Application of Artificial Neural Networks in Abrasive Water Jet Milling

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Abstract

In the present study, Artificial Neural Networks (ANN) is used to predict the geometrical characteristics of a micro-channel fabricated through Abrasive Water Jet Machining (AWJM) technique. The process parameters considered are abrasive size, traverse speed, abrasive flow rate and standoff distance respectively. The quality of the micro-channel can be assessed in terms of its width, depth, taper and surface roughness. The optimum values of the process parameters are used to predict the response parameters. The impact force of the abrasive water jet and the jet vibrations are considered as additional input to the process parameters. The ANN predicted values are 99% in agreement with the experimental results.

1. Introduction

Any component manufactured and the corresponding geometrical parameters obtained measure the performance of the concerned manufacturing process. Maintaining close dimensional tolerances throughout the process is well established in most of the conventional machining processes because of its large data base available. Unconventional manufacturing processes which were developed over the past few decades lack in achieving the required dimensional tolerances even after the major technological advancements. AWJM is one such process which needs to be elaborately studied. This process is gaining its popularity due to its added advantages over other unconventional processes like minimum heat affected zone, unchanged material characteristics after machining, faster material removal, etc. Although statistical regression modeling may be acceptable for process modeling, but such techniques may not precisely describe the underlying non-linear relationship between the input and response parameters.

A process model is a mathematical function that relates the process parameters and its performance. In general, models are categorized in three forms namely, experimental, analytical and Artificial Intelligence (AI) based models. Experimental and analytical models can be developed using conventional approaches like Statistical Regression techniques. While, AI based models are developed using non-conventional approaches such as ANN, Fuzzy, Genetic Algorithm (GA), etc. An ANN technique is a mathematical or
computational method which is a massively parallel, distributed processor having capability of storing experimental knowledge. Initially ANN learns by experience and then it stores the information in the form of synaptic weights. Modern neural networks are non-linear statistical data modeling tools to model complex relationships between inputs and outputs and also find patterns in the given data. The advantages of using ANN for model prediction are; ANN is able to handle nonlinear models that learns how to map input to output; ANN is successful in terms of speedy, simplicity to learn from the minimum input data; does not need any preliminary assumptions unlike in a conventional modeling process; the behavior of the experimental results are easy to understand from the neuron models; the performance of the predicted ANN model can be improved by defining more levels from the input process parameters. The neural network toolbox in MATLAB is very easy to understand and is used for training and testing the experimental data.

A review on the application of ANN to predict surface roughness in a conventional machining process is elaborated by Zain, et al. [2009]. The usage of ANN for unconventional machining processes is not enough matured based on the available literature and its application for AWJM in particular is very much limited. Reports on prediction of surface roughness [2] and jet speed [3] for a given pressure, abrasive flow rate, and thickness of the target material are available. ANN provides a better method of process parameter estimation based on the selection of most critical and optimal values of the parameters [4]. The reports by Yang et al. [2005] gives the cutting ability for several engineering materials with AWJM technique that can be assessed with ANN based numerical models. The reports on granite machining by Chakravarthy [1997, 2000] gives analysis of the experimental results through empirical modeling and the process parameters optimization through hybrid approach. The use of ANN has been attempted to measure the performance of the abrasive water jet machining process [9]. A review on the use of non-conventional machining processes gives an insight of use of neural networks for abrasive water jet machining [10]. The present paper discusses about the usage of ANN for predicting the micro-channel characteristics by machining at very high traverse rates. The innovative method of the work apart from the accomplished work is considering the force and vibrations of the jet as a part of the control parameters along with the process parameters.

Nomenclature

\[ \begin{align*}
  v & \quad \text{Traverse Speed} \\
  h & \quad \text{Standoff distance} \\
  m_a & \quad \text{Abrasive flow rate} \\
  d & \quad \text{Abrasive diameter} \\
  F & \quad \text{Impact force} \\
  \theta & \quad \text{Jet vibrations}
\end{align*} \]

2. Experimentation

In the present work, micro-channels are fabricated on SS304 material with varying process parameters. The input parameters, ranges and values at the corresponding levels are mentioned in Table 1. The process parameters range is selected based on the machine limiting conditions and the available literature. Considering each parameter at 3-levels, a full factorial experimental set is generated with MINITAB software which leads to 81 \((3^3)\) runs. All the trials are conducted on a SS304 plate using a CNC operated Abrasive Water Jet Machining Center (Model No. OMAX 2626, USA).

Table 1: Range of process parameters

| Process parameter | Level 1 | Level 2 | Level 3 |
|-------------------|---------|---------|---------|
| Traverse speed (mm/min) | 3000 | 3500 | 4000 |
| Abrasive flow rate (kg/min) | 0.27 | 0.38 | 0.49 |
| Standoff distance (mm) | 3 | 4 | 5 |
| Abrasive mesh size (\#) | 80 | 120 | 160 |
3. Approach

The work presented here is to show how artificial neural networks can be used for monitoring the dimensional characteristics of the AWJ machined micro-channels. The functional aspect of ANN developed for the AWJM process is described in the preceding sections. In the current work, the neural network toolbox in MATLAB is used for training the network using back propagation algorithm. A typical three layered network is shown in Fig. 5. Training is accomplished by sequentially applying input vector, while adjusting network weights according to a predetermined procedure. During training the network, the weights gradually converge to values such that each input vector produces the desired output vector. Various network architectures, number of layers, nodes, transfer function and the training patterns are chosen in the present study considering tangent sigmoidal functions for all layers. Of the various training functions available in MATLAB toolbox, \textit{trainlm} is used as the network training function which updates weight and bias values according to Levenberg-Marquardt optimization [6].

3.1 Preparation of training and target vectors

The jet impact force and the jet vibration are considered as the influencing parameters that affects the surface topology of the channel along with the other input process parameters. It is similar to a conventional metal cutting process where the cutting tool vibration and the cutting force influence the machining process that affects the surface roughness. Hence, the training vector consists of traverse speed ($v$), SOD ($h$) AFR (m$_b$), and abrasive size($d$), impact force ($F$) and the jet vibration ($g$). Accordingly the typical input and target data are presented in Appendix A. The normalized values of input and target values are used for training and testing the networks. The total 81 input sets are divided randomly into 70%, 20%, and 10% for training, validation and testing respectively, i.e., 57 for training, 16 for validation and 8 for testing in the selected architectures as per the standard procedures followed. The mean square error between the actual network output and the target output is minimized. Network parameters are adjusted to achieve the required goal. The network algorithm is trained for different architectures and training schemes. Generally, the behavior of the neural network architecture depends on various parameters like input patterns to networks, target vectors, number of layers and neurons, activation function, training function, number of epochs, and so on. The work carried here is to understand the application of ANN using force and vibration signals to monitor the channel topography.

4. Results and discussion

In AWJM, the major focus of the process for micro-channel fabrication is to achieve close dimensional tolerances and accuracies. To supervise and control the dimensions of the channel it is necessary to know the input parameter values so as to achieve the best possible results. Another way of accessing the feature dimensions are to use the indirect method of measurements which are force, vibration, sound, etc. In the present case, the sensor output in terms of jet impact force and jet vibrations are used to control the process. The impact force influences the channel depth and the jet vibration correlates the width of the channel. The combination of both force and vibration results in taper and surface roughness, a rare case which was never attempted before. The motive behind using ANN is to provide a new type of computer architecture in which the knowledge acquired and stored over time with the use of adaptive learning algorithms.
The ANN results for taper when compared with the experimental results shows that the error prediction is higher; when calculated the percentage error is of the order of 5-6%. In AWJ, taper is evaluated with a large set of input parameters. The results show that the channel taper is a difficult parameter to be predicted. An improved method to evaluate is to consider some more dominant parameters. The prediction for depth and width are the most appropriate parameters observed which are in the error range of 2-3 %. The method shows an effective way of monitoring the process in terms of the dimensional characteristics.

Conclusions

The present work shows the effectiveness of using back propagation neural networks for modeling the AWJM process for the micro-channel fabrication is demonstrated. Simulation results show a good agreement with the experimental results for the range of machining conditions chosen. Based on these results, the possibility of using ANN for predicting the channel characteristics has been confirmed. It is further observed that the learning process can be enhanced by network training with large set of process parameters. This model can be used directly to study AWJ milling without performing any physical measurements and examine the effect of process parameters with the aid of force and vibration signals. The neural network systems discussed is fairly general and can be extended to other applications of AWJM to improve the machining performance and efficiency.

Appendix A: Typical input parameters and the response data (partial set)

| Exp. No | Input | Target |
|---------|-------|--------|
|         | $v$ (mm/min) | $h_a$ (kg/min) | $d$ (mm) | $h$ (mm) | $F$ (N) | $\sigma_{cm}$ (g) | Width(μm) | Depth (μm) | Taper (Deg) | $R_a$ (μm) |
| 1       | 3000  | 0.49   | 0.177 | 4   | 10.33 | 0.000552 | 785 | 225.91 | 58.90 | 3.61 |
| 2       | 3500  | 0.49   | 0.125 | 5   | 11.60 | 0.000382 | 753 | 183.55 | 40.22 | 1.26 |
| 3       | 3500  | 0.38   | 0.110 | 4   | 11.63 | 0.000349 | 762 | 150.00 | 50.00 | 1.09 |
| 4       | 3500  | 0.38   | 0.177 | 4   | 10.47 | 0.000538 | 690 | 140.25 | 49.02 | 2.81 |
| 5       | 3500  | 0.27   | 0.177 | 3   | 10.91 | 0.000551 | 690 | 160.00 | 47.21 | 2.61 |
| 6       | 3500  | 0.38   | 0.177 | 5   | 10.35 | 0.000537 | 785 | 192.02 | 60.04 | 2.66 |
| 7       | 3000  | 0.49   | 0.125 | 4   | 11.89 | 0.000400 | 769 | 196.79 | 51.52 | 2.30 |
| 8       | 4000  | 0.38   | 0.177 | 3   | 10.94 | 0.000692 | 678 | 192.02 | 48.13 | 3.18 |
|   | 4000  | 0.38  | 0.177  | 4   | 10.17 | 0.000551 | 595   | 186.38 | 56.38 | 1.65 |
|---|-------|-------|--------|-----|-------|-----------|-------|-------|-------|------|
| 10| 3000  | 0.27  | 0.177  | 5   | 10.86 | 0.000548 | 785   | 193.91 | 51.20 | 1.95 |
| 11| 3000  | 0.27  | 0.110  | 4   | 10.47 | 0.000323 | 719   | 175.08 | 63.60 | 1.97 |
| 12| 3000  | 0.49  | 0.110  | 4   | 8.56  | 0.000355 | 812   | 208.02 | 60.56 | 1.26 |
| 13| 3000  | 0.38  | 0.177  | 3   | 11.07 | 0.000513 | 702   | 257.91 | 54.20 | 3.08 |
| 14| 4000  | 0.49  | 0.177  | 4   | 11.04 | 0.000547 | 678   | 126.13 | 66.21 | 1.74 |
| 15| 3500  | 0.38  | 0.177  | 3   | 10.93 | 0.000583 | 725   | 182.65 | 66.19 | 1.81 |
| 16| 3500  | 0.49  | 0.125  | 4   | 11.84 | 0.000403 | 876   | 205.20 | 50.26 | 1.56 |
| 17| 4000  | 0.49  | 0.110  | 4   | 8.94  | 0.000521 | 812   | 205.20 | 61.51 | 1.22 |
| 18| 3500  | 0.27  | 0.110  | 5   | 10.58 | 0.000402 | 734   | 180.73 | 59.35 | 1.94 |
| 19| 3000  | 0.27  | 0.177  | 3   | 10.45 | 0.000521 | 809   | 186.38 | 54.29 | 2.53 |
| 20| 3500  | 0.27  | 0.125  | 3   | 11.14 | 0.000357 | 861   | 193.91 | 50.05 | 2.18 |
| 21| 4000  | 0.27  | 0.177  | 4   | 10.51 | 0.000579 | 690   | 143.08 | 57.19 | 2.36 |
| 22| 4000  | 0.27  | 0.125  | 3   | 11.34 | 0.000477 | 846   | 159.08 | 47.64 | 2.14 |
| 23| 4000  | 0.49  | 0.125  | 3   | 11.42 | 0.000449 | 629   | 153.43 | 32.20 | 3.13 |
| 24| 4000  | 0.38  | 0.177  | 5   | 10.89 | 0.000702 | 773   | 186.38 | 54.60 | 1.46 |
| 25| 3000  | 0.27  | 0.125  | 4   | 10.88 | 0.000364 | 815   | 211.82 | 49.35 | 2.01 |
| 26| 4000  | 0.38  | 0.110  | 5   | 10.92 | 0.000387 | 688   | 153.43 | 60.65 | 1.61 |
| 27| 3500  | 0.49  | 0.177  | 4   | 9.82  | 0.000555 | 713   | 171.32 | 56.60 | 2.20 |

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