting forces and temperature in order to improve the surface finish, while increasing the cutting tool's life span. In the present work, the influence of nano sized solid lubricant (boric acid) with micro sized titanium dioxide particles in the turn machining of EN24 steel using tungsten carbide tool inserts is investigated. Measurements of the cutting forces, tool temperatures and surface roughness were performed and a predictive model was developed using neural network technique. Experiments show that the H3BO3-TiO2 combination has a dramatic effect in improving the machining performance. They help reduce the forces and the temperature to increase the tool life. The prediction (using ANN model) of cutting forces, tool temperatures and surface roughness align well with the experimental results for all test cases; error less than 5%. Suggesting that the model can be used for estimation the machining parameters thus facilitating the research work and reducing the lead time involved in the study.

***Keywords**: Turn machining, SAE-40 oil, Boric acid, Titanium dioxide, Minimum Quantity Lubrication (MQL), Artificial Neural Network (ANN)*

1. Introduction

In Minimum Quantity Lubrication (MQL) a flow rate of 50-500ml/ hour is used which is lower in comparison to those used in a flood cooling condition. This offers numerous advantages are as the MQL improves surface finish, improves tool life and decreases the temperature. Boric acid (H3BO3) is an effective solid lubricant which can have very low friction coefficient (~0.02) under dry-sliding conditions in open air. This solid can be used to lubricate sliding surfaces in a variety of ways. One of the approaches is to sprinkle fine powders of H3BO3 on a sliding surface. Alternative options could be – usage of thin solid films of H3BO3 formed on surfaces to be lubricated, or fine powders of H3BO3 can be mixed with metal, ceramic, or polymer matrices to achieve self-lubricating composites. Studies over the years have demonstrated that regardless of the form used, H3BO3-based solid lubricant films can afford low friction coefficients and high-wear resistance to sliding contact interfaces of metallic, ceramic. The unique property of the H3BO3 is the self-lubricating action that is attributed to its unique and layered crystalline structure. It provides lubrication activity by an interlayer shear mechanism. When applied or present

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on a sliding surface the crystalline layers of H3BO3 align themselves in parallel and along the direction of motion. In addition they can also slide over one another to provide lubrication. In some of experiments [1, 2], the application of boric acid powder was performed via aerosolization in jet of nitrogen gas in a rotating pin-on-disc tribometer. Friction coefficients were measured to be less than $\mu = 0.1$ and continued to persist as long as the flow continued. Wear rates were found reduced by two orders of magnitude. Drawing and stretching test suggest that the lubrication ability of the boric acid film is comparable to those of commercial solid and liquid lubricants and continue to sustain for a varied speeds [3]. Effectiveness of boric acid for operations – rolling, forging, and sheet metal drawing and stretching has been validated with ferrous and non-ferrous material [4]. It has been reported that the boric acid offers lowest friction during sheet drawing and stretching operation, a property of the boric acid due to its lattice layered structure facilitating sliding between the molecular layers. Pin-on-disk experiments indicate relative performance for set of lubricant combinations in a commercial brake valve assembly [5]. The reports also indicate that the environmental friendly lubricant, however, was inefficient in reducing the wear. Based on the experimental investigations, it is suggestive of using a combined lubricant comprising of boric acid and titanium dioxide with SAE40 oil to form a natural lubricant. Such, combination resulted in the best wear performance against the conventional lubricants, and signifying potential advantage for for use in manufacturing with a commercially viable and that is eco-friendly [6]. The layered crystal structure of the boric acid particles allows the sliding over each other even in combination to reduce the friction [7]. Boric acid as nanoparticles of size of 538, 80, 60, 50nm has been used as a solid lubricant for machining of the hardened steel. Boric acid with 50 nm particle size has been reported to be effective in reducing the cutting forces, tool temperatures and surface roughness [8]. Machining performance of SAE 40 oil containing different weight proportions of Titanium dioxide and boric acid were also investigated in turn machining [9]. Numerous papers have been reported suggesting that the addition of nanoparticles to lubricant is effective in reducing the wear and friction, thus improving the tool life expectancy. The lubrication ability depends on the nature of nanoparticles used, such as size, shape, and concentration. Oil mixed with a combination of micro and sub-micron boric acid powder show better lubrication ability than mixed with micro or sub-micron boric acid additive alone [13]. Therefore, we adopted boric acid particles as a solid lubricant for the lubrication study during turn machining.

2. Experimental Setup

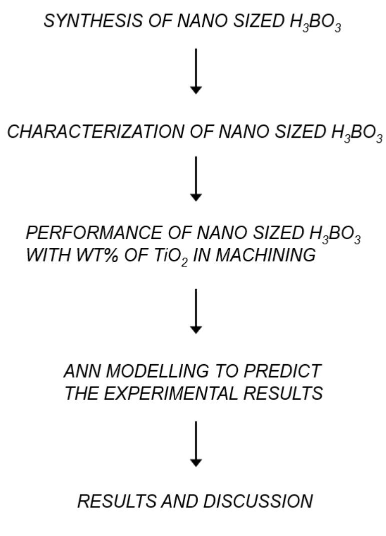


Figure 1. Methodology

High energy ball mill is used to reduce the size of micro sized H_3BO_3 powder in to Nano sized H_3BO_3 powder by using X.R.D. Machining experiments were conducted to verify the performance of Nano-sized H_3BO_3 particles with different weight percentages of TiO_2 (µm) subdivision suspensions in SAE40 oil. Measurements were made for the forces, tool temperature and surface roughness (Figure 1).

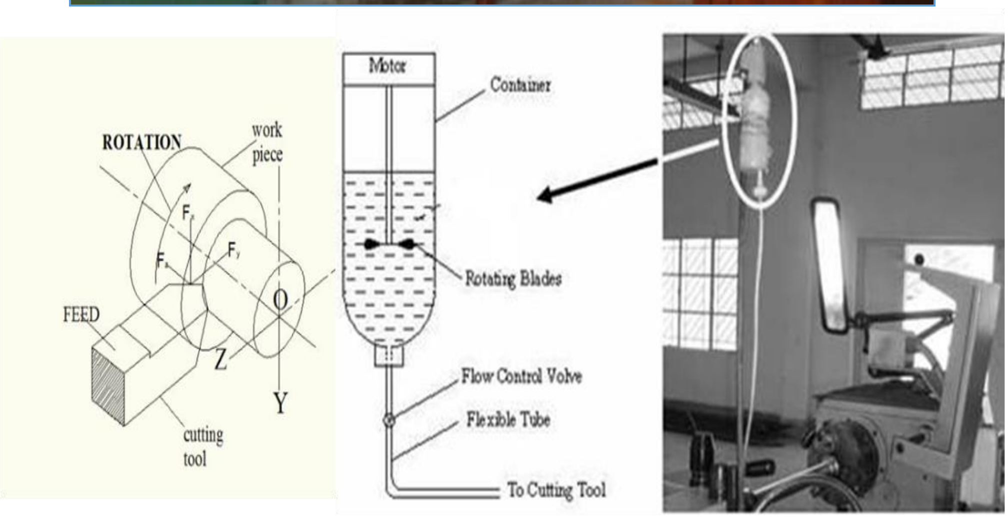


Figure 2. Experimental Setup Showing Flow Regulation System and the Location with Reference to the Lathe

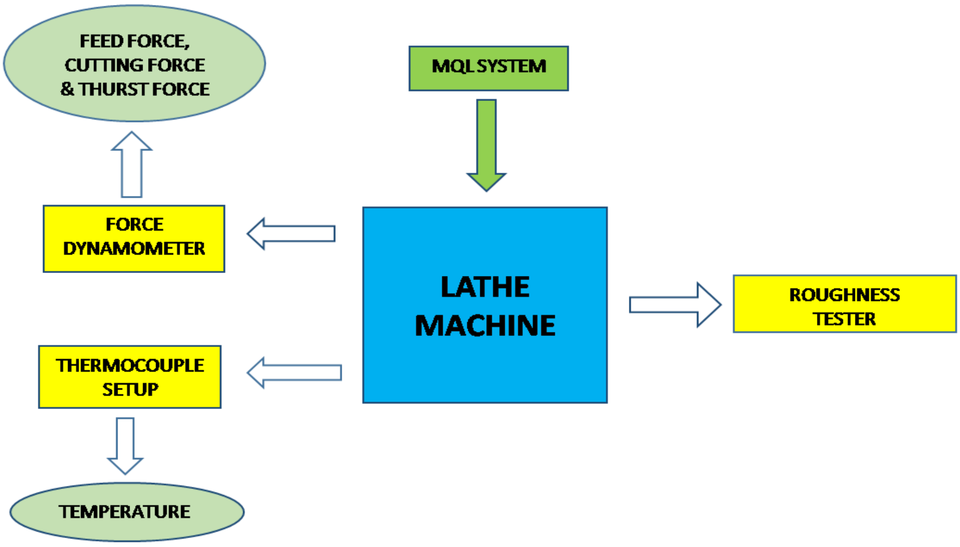


Figure 3. Block Diagram of the Experimental Setup

Experimental setup for the turning process using MQL containing H3BO3 and TiO2 particles, where a) Cutting tool and workpiece indicating the feed, thrust, and cutting forces, b) Turning process, c) Setup comprising of the container (MQL solution at atmospheric pressure) in the left panel and its placement shown in the right panel (Figure 2). The block diagram of the experimental setup is included where the force dynamometer for force measurement, thermocouple system for temperature and roughness tester for roughness measurement was made (Figure 3).

For the development of predictive model, we adopted the artificial neural network (ANN) for prediction of output parameters such as the cutting force, the thrust force, and the feed force, the temperature, the surface roughness of the lathe machining process is modelled using two input constraints such as particle size of Boric Acid (50, 60, 80, 538nm) and weight percentage (1%, 3%, 5%, 7%) of Titanium Dioxide (100µm).

3. Study of the Mechanical Properties

3.1. Comparison of the Mechanical Properties

Comparison of the mechanical properties such as force, temperature, surface roughness, H3BO3 particle size and TiO2 combination was performed (Figure 4). Results indicate a linear trend between the force vs temperature, surface roughness vs temperature, force vs surface roughness and a decreasing trend for force vs TiO2 combination.

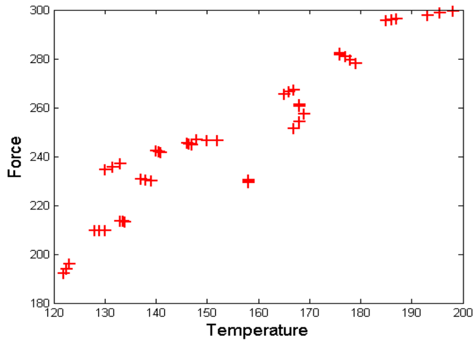


Figure (a)

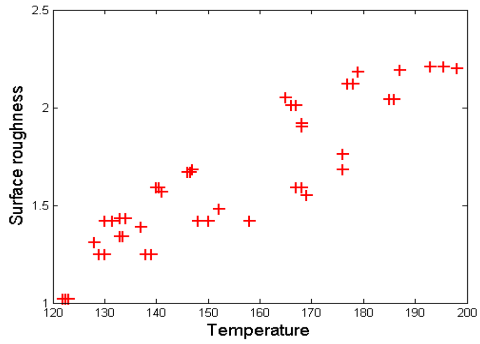


Figure (b)

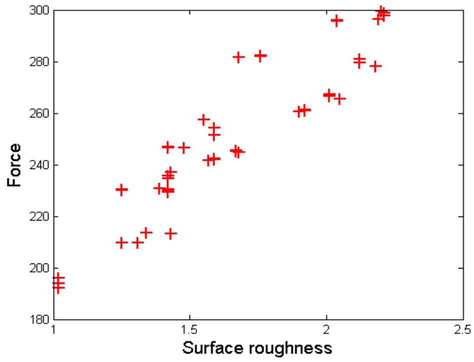


Figure (c)

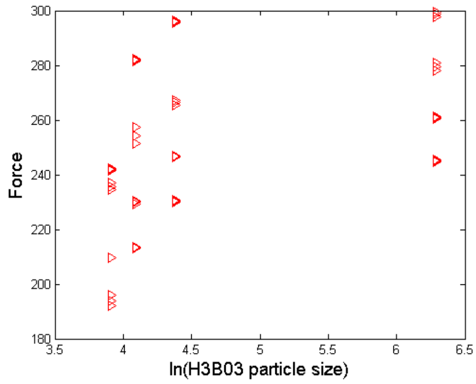


Figure (d)

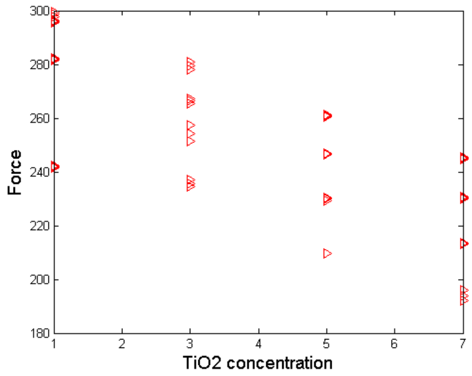


Figure (e)

Figure 4. Study on the Dependency of the Force (N), Temperature (^{O}), Surface Roughness, H_3BO_3 Particle Size, and Tio_2 Concentration

3.2. Study of the Mechanical Properties with Reference to the H_3BO_3-Tio_2 Combination

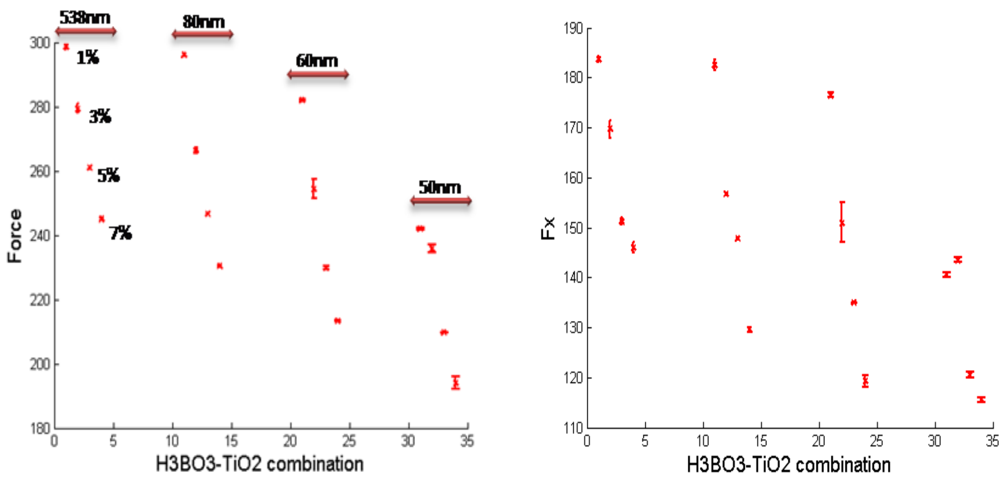
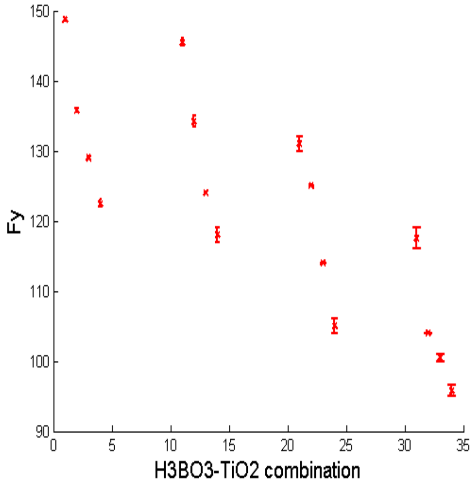


Figure 5. a) Force vs H_3BO_3-TiO_2 Combination, b) Fx vs H_3BO_3-TiO_2. H_3BO_3-TiO_2 Combinations were Represented in Four Columns where the Columns Indicate H_3BO_3 Particle Size and the Entries within the Column Indicate Percentage of the TiO_2

(Figure 5) The results obtained shows that the cutting forces considerably reduced. The feed force is reduced with reduction in boric acid particle size and increasing weight percentage of titanium dioxide as shown in figure.



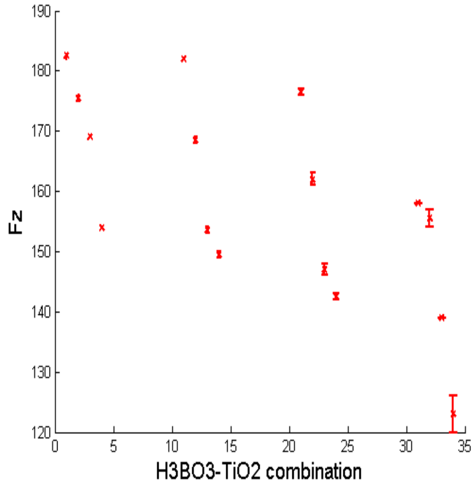
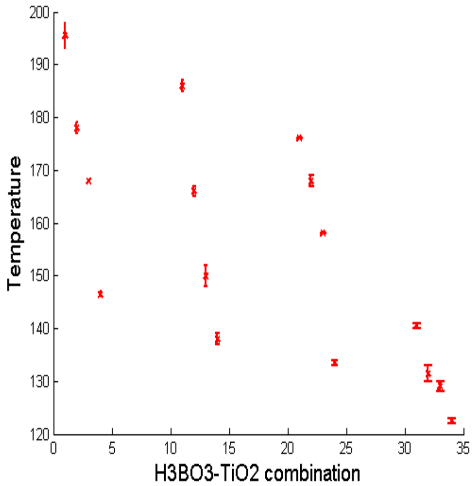


Figure 5. c) Fy vs H_3BO_3-TiO_2 combination, d) Fz vs H_3BO_3-TiO_2

Figure 5 (left panel): The thrust force is reduced with reduction in boric acid particle size and increasing weight percentage of titanium dioxide. Figure 5 (right panel): The main cutting force is reduced with reduction in boric acid particle size and increasing weight percentage of titanium dioxide.



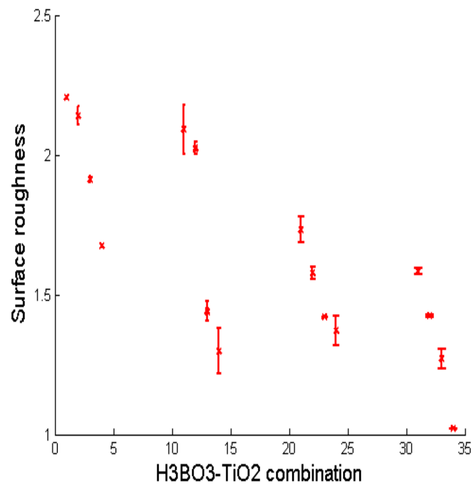


Figure 5. e) Temperature vs H_3BO_3-TiO_2 Combination, f) Surface Roughness vs H_3BO_3-TiO_2

Figure 5 (left panel): The tool temperature is reduced with reduction in boric acid particle size and increasing weight percentage of titanium dioxide. Figure 5 (right panel): The surface roughness is reduced with reduction in boric acid particle size and increasing weight percentage of titanium dioxide as shown in figure. With application of H_3BO_3 (538nm) and TiO_2 (1%) the surface roughness is 2.26, with H_3BO_3 (538nm) and TiO_2 (7%) the surface roughness is 1.66, with H_3BO_3 (50nm) and TiO_2 (1%) the surface roughness is 1.56 and with H_3BO_3 (50nm) and TiO_2 (7%) the surface roughness is 0.92.

4. Artificial Neural Network (ANN) Modelling and Prediction

Input output fitting tool of neural network toolbox (Matlab) [15] was used for developing the ANN model (Figure 6). The neural network model adopted is a two layer feed forward network that maps the output variables to the input using Levenberg-Marquardt back-propagation algorithm. The LM training involves an iteration process that attempts in finding the solution that performs the best least square fit of the data. From initial guess of the solution, an estimate for the predictive solution in the next iteration by is made by determining the best possible direction that uses the Jacobian matrix. Once the solution is reached or converged, the iteration stops.

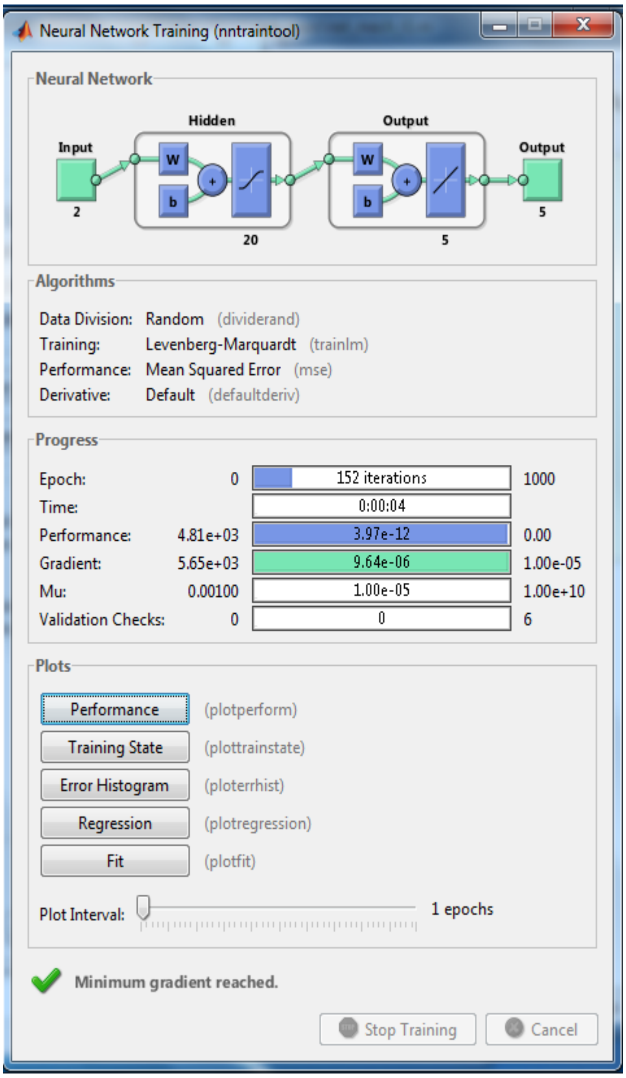


Figure 6. Neural Network Training Using *'nntraintool'* of Matlab

The experimentally obtained data is used to train the neural network and to develop the model. Datasets comprising of two inputs (H3BO3 particle size, TiO2 concentration) and five outputs (Fx, Fy, Fz, temperature, roughness) were provided. The dataset was categorized randomly into 70% for training, 15% for validation and 15% for testing purpose. Choices of 10-100 numbers of hidden layer neurons were considered and an optimal number was used by trial and error method that provides the best convergence.

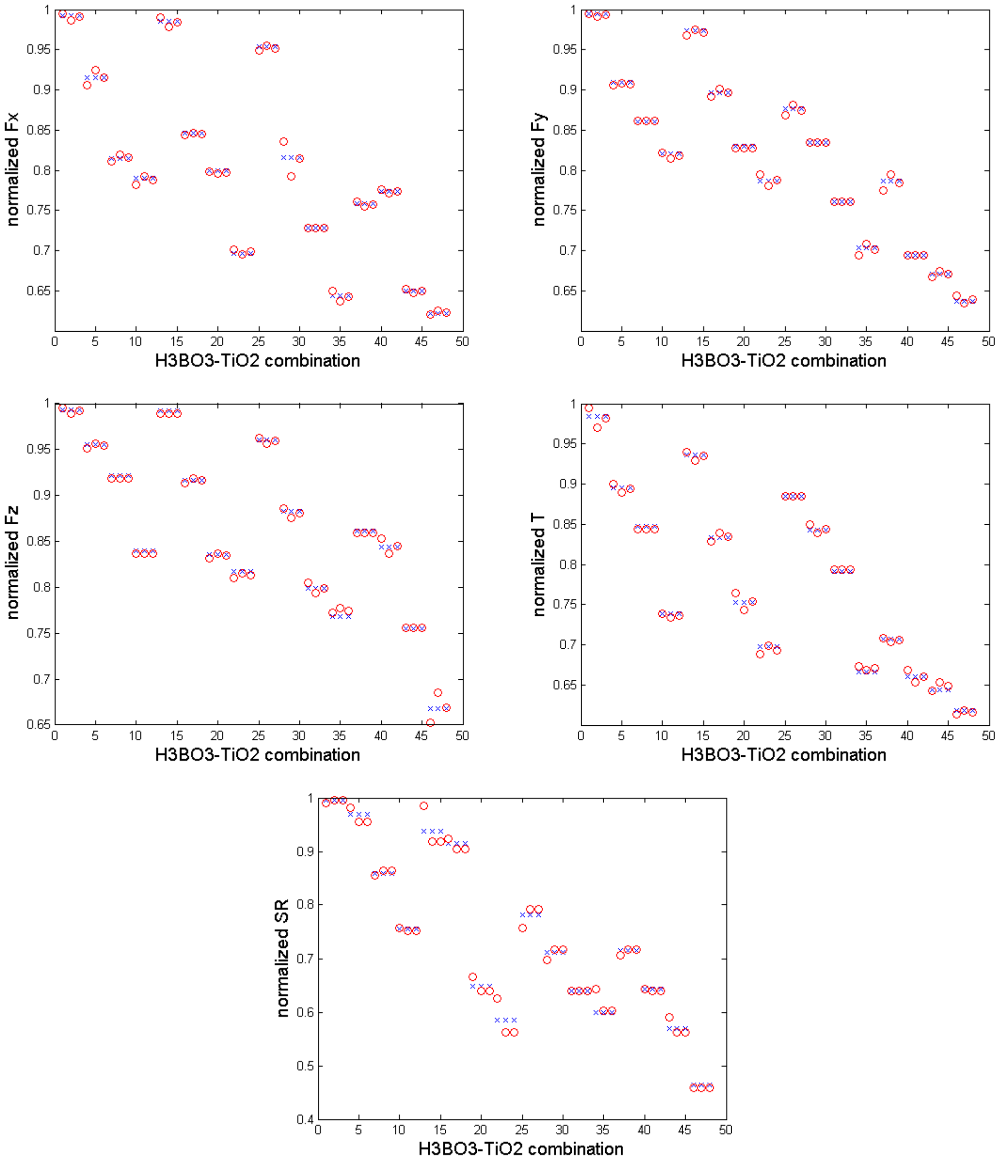


Figure 7: Normalized Parameters for force Components (Fx, Fy, Fz), Temperature (T), and Surface Roughness (SR) vs H3BO3-TiO2 Combination are Compared and Modelled Suing ANN Data Fitting Tool. A Set of Three Data Point were Used to Test the Prediction Using ANN Model against the Experimental Values. The H3BO3-TiO2 Combination along X-axis is presented for Boric Acid (50, 60, 80, 538nm) and Weight Percentage (1%, 3%, 5%, 7%) of Titanium Dioxide (100µm) as, for *e.g*. 50% H3BO3 with (1%, 3%, 5%, 7%) of TiO2 Giving Four Consecutive Data

The ANN model was developed with the experimental results for predicting the surface roughness, temperature, cutting forces, thrust forces and feed forces. Three numbers of test cases were considered for every combination of the experiment performed to test the prediction using the ANN model. Prediction results match close to the experimental results at 98% accuracy for most of the cases while for certain exception they are a 95% accurate (Figure 7).

4. Results and Discussions

The study shows that the cutting forces, tool temperature and surface roughness gets reduced with reduction in boric acid particle size (from 538nm to 50nm) and increasing weight percentage of titanium dioxide (from 1% to 7%). The ANN model has been developed with the experimental results for predicting the surface roughness, temperature & three forces based on the combination. The results obtained by the experimental work and the predictive model using ANN align well.

4. Conclusions

The tribological behavior of the Nano crystalline H3BO3 with weight percentages of the TiO2 (µm) has been studied by using it as a lubricant in the machining of EN24 STEEL. It was observed that the forces (cutting forces), temperature (tool temperature) and surface roughness gets reduced with reduction in boric acid particle size (from 538nm to 50nm) and increasing weight percentage of Tio2 (titanium dioxide from 1% to 7%). The ANN has been developed using the experimental results for predicting the surface roughness, temperature and forces (three forces). In this paper, ANN modeling was used to validate with experimental results for given conditions. It has been found that results generated by the designed ANN are close to the experimental results with more accuracy. The accuracy of the developed model can be improved by increasing the more experimental datasets.

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Authors

Penta Shreenivasa Rao, is an Associate professor in Department of Mechanical Engineering, Raghu Institute of Technology. He has obtained his degree in Mechanical Engineering from Kakatiya University and M. Tech (CAD/CAM) from JNTU Kakinada, Kakinada. Presently he is carrying his research work as a part time Research Scholar in the Department of Marine Engineering, Andhra University Visakhapatnam, India

Parvataneni Venkata Jagan Mohan Rao, is a Professor in Department of Marine Engineering, Andhra University, Visakhapatnam. He has done his B. Tech Degree in Mechanical Engineering. M.Tech degree in Heat Transfer and his Ph.D. from Andhra University (Visakhapatnam). His areas of specialization are Manufacturing Technology (welding, Casting and Forming), Marine Pollution and Heat Transfer, MQL. He has been active in teaching for more than 28 Years

Ravi Kant Avvari, is an Associate Professor in the Department of Electrical and Electronics Engineering, Sasi Institute of Technology and Engineering, Tadepalligudem, India. He has done his B. Tech degree in Electrical and Electronics Engineering from Government Engineering College, Thrissur, Ph.D. in the area of Biomedical Engineering from IIT Kanpur and PostDoctoral work in the area of Nanotechnology from IIT Kanpur. His research interest includes Control techniques, Biomedical sciences and Nanotechnology.