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Prediction of tangential force and maximum temperature generation at the tool tip using ANFIS model during CNC turning operations for an intricate shape

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ABSTRACT

In spite of vigorous research on advanced material processing and advanced manufacturing processes, the conventional processes are essential in building a country's economy till date. The disadvantage of this process is that machining industry is the most energy consuming and waste spawning industry. The main question is how the energy can be utilized in proper way such that energy consumption will be on lower side and will provide high productivity. The consumption is more whenever we concern the intricate shape of the job. The two factors that are important for the measurement of energy consumption during CNC turning of an intricate shape are tangential force and tool tip temperature generation. In the current research, experiments were conducted based on DOE by developing experiments with three factors i.e. cutting speed at four levels and feed and depth of cut at two levels corresponding to the L_8 experimental array to measure maximum tangential force and temperature generation at the tool tip during CNC turning operation. Prediction of maximum tangential force and tool tip temperature during CNC turning operation has been pursued with the help of Taguchi approach. At the end, a verification test was conducted to illustrate the effectiveness of this approach.

Keywords: CNC Turning, Tangential Force, Tool Tip Temperature, L_8 Orthogonal Array.

1. INTRODUCTION

The objectives in Indian machining industry are quite different than the other developed countries. Because of intense availability of skilled manpower, conventional machining is still being used in large quantity. Majority of workers in such a small scale industry lacks proper training and hence it is very difficult to make them understand the concepts of mathematical model and outcomes. Till date lots of the products are being developed and/or manufactured in CNC machining but sustainability assessment of a CNC turning process at small scale industry is rarely focused. Thus, there is a need of developing a simple model which will be easy to understand and can be easily incorporated in small scale industries working on CNC machining. The components of resultant force in machining process, especially the main cutting (tangential) force, is one of the main parameters providing information on machinability of materials. The machining force components are influenced by several factors such as cutting speed, feed rate, depth of cut, cutting fluids, tool geometry, and others, besides the properties of the material being machined [1, 2]. The forces, in turn, influence cutting temperature, tool wear and life, work piece surface integrity, machining dynamics, dimension of the machine-tool structures, machining power, and others [3-6].

Material removal processes are an integral part of many manufacturing processes. It is important to study the many factors influencing these operations in order to achieve better performance with minimum energy consumption. The chip formation process occurring during metal cutting is a complicated one, involving plastic deformation, work hardening, heat generation, and tool wear. Finding a range of cutting conditions that will give maximum efficiency can help manufacturers produce in sustainable way.

In machining process, the cutting energy is mostly transformed into heat and eliminated through the chips but some of this energy increases the temperature of the tool and work piece. The main source of energy that is converted into heat is the plastic deformation at shear zone, friction in the interfaces tool/chip and tool/work piece. During the cutting process, high temperatures are generated near the tool cutting edge, and these temperatures affect greatly the tool wear rate. These temperatures, whose maximum value occurs along the tool rake face at some distance from the cutting edge [7, 8], can be estimated from measure of the thermal electromotive force of tool-work piece thermocouple during cutting process. Rajemi et. al. [9] developed a model for optimizing energy footprint of machined product. They identified critical parameters in minimizing energy use and hence reducing energy cost and environmental impact. The aim of this research work is to study the effect of varying machining parameters on maximum temperature generated at tool tip during CNC turning of a complex shape on Aluminum work piece using HSS tools in order to develop prediction models for these by using Taguchi analysis (L_8) [10]. The machining parameters studied are speed (*v*), feed (*f*), and depth of cut (*d*). The result of the Taguchi analysis was further analysed with design of experiment (DOE) and then the data were fitted in an adaptive Neuro-Fuzzy system (ANFIS) [11, 12] to predict the optimum prediction of temperature generation at the tool tip during CNC turning operations.

2. EXPERIMENTAL PROCEDURE AND MEASUREMENTS

2.1 Cutting tool preparation

HSS cutting tools with 5% cobalt (M-grade SI 6) were used with specific cutting angles, such that the tools cut orthogonally. This meant a back rake angle, side rake angle, and side cutting angle of zero degrees, resulting in a rake angle of zero degrees as well as high relief angles. The tool signature is listed below.

(i) back rake angle = 0°;
(ii) side rake angle = 0°;
(iii) end relief angle = 16°;
(iv) side relief angle = 21.5°;
(v) end cutting edge angle = 23°;
(vi) side cutting edge angle = 0°;
(vii) nose radius = 0.25 mm.

2.2 Work material preparation

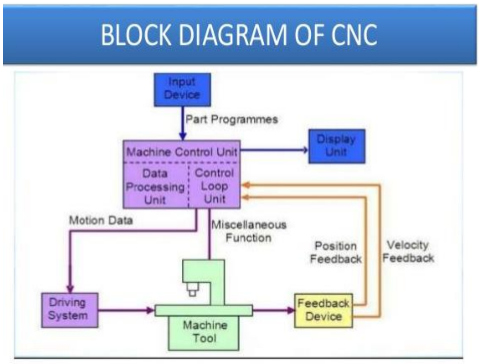
Work piece materials have been prepared by turning from the rod of Aluminum of grade 4. The dimension of the work piece is Ø25X100mm. The product was produced on both sides of the raw materials. The product cannot be made by mere longitudinal turning since a round shape was given in the product shape. The generated products are shown in Figure 1.

Figure 1. Photograph of the generated products (with magnification 20X)

2.3 Experimental setup

The experiments were performed in a HYTECH CNC turning center (model. Nano-CNC-PC) at advanced technology lab of MCKVIE. It has 0.010 mm and 0.005 mm minimum movement along X direction and Z direction respectively. The photographs of the machine set up along with the MCU have been shown in Figure 2.

a) MCU



b) Block diagram

Figure 2. Experimental setup (HYTECH CNC turning center with MCU)

2.4 Design of experiment

Taguchi's approach provides the designer with a systematic and efficient approach for conducting experimentation to determine near optimum settings of design parameters for performance and cost. The method emphasizes pushing quality back to the design stage, seeking to design a product/process, which is insensitive to quality problems. The Taguchi method utilizes orthogonal arrays to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. The conclusions drawn from small-scale experiments are valid over the entire experimental region spanned by the control factors and their settings. This method can reduce research and development costs by simultaneously studying a large number of parameters. In order to analyze the results, the Taguchi method uses a statistical measure of performance called signal-to- noise (S/N) ratio. The S/N ratio takes both the mean and the variability into account. The S/N equation depends on the criterion for the quality characteristic to be optimized. After performing the statistical analysis of S/N ratio, an analysis of variance (ANOVA) needs to be employed for estimating error variance and for determining the relative importance of various factors.

(a) L_8 orthogonal array
In L_8 array 8 rows represent the 8 experiments to be conducted with 3 columns at, 4 levels of one factor and 2 levels of the rest 2 factors. The matrix forms of these arrays are shown in Table 1. Where 1, 2, 3, etc. in the table represents the level of each parameters.

(b) Determination of S/N ratio curve

S/N ratio is a mathematically transformed form for quality/ performance characteristic, the maximization of which minimizes quality loss and also improves (statistically) the additive of control factor effects.

From each experimental result, S/N value can be calculated as

$$\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right] \qquad (1)$$

for the smaller is better type problem and for larger is better type problem.

$$\eta = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^{2}}\right] \qquad (2)$$

where η denotes the S/N ratio calculated from the observed or experimental values y_i represents the experimental observed value of the *i*th experiment, and *n* is the number of times each experiment is repeated.

Table 1. Factors with their levels

Control Factor	Level 1	2	3	4	Unit
A. Cutting Speed	500	1000	1500	2000	RPM
B. Feed Rate	30	90	-----	-----	mm/min
C.DOC	0.5	1.5	-----	------	mm

2.5 Maximum temperature at the tool tip measurement

Table 2. L_8 orthogonal array

Expt. No	Column No.& Factor assignment A	B	C
1	1	1	1
2	1	2	2
3	2	1	1
4	2	2	2
5	3	1	2
6	3	2	1
7	4	1	2
8	4	2	1

It is assumed that the process has orthogonal cutting geometry and the chip is sheared from the blank at an infinitely thin shear plane (i.e. primary deformation zone). The chip slides on the rake face (i.e. secondary deformation zone) with a constant average friction coefficient. The thermocouple which was used could measure from -50°C to 1300°C with a resolution of 1°C and accuracy of ± (0.3% rdg+1°C). The display unit has 3.5 digits LCD with maximum reading of 1999. During the experiment 4-foot type "K" thermocouple bead probe (Teflon tape insulated).

Maximum insulation temperature 260°C. Probe accuracy ±2.2°C or ±0.75% of reading whichever is greater. The probe was touched firmly against the tool tip during experiment to measure the temperature. The reading was taken after the reading become stable.

Figure 3. Thermocouple for measurement of temperature of tool tip

3. RESULTS AND DISCUSSION

3.1 Analysis of main cutting force(Fc) based on S/N ratio curve and ANOVA table

From the S/N ratio curve for feed force as depicted in Figure 8, it has been found that feed force have an increasing trend with the increase of depth of cut, feed rate and cutting speed. This is due to the fact that with increase of depth of cut, feed rate and cutting speed the tool and work interaction is more . As a result the feed force increases. From Fig 7 depicts residual plots of feed force.

Table 3. ANOVA analysis for main cutting force

Factors	D.O.F.	S.O.S.	Mean Square	F	p
Regression	3	8590	2863.33	71.58	0.0006
A	1	90	90.00	2.25	0.2080
B	1	2450	2450.00	61.25	0.0014
C	1	6050	6050.00	151.25	0.0002
Error	4	160	40.00		
Total	7	8750			

S = 6.32456 R-Sq = 98.17% R-Sq(adj) = 96.80%

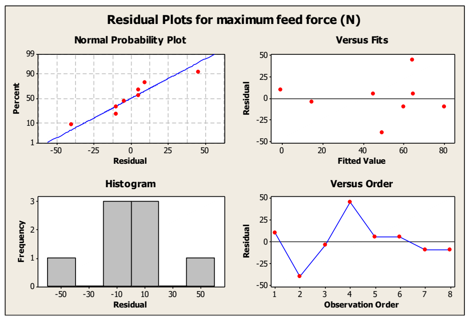


Figure 4. Residual plots for main cutting force

[a] Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

Referring to the sum of squares column in Table 3, notice that D.O.C. makes the largest contribution to the total sum of squares. Feed rate makes the next largest contribution for the response and cutting speed has very small contribution to the total sum of squares. The larger contribution of a particular factor to the total sum of squares, the larger the ability is of that factor to influence η. So, depth of cut and feed rate has more effect on chip thickness. For minimization of chip thickness, we have to control the depth of cut and feed rate and we have to set these two parameters very carefully.

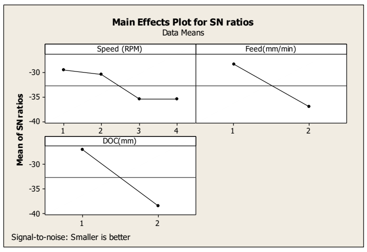


Figure 5. S/N ratio plots for main cutting force

3.2 Analysis of T_{max} based on S/N ratio curve and ANOVA table

From the S/N ratio curve of T_{max} as depicted in Figure 10, T_{max} has been found to have an increasing trend with the increase of depth of cut and speed of machining. This is due to the fact that with increase of cutting speed and feed rate the frictional forces increases. As a result the T_{max} increases. With the increase of depth of cut the T_{max} increases because of increase of friction between the tool tip and workpiece. Figure 9, sows the residual plot of T_{max}.

From Table 3, it can be observed that cutting speed makes the largest contribution to the total sum of squares. The factor depth of cut makes the next largest contribution to the total sum of squares. Factor feed rate has relatively small contribution to the total sum of squares. So cutting speed and depth of cut have more effect on Tmax and other factor has less effect on the T_{max}.

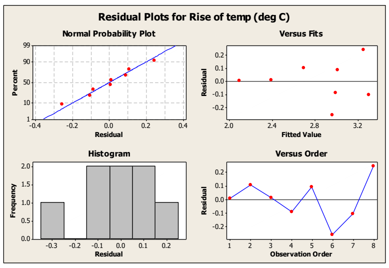


Figure 6. Residual plots for maximum rise of temperature (degree centigrade)

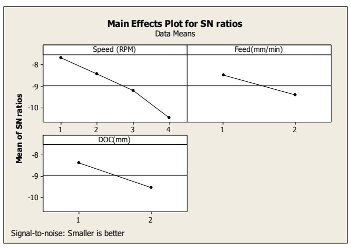


Figure 7. S/N ratio plots for maximum rise of temp (Degree centigrade)

[a] indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.

3.3 Outcomes of the analysis

From the S/N ration curve for feed force and Tmax the optimum parametric combinations are noted. The cutting speed, depth of cut and feed rate is shown in Table 4 below.

3.4 Validation experiment

To verify the proposed model another set of experiment has been carried out as shown in Table 4 It is observed from Table 5 that prediction based on additive model is quite close to the experimental observation. Prediction error in the Table 6 has been defined as follows.

Table 3. ANOVA analysis for Tmax

Factors	D.O.F.	S.O.S.	Mean Square	F	p
Regression	**3**	**1.23**	**0.41**	**9.90**	**0.03**
A	**1**	**0.87**	**0.87**	**20.97**	**0.01**
B	**1**	**0.15**	**0.15**	**3.64**	**0.13**
C	**1**	**0.21**	**0.21**	**5.09**	**0.09**
Error	**4**	**0.17**	**0.04**		
Total	**7**	**1.40**			

S = 0.203715 R-Sq = 88.13% R-Sq(adj) = 79.23%

Table 4. Optimum parametric combination

Physical requirement	Optimal combination For feed force	For T_{max}
A. Cutting Speed (RPM)	1	1
B. Feed Rate (mm/min)	1	1
C. Depth of Cut (mm)	1	1

$$\textbf{Prediction Error}(\%) = \left|\frac{\textbf{Exp.result} - \textbf{Predicted result}}{\textbf{Exp.result}}\right| \times 100 \qquad (3)$$

Table 5. Verification experiment

Exp. No.	Control factors			Responses	
	Cutting Speed (RPM)	Feed Rate (mm/min)	DOC (mm)	Feed Force (N)	Rise of temp (degree C)
1	1	1	1	9.51	2.15

Table 6. Prediction error calculation

Exp. No.	Experimental Result		Predicted Value		Prediction Error (%)	
	Feed Force (N)	Rise of temp (degree C)	Feed Force (N)	Rise of temp (degree C)	Feed Force	Rise of temp
1	10	2.1	9.51	2.15	4.9	2.4

It is clear that the data agree very well with the predictions. Therefore, the optimum settings given in Table 5 may be adopted and implemented accordingly.

4. PREDICTION OF OPTIMUM TMAX BY ANFIS APROACH

The adaptive network-based fuzzy inference system (ANFIS) is a Takagi-Sugeno based fuzzy inference system proposed by Jang [7]. Assuming a fuzzy rule with two inputs and a single output, the first order Takagi-Sugeno if-then rules can be written as follows.

Rule 1. If x is A1 and y is B1 and z is C1 then F1=p1 x+q1 y+r1 z+ s1

Rule 2. If x is A2 and y is B2 and z is C2 then F2=p2 x+q2 y+r2 z+ s2

ANFIS employs back propagation learning to determine the premise parameters and least mean square estimation to determine the consequent parameters.

This algorithm works in two-pass hybrid learning cycles. In the forward pass, the set of premise parameters are fixed and the inputs are propagated to layer 4, and the set of consequent parameters is computed using least mean square algorithm. In the backward pass, the consequent parameters are fixed and the error signals are propagated backwards and the premise parameters are updated using gradient descent [7].

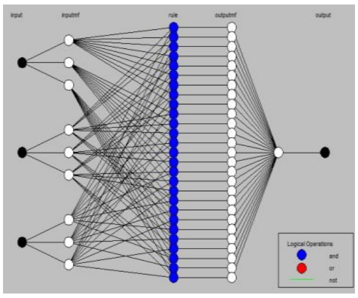


Figure 8. ANFIS architecture

Figure 6 shows the structure of the ANFIS model, which has three inputs, 27 rules and five layers. Function of each layer is briefly described below.
The regression equation of from the taguchi method was obtained as follows.

Tmax=16.625+0.00705*x+0.03125*y+0.125*z (4)

Fc = -85 +3*x+3.5*y+5.5*z (5)

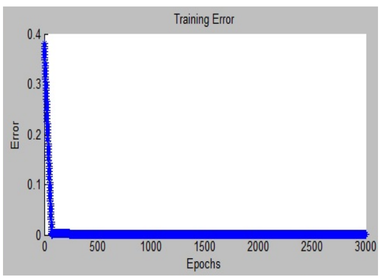


Figure 9. Training error for tmax at 3000 epochs (error. 0.0018697)

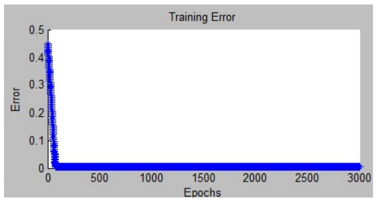


Figure 10. Training error for Fc at 3000 epochs (error. 0.0018697)

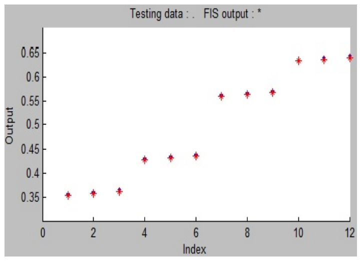


Figure 11. Test error for Tmax (average testing Error 0.0033855)

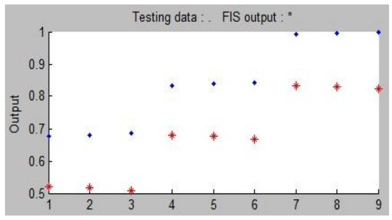


Figure 12. Test error for Fc (average testing Error 0.16512)

From the Eqn (4) 27 set of training data and 9 set of test data were generated. These data were first normalized and then fitted to the ANFIS model as shown in Figure 6. The analysis was made in MATLAB 7.12.

The training error at 3000 epochs was obtained as 0.0018697 (Figure 7) i.e. 0.19% and average testing error was obtained as 0.00255966 (Figure 8) i.e. 0.26%. Both errors were within in acceptable range. The obtained optimum level setting and defuzzified output were 0.333, 0.5, 0.5 and 0.358 respectively. These were coded value. The actual values are as shown in Table 6. The verification experiment was carried out for the optimum level setting and it has been observed from table 6 that the prediction error is almost 1.09% which is very small. So, the ANFIS model produces the optimum result which is within acceptable range.

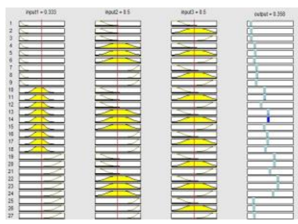


Figure 13. Inputs and output at the final iterations for Tmax

It has been observed from table that 1000 rpm cutting speed, 60 mm/min feed rate and 1 mm depth of cut is the optimum level setting produce by ANFIS model. From the surface graph obtained during final iteration of ANFIS as shown in Figure 10, it has been observed that with cutting speed the variation of output is noticeable. At first it is increasing and then it decreased and after the optimum value it increases. Almost same nature is obtained for the other parameters also.

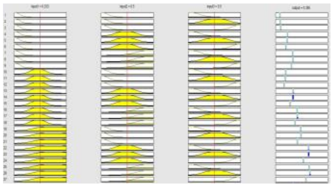
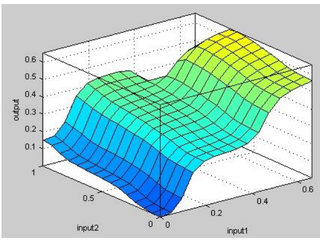


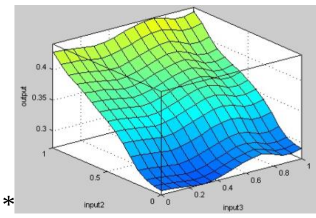
Figure 14. Inputs and output at the final iterations for Fc

Table 7. Optimum parametric combination and verification test

Control factors			Predicted Value	Experimental Result	Prediction Error (%)
Cutting Speed (RPM)	Feed Rate (mm/min)	DOC (mm)	Rise of temp (degree C)	Rise of temp (degree C)	
1000	60	1	4.65	4.6	1.09



(a) Tmax v/s cutting speed and feed rate



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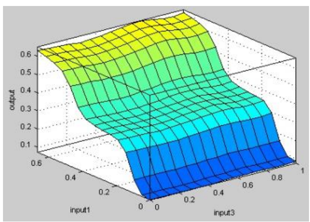
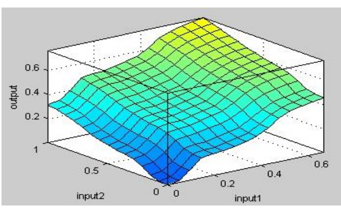
(b) Tmax v/s cutting speed and feed rate

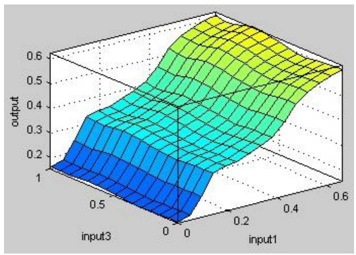


(c) Tmax v/s cutting speed and feed rate

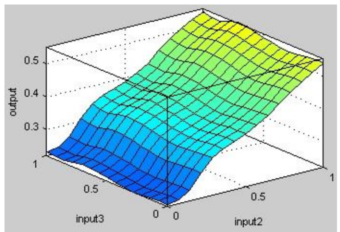
Figure 15. Output i.e. Tmax v/s different inputs at the optimum level setting predicted by ANFIS Model



(a) Fc v/s cutting speed and feed rate



(b) Fc v/s cutting speed and feed rate



(c) Fc v/s cutting speed and feed rate

Figure 16. Output i.e. Fc v/s different inputs at the optimum level setting predicted by ANFIS Model

Table 8. Optimum parametric combination and verification test

Control factors			Predicted Value	Experimental Result	Prediction Error (%)
Cutting Speed (RPM)	Feed Rate (mm/min)	DOC (mm)	Rise of temp (degree C)	Rise of temp (degree C)	
1000	60	1	35	40	12.5

5. CONCLUSIONS

Carrying the experimental investigation based on Taguchi L_8 orthogonal array and followed by ANFIS model approach the following assumption are made.

Prediction of maximum temperature generation at the tool tip is an important phenomenon because it is directly related to energy consumption leading towards sustainability issues.

It has been observed that Taguchi model predict that lowest level setting will produce the minimum tool tip temperature during CNC turning that is true but in these case 8 data were analyzed. To analyze more data the regression equation was applied.

The generated data were fitted to the ANFIS model and the ANFIS model predict that 1000 rpm cutting speed, 60 mm/min feed rate and 1 mm depth of cut is the optimum level setting that can produce temperature 4.65° (i.e. difference between tool tip and room temperature) which is very close to experimental result with an error of 1.09%. This method of prediction can be applied for other parameters of the CNC turning also and can help the operator of CNC machine.

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NOMENCLATURE

v	cutting speed in rpm
f	feedin mm/min
d	*depth of cut in mm*
DOE	Design of Experiment
ANFIS	Adaptive Neuro-Fuzzy System
η	Signal to noise ratio in db
D.O.F.	degree of Freedom
S.O.S.	Sum of Square
F	Fitness value
P	probability value