Application of Artificial Neural Network and Response Surface Methodology in Modeling of Surface Roughness in WS$_2$ Solid Lubricant Assisted MQL Turning of Inconel 718

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Abstract. In the present paper, the artificial neural network (ANN) and response surface methodology (RSM) are used in modeling of surface roughness in WS$_2$ (tungsten disulphide) solid lubricant assisted minimal quantity lubrication (MQL) machining. The real time MQL turning of Inconel 718 experimental data considered in this paper was available in the literature [1]. In ANN modeling, performance parameters such as mean square error (MSE), mean absolute percentage error (MAPE) and average error in prediction (AEP) for the experimental data were determined based on Levenberg–Marquardt (LM) feed forward back propagation training algorithm with tansig as transfer function. The MATLAB tool box has been utilized in training and testing of neural network model. Neural network model with three input neurons, one hidden layer with five neurons and one output neuron (3-5-1 architecture) is found to be most confidence and optimal. The coefficient of determination ($R^2$) for both the ANN and RSM model were seen to be 0.998 and 0.982 respectively. The surface roughness predictions from ANN and RSM model were related with experimentally measured values and found to be in good agreement with each other. However, the prediction efficacy of ANN model is relatively high when compared with RSM model predictions.

1. Introduction

Materials with high strength, stability and corrosion resistance and superior thermo-mechanical properties even at elevated temperatures makes researchers and scientists positively attractive to use in aerospace applications. Among several metals and alloys, nickel based super alloys are most commonly used materials in making aerospace as well as gas turbine engine components [2,3]. Nickel based super alloy, Inconel 718 is a very high heat resistant alloy and is referred to one of the most difficult to cut material in normal machining environments. In addition, low thermal conductivity and specific heat of Inconel 718 is a major concern for researchers as it leads to high temperatures at tool-chip contact interface and consequently minimizes tool life and machining productivity [4,5]. Abnormal thermal and mechanical stresses during machining Inconel 718 leads to several challenges like its affinity to weld and form built up-edge, excessive tool-work contact heat, tool...
burning and mechanical breakage, surface integrity (surface roughness and surface metallurgy) and residual stresses, surface hardening, surface micro-cracks, functional performance and altered mechanical properties of machined components [6-8]. Among these issues, surface quality of the machined component is utmost important as it directly influences the safety and life of the components used in aerospace applications [9].

Use of conventional cutting fluids have been the prime choice in machining industry to enhance the cutting tool life and surface quality of machined surface and minimise the tool-work heat generation and contact stresses during machining difficult to cut materials [10]. Though the cutting fluids offer several advantages, growing cognizance for green machining internationally laid enormous pressure on researchers and manufacturers to avoid or minimise the usage of cutting fluids. The impact of minimal quantity lubrication (MQL) on machinability performance has been investigated by several researchers for over the last few years in different machining applications like turning, milling, drilling and grinding [11-14]. All these studies show that the application of MQL can significantly enhance the machinability performance as well as minimise the maintenance expenses connected with used cutting fluids [15,16].

In machining processes, it is essential to attain the desirable requirement of surface roughness as it not only predicts the finish quality of machined workpiece but also affects the performance of mechanical components and manufacturing costs. Therefore, it is vital to select the best modeling method to predict and optimize the surface quality of machined workpiece. Currently, response surface methodology (RSM) or regression analysis (RA), artificial neural networks (ANN) and Genetic algorithm (GA) are the most commonly used modeling techniques to describe the desired output variables by establishing mathematical models with the relationship between the process input and output factors. RSM is an empirical modeling method for defining the relationship among several process factors and responses with certain desired conditions and searching the significance of these process factors on the coupled responses [17-19]. RSM technique uses several statistical, graphical, and mathematical principles to attain, improve or optimize the process performance. ANN is another important empirical approach analogous to the behaviour of biological neural structure and can recognize extremely complex relationships through input and output data sets. Several researchers [20-25] developed RSM and ANN models to predict and comprehend the machinability performance by considering cutting conditions and tool geometry. In most of these studies results displayed that both the RSM and ANN models can effectively applied in modeling and predicting the surface roughness, cutting force, cutting temperature, tool wear and other responses with a great accuracy rate up to 99%. However, most of the earlier reports indicate that comparatively the prediction ability of ANN model was appreciated to be marginally superior to the RSM model.

In the current paper, an effort has been made to apply ANN and RSM modeling techniques to predict the surface quality (surface roughness) of machined Inconel 718 work material in both the MQL turning and WS2 solid lubricant assisted MQL turning. In ANN and RSM modeling, the experimental data available in the previous work [1] is used. The surface roughness predictions from ANN and RSM model were compared with the experimental results. Also, this study established a comprehensive comparison between ANN and RSM models and to select the best approach for predicting surface roughness when turning Inconel 718 alloy with and without WS2 assisted MQL approach.

2. Experimental Procedure

The turning tests were performed on Inconel 718 alloy with a high-precision lathe machine at different cutting conditions such as cutting speed \( v_c \) = 60, 80 and 100 m/min, feed rate \( f \) = 0.1, 0.2 and 0.3 mm/rev) and depth of cut \( a_c \) = 0.05, 0.075 and 0.1 mm). In turning experiments, SNMG 120408 carbide tool inserts, characterized by a clearance angle = 6°, rake angle = -6°, and nose radius = 0.8 mm were employed and fixed on an ISO standard tool holder. MQL mixture is prepared with micron-sized WS2 particles of 0.5% (wt.) dispersed in water based (20:1) emulsifier cutting fluid. A high intensity ultrasonic homogenizer was employed in dispersing WS2 particles into cutting fluid.
mixing process was conducted at room temperature. In order to minimise the surface energy and avoid the aggregation of WS₂ particles in water based cutting fluid, Cetyl Trimethyl Ammonium Bromide (CTAB) surfactant was added to the mixture. Two different environments in machining experiments were considered as follows: (i) MQL machining (water based emulsifier cutting fluid) and (ii) WS₂ assisted MQL machining (WS₂ + water based emulsifier cutting fluid). Machining test setup equipped with MQL supply system is depicted in figure 1. Each experiment was conducted for 10 min for all the cutting condition selected. To ensure the constancy of results, each experiment was repeated for three times and the average value of three measurements was considered to represent the process performance, i.e. surface finish of machined work material. Surftest SJ 301 is used in measuring quality of the machined surface. In MQL turning, WS₂ and cutting fluid mixture is supplied to the tool-work contact at flow rate of 199 ml/hr. The experimentally measured surface roughness values in both the machining environments are shown in table 1.

Figure 1. (a) MQL machining experimental setup and (b) a sample measure of surface roughness with talysurf.
Table 1. Surface roughness results.

| Exp. No. | Cutting speed (m/min) | Feed (mm/rev) | Depth of cut (mm) | MQL machining | WS assisted MQL machining |
|----------|-----------------------|---------------|------------------|---------------|--------------------------|
| 1        | 60                    | 0.1           | 0.05             | 0.68          | 0.49                     |
| 2        | 60                    | 0.1           | 0.10             | 0.72          | 0.54                     |
| 3        | 60                    | 0.1           | 0.15             | 0.81          | 0.59                     |
| 4        | 60                    | 0.2           | 0.05             | 0.95          | 0.73                     |
| 5        | 60                    | 0.2           | 0.10             | 1.04          | 0.81                     |
| 6        | 60                    | 0.2           | 0.15             | 1.08          | 0.85                     |
| 7        | 60                    | 0.3           | 0.05             | 1.25          | 0.97                     |
| 8        | 60                    | 0.3           | 0.10             | 1.31          | 1.01                     |
| 9        | 60                    | 0.3           | 0.15             | 1.36          | 1.07                     |
| 10       | 80                    | 0.1           | 0.05             | 0.61          | 0.42                     |
| 11       | 80                    | 0.1           | 0.10             | 0.68          | 0.47                     |
| 12       | 80                    | 0.1           | 0.15             | 0.75          | 0.56                     |
| 13       | 80                    | 0.2           | 0.05             | 0.89          | 0.66                     |
| 14       | 80                    | 0.2           | 0.10             | 1.02          | 0.77                     |
| 15       | 80                    | 0.2           | 0.15             | 1.13          | 0.89                     |
| 16       | 80                    | 0.3           | 0.05             | 1.28          | 0.96                     |
| 17       | 80                    | 0.3           | 0.10             | 1.42          | 1.09                     |
| 18       | 80                    | 0.3           | 0.15             | 1.51          | 1.14                     |
| 19       | 100                   | 0.1           | 0.05             | 0.44          | 0.33                     |
| 20       | 100                   | 0.1           | 0.10             | 0.53          | 0.38                     |
| 21       | 100                   | 0.1           | 0.15             | 0.62          | 0.44                     |
| 22       | 100                   | 0.2           | 0.05             | 0.71          | 0.51                     |
| 23       | 100                   | 0.2           | 0.10             | 0.77          | 0.59                     |
| 24       | 100                   | 0.2           | 0.15             | 0.86          | 0.65                     |
| 25       | 100                   | 0.3           | 0.05             | 1.02          | 0.76                     |
| 26       | 100                   | 0.3           | 0.10             | 1.12          | 0.83                     |
| 27       | 100                   | 0.3           | 0.15             | 1.26          | 0.94                     |
| 28      | 70                    | 0.15           | 0.05             | 0.91          | 0.69                     |
| 29      | 90                    | 0.25           | 0.1             | 1.16          | 0.86                     |
| 30      | 100                   | 0.3           | 0.125            | 1.18          | 0.89                     |

3. Response Surface Methodology (RSM)

Response surface methodology (RSM) and regression analysis (RA) are statistical tools often used in process modelling and optimization, where process response depends on number of input variables. It gives a polynomial relation based on experimental results and predicts optimal combination among input parameters and process response. In this work, the quadratic model has been used in establishing RSM relation. Based on the quadratic model, the relationship established among independent parameters, cutting speed, feed rate and depth of cut with one dependent variable such as surface roughness is represented with the following multiple linear regression equation (1).

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{23} x_2 x_3 + \beta_{31} x_3 x_1 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \]  

(1)

Where, \( y \) stands for response, \( \beta_0, \beta_1, \beta_2 \) and \( \beta_3 \) are regression coefficients of linear part of the model, \( \beta_{12}, \beta_{23} \) and \( \beta_{31} \) are regression coefficients of cross portion of the model, and \( \beta_{11}, \beta_{22} \) and \( \beta_{33} \) are regression coefficients of quadratic portion of the model.
4. Artificial Neural Network (ANN)

Neural network MATLAB toolbox was utilized in ANN model training and testing. ANN model comprises of three neurons such as cutting speed, feed rate and depth of cut in the input layer and one neuron of surface roughness in the output layer. Several models were designed and tested to choose the optimal neural network structure. The available experimental data as presented in Table 1 is split into training, testing and validation data into 70%, 15% and 15% respectively. In network modeling, the Levenberg–Marquardt (LM) algorithm was used for the training and hyperbolic tangent sigmoidal (tansig) activation function used in the hidden and output layer. Gradient-descent with momentum (traingdm) back propagation algorithm was used to minimize the mean squared error of the output. This makes the neural network capable of sorting nonlinear relationships between the inputs and the output. Data normalization between minimum and maximum values from -1 to +1 was carried out prior to training and testing of the network model. The optimal ANN architecture was established according to performance indices such as the mean sum squared error (MSE), average absolute error in prediction (AEP) and mean absolute percentage error (MAPE) of the trained data. MSE, AEP and MAPE values in this study are calculated using equations (2), (3) and (4) respectively.

\[
MSE = \frac{1}{N} \sum_{i=1}^{N} (t_i - td_i)^2 \]

\[
AEP = \frac{1}{N} \sum_{i=1}^{N} |t_i - td_i| \]

\[
MAPE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{t_i - td_i}{td_i} \right| \]

Where, \( t_i \) is the real output (targeted values), \( td_i \) is the ANN output (predicted results), and \( N \) is the size of data sets.

5. Results and Discussion

5.1. RSM Modeling

In this paper, Minitab-16 statistics software is applied in establishing and examining the RSM model. The developed relationship among three independent variables, cutting speed, feed rate and depth of cut and with the predicted value, surface roughness for the experimental conditions when turning Inconel 718 with and without WS\(_2\) assisted MQCL approach is represented using equation (5) and equation (6).

\[
R_{a_{MQL\;machining}} = -0.85 + 0.038 \times A + 1.567 \times B + 0.00 \times C - 0.0003 \times A^2 + 2.611 \times B^2 - 0.222 \times C^2 + 0.004 \times A \times B + 0.017 \times A \times C + 2.167 \times B \times C \)

(5)

\[
R_{a_{WS_2\;MQL\;machining}} = -0.699 + 0.027 \times A + 2.356 \times B + 0.433 \times C - 0.0002 \times A^2 + .389 \times B^2 - 0.444 \times C^2 - 0.002 \times A \times B + 0.009 \times A \times C + 1.833 \times B \times C \)

(6)

5.2. ANN Modeling

The optimal ANN structure was established based on network performance indices such as MSE, AEP and MAPE. Figure 2 and figure 3 shows of MSE, AEP and MAPE of all data, trained data and test
data against different neurons with single and two hidden layers respectively in WS₂ assisted MQL machining. From the results, it was observed that ANN model was steadier and exhibiting lowest errors with one hidden layer consists of five neurons. On the basis of MSE, AEP and MAPE results, it has been established that the 3-5-1 ANN architecture is more confidence and optimal. The optimum ANN structure obtained in this work is presented in figure 4. Further, the obtained optimal neural network is trained from 1000 iterations to 10000 iterations to achieve the desired output. From figure 5, it was noticed that after 8000 iterations the MSE, AEP and MAPE of the test data and training data started continuously increasing. Therefore, the training was stopped at 8000 iterations to avoid over training.

Figure 2. MSE, AEP and MAPE as a function of varying neurons in single hidden layer.

Figure 3. MSE, AEP and MAPE as a function of varying neurons in double hidden layer.

Figure 4. Optimal ANN architecture for surface roughness.
5.3. ANN and RSM Model surface roughness comparison

ANN and RSM model predictive capabilities were evaluated by comparing the model surface roughness prediction results with the experimentally measured results. The absolute percentage error (Δ) between proposed model predictions and experimentally measured results is determined using equation (7). The estimated absolute percentage error values are listed in Table 2.

\[ \Delta = \left| \frac{Ra_{exp} - Ra_{pred}}{Ra_{exp}} \right| \]  

(7)

From the results, during WS\(_2\) assisted MQL machining it is noticed that the maximum absolute percentage error predictions with ANN and RSM models are 3.15% and 18.48% respectively. In addition to the above, mean absolute percentage error with ANN model is found to be only 0.813%, whereas the corresponding value with RSM can be seen as 4.088%. From both the model prediction results it is obvious that the ANN model exhibits quite higher predictive capability of surface roughness in both the MQL and WS\(_2\) assisted MQL machining environments as it has a very low absolute percentage error when compared with that of RSM model. Further, the agreement of ANN model predictions with experimentally measured surface roughness results is very high when compared with RSM model. It is true because the correlation coefficient between the ANN model predictions and experimental results was about 0.998 (Figure.6), whereas the correlation coefficient (R\(^2\)) value for the RSM model is 0.982 (Figure.7). Thus, the ANN model is quite effective in predicting the surface roughness when turning Inconel 718 alloy with and without WS\(_2\) assisted MQL approach.

Figure 5. MSE, AEP and MAPE as a function of varying iterations with optimal ANN structure.
Table 2. RSM and ANN model surface roughness prediction comparison with experimentally values.

| S.No. | Experimental results | RSM predictions (%) | ANN model prediction (%) | Absolute percentage error with RSM model (%) | Absolute percentage error with ANN model (%) |
|-------|----------------------|---------------------|--------------------------|--------------------------------------------|--------------------------------------------|
|       | MQL assisted machining | MQL assisted machining | MQL assisted machining | MQL assisted machining | MQL assisted machining |
| 1     | 0.68                 | 0.681               | 0.679                   | 0.679                                     | 0.679                                     |
| 2     | 0.72                 | 0.74                | 0.720                   | 0.720                                     | 0.720                                     |
| 3     | 0.81                 | 0.798               | 0.809                   | 0.809                                     | 0.809                                     |
| 4     | 0.95                 | 0.952               | 0.950                   | 0.950                                     | 0.950                                     |
| 5     | 1.04                 | 1.022               | 1.040                   | 1.040                                     | 1.040                                     |
| 6     | 1.08                 | 1.091               | 1.107                   | 1.107                                     | 1.107                                     |
| 7     | 1.25                 | 1.275               | 1.239                   | 1.239                                     | 1.239                                     |
| 8     | 1.31                 | 1.356               | 1.289                   | 1.289                                     | 1.289                                     |
| 9     | 1.36                 | 1.435               | 1.375                   | 1.375                                     | 1.375                                     |
| 10    | 0.61                 | 0.679               | 0.602                   | 0.602                                     | 0.602                                     |
| 11    | 0.68                 | 0.755               | 0.679                   | 0.679                                     | 0.679                                     |
| 12    | 0.75                 | 0.830               | 0.754                   | 0.754                                     | 0.754                                     |
| 13    | 0.89                 | 0.958               | 0.892                   | 0.892                                     | 0.892                                     |
| 14    | 1.02                 | 1.045               | 1.020                   | 1.020                                     | 1.020                                     |
| 15    | 1.13                 | 1.130               | 1.126                   | 1.126                                     | 1.126                                     |
| 16    | 1.28                 | 1.290               | 1.269                   | 1.269                                     | 1.269                                     |
| 17    | 1.42                 | 1.387               | 1.398                   | 1.398                                     | 1.398                                     |
| 18    | 1.51                 | 1.484               | 1.494                   | 1.494                                     | 1.494                                     |
| 19    | 0.44                 | 0.453               | 0.437                   | 0.437                                     | 0.437                                     |
| 20    | 0.53                 | 0.546               | 0.537                   | 0.537                                     | 0.537                                     |
| 21    | 0.62                 | 0.637               | 0.614                   | 0.614                                     | 0.614                                     |
| 22    | 0.71                 | 0.741               | 0.706                   | 0.706                                     | 0.706                                     |
| 23    | 0.77                 | 0.844               | 0.773                   | 0.773                                     | 0.773                                     |
| 24    | 0.86                 | 0.946               | 0.849                   | 0.849                                     | 0.849                                     |
| 25    | 1.02                 | 1.081               | 1.019                   | 1.019                                     | 1.019                                     |
| 26    | 1.12                 | 1.195               | 1.120                   | 1.120                                     | 1.120                                     |
| 27    | 1.26                 | 1.308               | 1.249                   | 1.249                                     | 1.249                                     |
| 28*   | 0.91                 | 0.955               | 0.910                   | 0.910                                     | 0.910                                     |
| 29*   | 1.16                 | 1.207               | 1.153                   | 1.153                                     | 1.153                                     |
| 30*   | 1.18                 | 1.225               | 1.190                   | 1.190                                     | 1.190                                     |

*validation data
Figure 6. Correlation coefficient values for training, test, validation and all data with ANN model.

Figure 7. Correlation coefficient with RSM model.
6. Conclusion
The scope of the current work is to apply ANN method with LM feed forward back propagation training algorithm and RSM technique to model and predict the finish quality (surface roughness) when turning Inconel 718 alloy with and without WS$_2$ assisted MQL approach. The surface roughness prediction values obtained from ANN and RSM models are proved to be in quite realistic agreement when compared to the surface roughness results determined as experimentally [1]. Results show that both the ANN and RSM models relate the independent variables with response variable quite effectively and therefore give a very high estimate of linear dependence of fit between predicted and experimental surface roughness values. This is true because correlation coefficient obtained in both the models as high as above 0.98. Relatively proposed ANN model deliver an accurate prediction of surface roughness with experimentally observed results in both the MQL and WS$_2$ assisted MQL machining environments as it has a very low absolute percentage error and very high correlation coefficient in prediction. The outcome demonstrate that both statistical and computational intelligence modeling can make a potential alternative to time consuming experimental studies in addition minimizing the costly machining test trials.

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