Investigations into Machining of Inconel 718 By Using Adaptive Fuzzy Based Inference System

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***Abstract* - Approximately 60% of all the superalloys produced are having application in the aerospace industry for the manufacture engines and its components, mainly in the hot end of aircraft engines and land-based turbines. The remaining 40% of superalloy consumption is used by the chemical, medical and structural industries in applications requiring high temperature properties. Superalloy, Inconel 718 is widely used in various engineering applications in gas turbine; aircraft engine parts, chemical processing, pressure vessels, steam turbine power plants, space vehicles, medical applications, marine applications, pollution control equipment and automotive sector etc. Other areas of usage are within space exploration (main space shuttle engine, nickel–hydrogen batteries (international space station), power generation (industrial gas turbines), and chemical industry (cryogenic tanks). Due to peculiar characteristics and properties posses by inconel 718 it is referred to as difficult -to-cut and costly. The present work is an attempt to make use of adaptive-network based fuzzy inference system (ANFIS) to predict the workpiece surface roughness after the turning inconel 718 using carbide tool. Analysis of variance (ANOVA) is used to study the effect of process parameter and establish the correlation among the cutting speed, feed with respect to surface roughness. Validations of the statistical and ANFIS model are proving to be well within agreement with experimental data. Two most influencing parameters that have a major impact on the surface roughness and flank wear, including spindle speed, and feed rate were analyzed. The predicted surface roughness values derived from regression analysis and ANFIS model were compared with experimental data. The comparison indicates that the adoption of regression analysis and ANFIS achieved very satisfactory. Predictably of coefficient correlation is 91% and ANFIS model reach as high as 94%.**

Keywords-- Turning; Adaptive-network based fuzzy inference system; Roughness

I. INTRODUCTION

Inconel 718 is nickel based super alloys referred as most difficult material to machine because of high hardness, high strength at high temperatures, affinity to react with tool materials and low thermal diffusivity. It is widely used in the fabrication of critical components of turbine engines in aero space applications. These alloys have excellent mechanical properties at elevated temperatures and good corrosion resistance. Cemented carbide tools are still largely used for machining the nickel-based superalloys, especially Inconel718. Over the years, the use of carbides for cutting tools has been established. However, with the increasing demand to achieve fast material removal and better surface quality, high speed machining was introduced and the use of the cemented carbide tools has become more problematic. For nickel-based alloys, the concept of high speed machining refers to speeds over 50 m/min (Dudzinski et al., 2004).

Increasing the productivity and the quality of the machined parts are the main challenges of manufacturing industry, in particular for heat resistant super alloys employed in aeronautic and aerospace applications. This requires better management of the machining system corresponding to cutting tool-machine tool- study piece combination to go towards more rapid metal removal rate. Exploring higher cutting speed depends to a greater extend on the cutting tool materials (Ezuguw, 2005).Turned surface with good quality improves fatigue strength, corrosion resistance, and creep of component. Surface roughness also affects several functional attributes of parts such as contact causing surface friction, light reflection, heat transmission ability to distributing and holding the lubricant. Turning process is a widely used operation in the engineering industry. Mostly the cutting parameters are selected based on the experience or by use of handbook. However, this does not guarantee that the selected parameters are optimal one. Selection of wrong or non optimal parameters leads to the wastage of raw material, man power, electricity, cutting fluid, cutting tools, etc. Hence, there is an increase in manufacturing cost of the product (Thakur et al., 2009). Therefore development of predictive models for machining responses can avoid numbers of trials to understand and investigate the effect of influencing factors and their combined effect of interactions.

In this paper, attempt is made to understand and investigate the influence of cutting speed and feed on surface roughness into turning of inconel 718. In this work, experimental study on turning on inconel 718 is presented. Classical full factorial experimental design (DOE) methodology has been used for this study. Multiple regression analysis has been used to develop statistical correlation between speed, feed and surface roughness. In addition an adaptive neuro-fuzzy inference system (ANFIS) was used to develop model for surface roughness. Both these models compared with the experimental results.

II. EXPERIMENTAL DETAILS

The wok piece material used was inconel 718 round bar of Φ25 mm diameter. The machine tool used was Micromatic make Jobber XL CNC Lathe machine carbide cutting tool insert (K20), Surface roughness was measured by using Mitutoyo SJ-401surface roughness tester. The measuring head of the tester moved along (parallel to) the rotational axis of work piece. The chemical composition, mechanical and physical properties of inconel 718 is as in table1.

TABLE 1: CHEMICAL COMPOSITION OF INCONEL 718

Element	***Ni (+Co)***	***Ti***	***Cr***	***Nb(+Ta)***	***Al***	***Fe + Other***
Weight (%)	50-55	0.65-1.5	17-21	4.75-5.5	0.2-0.8	Balance

A. *Design of Experiment (DoE)*

In this study, full factorial design has been used. In this work, two factors at three levels are used as shown in the Table 2. The factor levels are chosen of the values used recommended in high speed machining of inconel 718, so the likely values used in production will be in these ranges. The effect of these factors and effect of their interaction on the surface roughness (response) has also been studied.

TABLE 2: PARAMETERS AND THEIR LEVELS

Parameters	**Levels**		
	Level 1	***Level 2***	***Level 3***
Cutting Speed, Cs (m/min)	50	60	70
Feed, f (mm/rev)	0.08	0.12	0.16

B. *Experimental results*

Table 3 shows the various values of surface roughness and flank wear for tow replicates for turning of inconel 718.

TABLE 3: OVERALL EXPERIMENTAL RESULTS

Factors		**Surface Roughness**		**Flank wear**	
Speed (m/min)	***Feed (mm/rev)***	***Replicate 1 Ra (µm)***	***Replicate 2 Ra(µm)***	***Replicate1 (mm)***	***Replicate 2 (mm)***
50	0.08	0.19	0.19	0.42	0.26
50	0.12	0.21	0.20	0.43	0.39
50	0.16	0.29	0.27	0.44	0.47
60	0.08	0.31	0.3	0.49	0.47
60	0.12	0.32	0.32	0.52	0.49
60	0.16	0.36	0.33	0.36	0.37
70	0.08	0.25	0.24	0.38	0.42
70	0.12	0.26	0.24	0.4	0.41
70	0.16	0.23	0.21	0.42	0.44

The data given in the Table 3 is analysed by using a softwarepackage Minitab 16. The regression analysis model in table 3 and ANOVA are presented in Table 5. The model and includes all the main and two way interactions.

C. *Regression model*

Based on the experimental data, statistical regression analysis enabled to study the correlation of process parameters with the surface roughness. Non-linear regression model was examined; acceptance was based on high to very high coefficients of correlation calculated. The coefficients of regression model can be estimated from the experimental results. The effects of these variables and the interaction between then were included in this analyses and the developed model is expressed as in interaction equation. The unknown coefficients are determined from the experimental data as presented in Table 4. The standard errors on estimation of the coefficients are tabulated in the column ’SE coef. The F ratios are calculated for 95% level of confidence and the factors having p-value more than 0.05 are considered insignificant (shown with ** in p-column) for the appropriate fitting of surface roughness. The model made to represent surface roughness depicts that cutting speed, feed and their interaction are the most influencing parameters in order of significance. The final response equation for surface roughness is given in equation 1.1.

TABLE 4: ESTIMATED REGRESSION COEFFICIENTS FOR RA

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	-3.581	0.2923	-12.10	0.000*
Cs	0.119292	0.009222	12.93	0.000*
f	3.875	1.393	2.78	0.017*
Cs * Cs	-0.00091667	0.00007560	-12.13	0.000*
f * f	3.646	4.725	0.77	0.455**
Cs * f	-0.07187	0.01336	-5.38	0.000*
*-Significant, **-Non-significant				

S = 0.01512   R-Sq = 94.2%   R-Sq (adj) = 91.8%

The empirical equation for predicting the surface roughness Ra is given by regression analysis is

$$\text{Ra Value} = -3.58 + 0.119\, Cs + 3.87\, f - 0.000917\, Cs * Cs + 3.65\, f * f - 0.0719\, Cs * f \ldots\ldots\ldots\ldots\ldots (1.1)$$

Table 5 shows the ANOVA for surface roughness. The purpose of the ANOVA is to determine the process parameters which significantly affect the performance characteristics. It was found that the cutting speed and feed rate and interactions are the significant cutting parameters for affecting the surface roughness. The ANOVA table for the model (Table 5) depicts the value of Coefficient of determination R-sq as 94.2%, which signifies that how much variation in the response is explained by the model. The higher of R-Sq, indicates the better fitting of the model with the data. However, R-sq adj is 91.8%, which accounts for the number of predictors in the model describes the significance of the relationship. It is important to check the adequacy of the fitted model, because an incorrect or under-specified model can lead to misleading conclusions. The model adequacy checking includes the test for significance of the regression model, model coefficients, and lack of fit, which is carried out subsequently using ANOVA is presented in table 5. The total error on regression is sum of errors on linear, square, and interactions terms (0.044567). The residual error is the sum of pure and lack-of-fit errors. The fit summary recommended that the model is statistically significant for analysis of surface roughness. In the table, all the p-value values are significant. Moreover, the mean square error of pure error is less than that of lack-of-fit. The final model tested for variance analysis (F-test) indicates that the adequacy of the test is established. The computed values of response parameters, model graphs are generated for the further analysis in the next section.

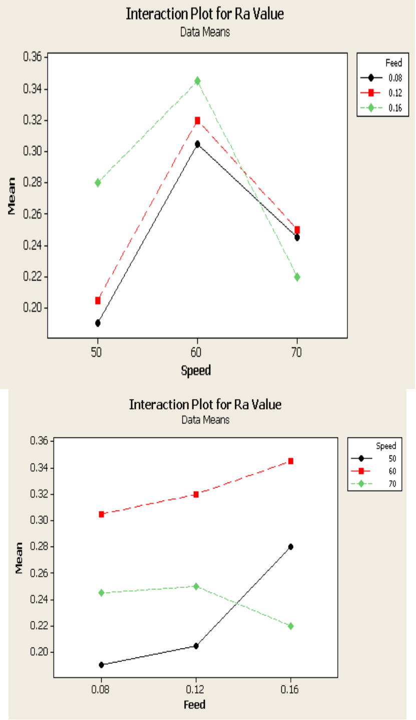
TABLE 5: ANOVA TABLE FOR FITTED MODEL

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	5	0.044568	0.044568	0.008914	38.99	0.000
Linear	2	0.004208	0.004208	0.002104	9.21	0.004
Square	2	0.033747	0.033747	0.016874	73.82	0.000
Interaction	1	0.006612	0.006612	0.006612	28.93	0.000
Residual Error	12	0.002743	0.002743	0.000229	--	--
Lack-of-Fit	3	0.001543	0.001543	0.000514	3.86	0.050
Pure Error	9	0.001200	0.001200	0.000133	--	--
Total	17	0.047311	---	---	---	---

III. RESULT AND DISCUSSIONS

In this section, the influence of cutting speed, feed and their interaction on surface roughness has been presented. As certain properties of Inconel 718 also contribute to the tool wear effect on surface quality. The interaction plots has been drawn by using minitab to understand the Effect of speed and feed on surface roughness (Ra) and effect of flank wear on surface roughness.

The results show that the surface roughness is affected significantly by the cutting speeds and feed rates. Figure 1: (a) and (b) shows the influence of cutting speed and feed on surface roughness during turning of Inconel 718. The turning was performed at different cutting speed and feed rate at a constant depth of cut of 0.5 mm.



(a) (b)

Figure 1: Interaction plot of surface roughness (Ra) Vs speed and feed

The effect on surface roughness in machining of Inconel 718 was found to following facts:

In turning of inconel 718 cutting force components are always higher in magnitude than feed force component (Thakur, et al. 2009). Further, as the cutting speed increases, the forces decrease. At low cutting speed between 50 to 60 m/min cutting forces might be higher because of the higher coefficient of friction between the tool and the work material. This , in turn increases the surface roughness.

At 60 m/min the surface roughness is high due to rapid tool wear rate and deformation of cutting edge due to more heat generation rate and also due to presence of hard carbide particles present in the matrix.

At higher cutting speed between 60 to 70 m/min, as the thermal conductivity and specific heat of the inconel 718 is low, the cutting temperature gets increased and heat dissipation into the workpiece gets reduced. Due to the higher temperature generation rate the material becomes soft at cutting zone. It might reduce the material strain hardening capacity and therefore, the shear instability takes place in a narrow band of chips. This helps in removing the material at lower cutting forces and improves surface roughness.

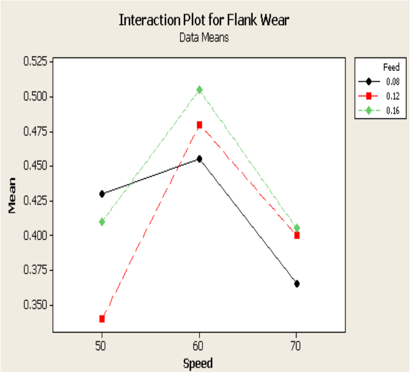
For low speed cutting conditions the chip shapes are continuous. In some cases segmented and saw tooth edged chips were observed. The deformation of chip is generally found to be inhomogeneous. In turning of inconel 718 localization of shear in the chip produces abrasive saw toothed edges, the mechanism of chip formation and separation is due to the extreme strain rate that occurs during the machining process. Figure 2: shows the images of chips at various cutting speed. As the cutting speed increases the chip gets thinner and forces drops. Therefore, decrease in both cutting force and feed force is due to decrease in contact area and partly due to drop in shear strength in the flow zone because of increase in temperature. It is expected that the chip thickness varies along the cutting edge. At the material at the trailing edge of the tool, where the chip thickness is a minimum, is subjected to high stress that causes tearing on the weakest edge of the chip.

(a) (b) (c)

Figure 2: Images of chips produced during turning of Inconel 718: (a) 50 m/min, (b) 60 m/min, and (c) 70 m/min. at 0.08 mm/rev

In addition, the variation in the chip velocity facilitates the non-uniform displacement along the chip width, which leads to chip edge serration. The existence of the chip edge serration facilitates trailing edge wear. Grooves are worn in the tool at the positions where the chip edge moves over the tool. These grooves deteriorate the surface roughness.

The results obtained from the machining experiment have shown that the flank wear were affected significantly by the cutting speed and feed rates. Effect of speed on flank wear at various feed level is shown in figure 4.6 (a).

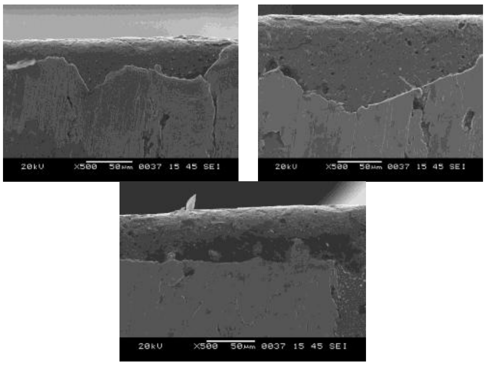


(a)

Figure 3: Interaction plot for flank wear Vs speed and feed

Increase in cutting speed from 50 to 60 m/min and feed rate 0.08 to 0.16 mm/rev might cause a greater increase in cutting temperature at the cutting edge of the tools. The higher temperature generated caused the tools to lose their strength and may be leads to plastic deformation. Therefore, increase in flank wear increases the surface roughness. Feed has significant impact on surface roughness. When feed increases from 0.08 to 0.12 m/min flank wear reduces even though increase in roughness because of feed is influencing factor. Further increase in feed from 0.12 - 0.16 mm/rev flank wear increases and both flank wear and increased feed are the influencing factor.

The figure below shows the result of observation by SEM of the tool after Inconel 718. It is believed that the adhesion of Inconel 718 work piece was deposited on the flank face of the tool.



(a) Cs = 50 m/min (b) at Cs = 60 m/min (e) at Cs = 70m/min

Figure 4: SEM images of cutting tool insert wear

SEM micrographs of the tool section shows the coating film after cutting adhesive was observed on the flank face of the tool. Immediately after cutting is started, the workpiece adheres to the flank face and because this adhesive becomes a stable built-up edge, wear of the rake face is almost not found and only the flank wears observed.

IV. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (ANFIS)

In this section, the ANFIS architecture and its learning algorithm for the Sugeno fuzzy model are primarily described. For simplicity, let the fuzzy inference system under consideration has two inputs m and n and one output f. For a first-order Sugeno fuzzy model, a typical rule set with two fuzzy if–then rules can be expressed as

· Rule 1: If (m is A1) and (n is B1) then $f1 = p1m + q1n + r1$…………… (2.1)

· Rule 2: If (m is A2) and (n is B2) then $f2 = p2m + q2n + r2$ ………… (2.2)

Where p1, p2, q1, q2, r1 and r2 are linear parameter and A1, A2, B1 and B2 are nonlinear parameter.

The corresponding equivalent ANFIS architecture is as shown in Figure 4. The entire system architecture consists of five layers, namely, the fuzzy layer, product layer, normalized layer, de-fuzzy layer and total output layer. The following sections discuss in depth the relationship between the output and input of each layer in ANFIS.

Layer 1 is the fuzzy layer, in which m and n are the input of nodes A1, B1 and A2, B2, respectively. A1, A2, B1 and B2 are the linguistic labels used in the fuzzy theory for dividing the membership functions. The membership relationship between the output and input functions of this layer can be expressed as below:

$O1,i = \mu Ai(m),\ i = 1, 2, \quad O1,j = \mu Bj (n),\ j = 1, 2$ …………………….. (2.3)

Where O1,i and O1,j denote the output functions and μAi and μBj denote the membership functions.

Layer 2 is the product layer that consists of two nodes labeled II. The output W1 and W2 are the weight functions of the next layer. The output of this layer is the product of the input signal, which is defined as follows:

$O2,i = wi = \mu Ai(m)\mu Bi(n),\ i = 1, 2$ …………………………………….. (2.4)

Where O2,i denotes the output of Layer 2.

Layer 3 is the normalized layer, whose nodes are labeled N. Its functions are to normalize the weight function in the following process:

$O3,i = Wi = (wi / W1 + W2),\ I = 1, 2$………………………………….. (2.5)
Where O3,i denotes the Layer 3 output.

Layer 4 is the de-fuzzy layer, whose nodes are adaptive. The output equation is W. (pm+qn+r), where pi, qiand ri denote the linear parameters or so-called consequent parameters of the node. The de-fuzzy relationship between

the input and output of this layer can be defined as follows:

$O4,i = Wifi = Wi (pim + qin + ri),\ i = 1, 2$ …………………………….. (2.6)

Where O4,i denotes the Layer 4 output.

Layer 5 is the total output layer, whose node is labeld as ∑. The output of this layer is the total of input signals, which represents the results of surface roughness. The results can be written as below:

$O5,i = \sum Wifi = \sum iwifi / \sum iwi,\ i= 1, 2$ ………………………………… (2.7)

Where O5,i denotes the Layer 5 output.

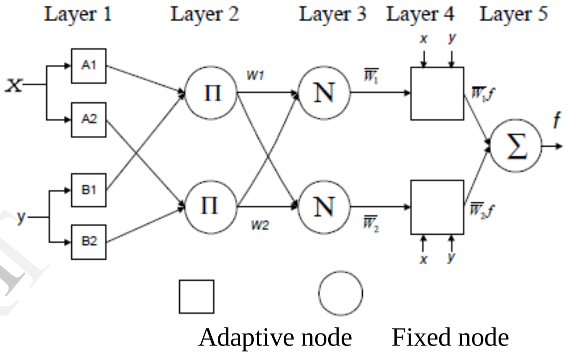


Figure 5: ANFIS architecture

Spindle speed and feed rate were selected as the machining parameters to analyze their effect on surface roughness. The construction of model based on numbers of input functions having influence on responses. For this study speed and feed are the adjustable input factor having influence on output machining parameter surface roughness.

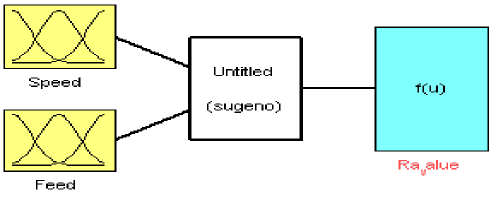


Figure 6: The Sugeno model Fuzzy rule architecture of the triangular membership function.

Experimental result replicate 1 and 2 were used as training and testing data to develop the ANFIS method. The settings of cutting speed include 50, 60 and 70 m/min; those of feed rate include 0.08, 0.12, 0.16 mm/rev. The value of surface roughness was measured after turning according to the above machining conditions and then used as the training and testing data in ANFIS, as listed in Table 3. Figure 7shows the fuzzy rule architecture of ANFIS when the triangular membership function is adopted, respectively. The architectures shown in Figure 6 consist of 9 fuzzy rules.

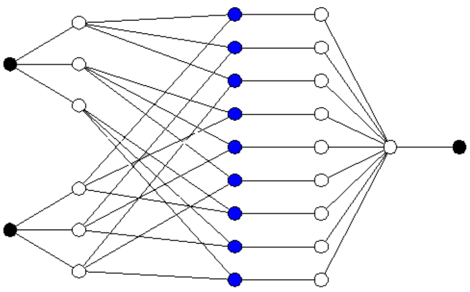


Figure 7: Fuzzy rule architecture of ANFIS for turning.

The initial value for the adaptation of parametric pace was 0.01. The membership function of every input parameter within the architecture can be divided into three areas, i.e. low, medium and high areas. Figures 8–9 show the initial and final membership functions of the two turning parameters derived by training via the triangular membership function. In Figure 8, the initial membership function and the final membership function of parameter Speed only experience changes in the small, medium and large areas. Figure 9 shows the initial and final membership functions of parameter Feed. There are obviously very small changes in the final membership function.

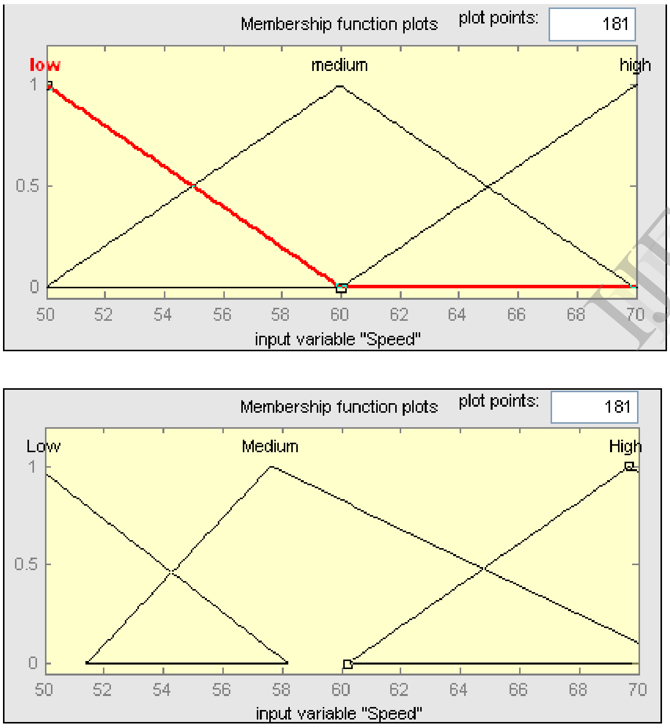


Figure 8: Initial and final membership function for cutting speed

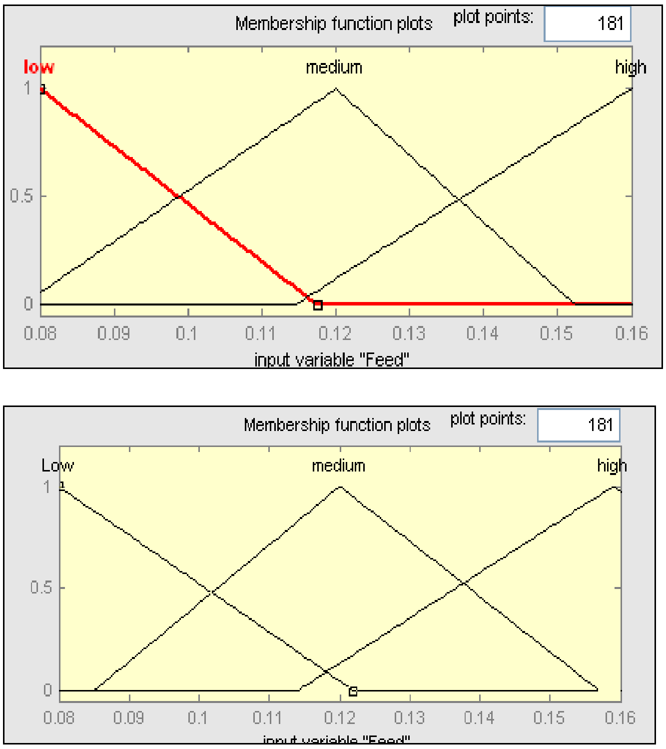


Figure 9: Initial and final membership function for feed

The surface roughness values predicted by regression analysis and ANFIS are compared with the measured values sets in order to determine the error of statistical and ANFIS models. Table 6 compares the predicted values and experimental data of the surface roughness by Regression and ANFIS

TABLE 6: RESPONSES OF REGRESSION AND ANFIS AGAINST MEASURED RA VALUE

Factors		**Measured Value**	**Predicted values Regression**	**Error**	**Predicted values (ANFIS)**	**Error**
Speed (m/min)	***Feed (mm/rev)***	***Ra (µm)***	***Ra (µm)***	***(%)***	***Ra (µm)***	***(%)***
55	0.1	0.27	0.28	-3%	0.266	1%
55	0.12	0.27	0.29	-9%	0.277	-3%
55	0.16	0.34	0.33	3%	0.332	2%
60	0.1	0.33	0.31	5%	0.312	5%
60	0.12	0.34	0.32	6%	0.32	6%
60	0.16	0.36	0.34	5%	0.36	0%
65	0.16	0.3	0.31	-3%	0.292	3%

The Figure 10 shows the comparison between predicted surface roughness values form regression analysis and ANFIS with measured values. Both regression and ANFIS models found significant for prediction of surface roughness.

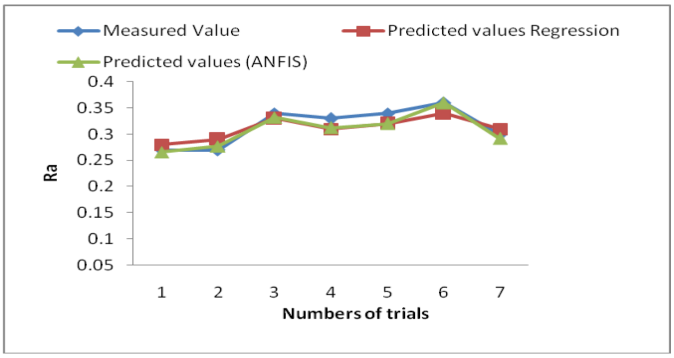


Figure 10: Comparison between Measured value, regression and ANFIS predicted values of surface roughness

V. CONCLUSIONS

Based on the present study following conclusions have been drawn in turning of Inconel 718 with multilayered PVD (Ti, Al) N coated carbide tool At low cutting speed between 50 to 60 m/min and higher feed rates 0.12 to 0.16 mm/ rev., the cutting forces may be higher because of the higher coefficient of friction between the tool and the work material. This in turn increases the surface roughness.

At higher cutting speed between 60 to 70 m/min and higher feed rates 0.12 to 0.16 mm/rev., the temperature generation rate might be higher which makes the material soft at cutting zone. Further reduced thermal conductivity, assist the softening effect. This helps in removing the material at lower cutting forces and improves surface roughness.

As speed increases from 50 to 60 m/min, the flank wear increases which result in high surface roughness and reduce when further increase in speed up to 70 m/min. After 60 m/min., flank wear reduces and improves surface quality. At speed 70 m/min. even though increase in feed from 0.12 to 0.16 m/rev., the flank wear is low and with constant trend. As speed increases, the time for heat dissipation decreases and thus temperature raises, this makes the material soft at cutting zone. It also helps in removing the material at lower cutting forces and improves surface roughness.

A correlation coefficient and ANFIS is used to predict the work piece surface roughness for turning process and analyze the effect of cutting speed and feed rate on the surface roughness. The surface roughness values predicted by regression analysis and ANFIS are compared with the measured values sets in order to determine the error of statistical and ANFIS models. Besides, the few sets of experimental data are analyzed to verify the results obtained by ANFIS. The predictability of regression analysis is 91% whereas of ANFIS with 94%.

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