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Analysis on Influence of feed rate and tool geometry on cutting forces in turning using Taguchi method and Fuzzy Logic

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Abstract

In this paper, the influence of feed rate and tool geometry on cutting force during turning is studied by using Taguchi Method and Fuzzy Logic. Series of turning experiments are conducted according to Taguchi Experimental Design on Aluminiumwork piece with the HSS cutting tools having different angle geometry at different feed rates and the values of responses (cutting forces) are recorded. Taguchi orthogonal array is designed with three factors each at four levels using MINITAB software. The experimental data is analyzed and the influence of feed rate and tool geometry on cutting forces is studied and the optimum values of these factors are identified. A fuzzy rule based system is developed for the estimation of cutting forces for the optimum values obtained from Taguchi Method. Finally a confirmation test is conducted for the Fuzzy Logic estimated values at optimized input parameters, and found that the prediction error of fuzzy results is about 4.56 and the percentage of accuracy is 95.44%.

Keywords: Taguchi method; tool geometry, cutting forces, feed rate, optimum values, Analysis of variance, fuzzy inference system, fuzzy sets;

1. Introduction

The challenge of modern machining industries is mainly focused on the achievement of high quality in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy in machining. Measurement and analysis of Cutting forces are necessary for evaluation of power required for machining, design of machine tool components and tool body.The cutting forces are determined mainly by depth of cut and feed rate, respectively more than by cutting speed (NicoletaLungu et al., 2012). The cutting force

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components are very sensitive even to the smallest changes in the cutting process. Therefore, instead of calculating the cutting force theoretically, measuring them in process by dynamometers is preferred(Saglam, H et al., 2007).

1.1. *Feed rate*

The feed rate is the amount of tool advancement per revolution of job parallel to the surface being machined and is measured in mm/revolution. Feed rate is effective on all cutting forces, in the case of increasing feed rate, especially feed force increases and residual stresses change from compressive to tensile(Thiele, J.D et al., 2000).Increase in feed rate raises the compressive residual stress maximal and deepens the affected zone(A. Fata et al., 2010).

1.2. *Tool geometry*

In tool geometry rake angle (*α*) is the angle contained by a plane perpendicular to the main cutting edge of the tool and is a measure of the edge in relation to the cut itself. This angle can be take positive or negative value. Positive rake angle produces higher shear angle and therefore, it leads to reduction of cutting forces. But excessive value of this angle causes tool breakage(HacıSağlam et al., 2011). Negative rake angle strengthens tool edge against hammering effects and heavy machining loads. In contrast the tools having positive rake (negative rake) tools produce high specific cutting pressure consequently high cutting forces.
The approaching angle (*k*) is the angle at which cutting tool enters and leaves the cutting zone. The chip cross-section is determined by the approaching angle, but it has a relatively low influence on the cutting forces. Since the main cutting edge enters and leaves cutting zone suddenly at 90^0 of approaching angle it is subjected to maximum loading and unloading. The angle produces a large feed force and also smaller radial force at 90^0(Stori, JA et al., 1998). When the tool is fed along a line at 90^0 to the axis of work-piece, namely cutting action is orthogonal (Satyanarayana.Kosaraju et al., 2011). In oblique cutting, approaching angle is $0^0<k<90^0$.The tool geometry is given in Fig1(a).

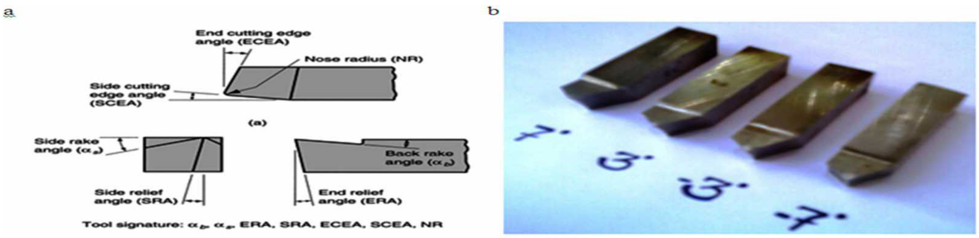

Fig. 1(a) Tool geometry of Cutting tool; (b) Cutting tools with rake angles.

The objective of this Paper is to analyze the influence of feed rate, rake angle and approach angle on cutting forces. And to determine, the optimized feed rates and tool angles with reference to cutting forces.

2. Influential factors and taguchi experimental design

The factors feed rate and tool geometry have more influence on cutting forces. The factors and their levels are summarized in Table 1.

Table 1: Factors and factor levels

Factors	Symbols	Factor levels			
Rake angle (degree)	α	-7^0	-3^0	3^0	7^0
Approach angle(degree)	k	45^0	60^0	75^0	90^0
Feed rate (mm/rev)	f	0.16	0.20	0.25	0.30

For three-factor four-level, a Taguchi design orthogonal array L16 experimental design is selected (Table 2) to conduct the experiments and to record the responses.

Table 2.Design of experiments

Exp. No.	*Rake Angle(α)*	*Approach Angle(k)*	*Feed Rate(f)*
1	-7	45	0.16
2	-7	60	0.2
3	-7	75	0.25
4	-7	90	0.32
5	-3	45	0.2
6	-3	60	0.16
7	-3	75	0.32
8	-3	90	0.25
9	3	45	0.25
10	3	60	0.32
11	3	75	0.16
12	3	90	0.2
13	7	45	0.32
14	7	60	0.25
15	7	75	0.2
16	7	90	0.16

3. Experimental work

The turning experiments are performed according to Taguchi experimental design given in Table 2, on Aluminium work-piece of size Φ36x100 mm with different HSS cutting tools having different rake angles (-7^0, -3^0, 3^0 and 7^0) at different approach angles (45^0, 60^0, 75^0 and 90^0) and with different feed rates (0.16, 0.20, 0.25 and 0.32) at dry cutting conditions(Sijo M.T et al., 2010) on PSG A141 conventional lathe. The experimental setup is shown in Fig 2.

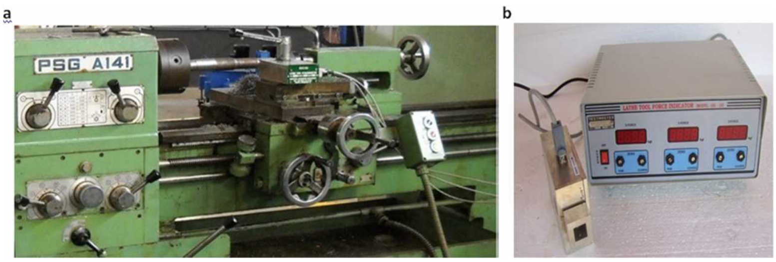

Fig. 2 (a) Experimental setup; (b) Lathe tool force indicator.

Cutting forces are measured with a three-component compact force dynamometer and transferred from over serial port to the PC directly for further evaluation. The Fig. 3 shows lathe tool dynamometer (Lathe tool force indicator). The experimental outcomes namely feed force (F_f), Cutting force (F_c) and Radial force (F_r) are recorded Table 3. The test is conducted at constant speed v_c= 450 n/min and depth of cut = 1 mm.

4.1. Analysis of experimental data using TAGUCHI method

Taguchi is a powerful tool for the design of high quality systems. Compared to the conventional approach of experimentation, this method reduces significantly the number of experiments that are necessary to model the response functions.

Table 3: Experimental data

	Input parameters			Cutting forces			S/N ratio for cutting forces		
Ex No.	A	K	f	F_t	F_x	F_y	SNRA1(F_t)	SRA2(F_x)	SRA3(F_y)
1	-7	45	0.16	157	245	39	-43.917	-47.783	-31.821
2	-7	60	0.2	127	235	88	-47.421	-47.4213	-38.89
3	-7	75	0.25	88	265	186	-48.465	-48.465	-45.39
4	-7	90	0.32	108	333	255	-50.449	-50.449	-48.131
5	-3	45	0.2	137	216	29	-46.3689	-46.689	-29.248
6	-3	60	0.16	127	216	39	-46.689	-46.689	-31.821
7	-3	75	0.32	226	382	108	-51.641	-51.641	-40.668
8	-3	90	0.25	229	333	216	-50.449	-50.449	-46.689
9	3	46	0.25	157	275	39	-48.787	-48.787	-31.821
10	3	60	0.32	137	265	59	-48.465	-48.465	-35.417
11	3	75	0.16	108	186	39	-45.39	-45.39	-31.821
12	3	90	0.25	137	225	69	-47.044	-47.044	-36.777
13	7	45	0.32	98	196	49	-45.845	-45.845	-33.804
14	7	60	0.25	118	196	39	-45.845	-45.845	-31.821
15	7	76	0.2	108	206	49	-46.277	-46.277	-33.804
16	7	90	0.16	137	284	98	-49.066	-49.066	-39.825

Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value(Rama Rao S et al., 2012). In Taguchi method, the term ‘signal‘ represents the desirable value (mean) for the output characteristic and the term ‘noise‘ represents the undesirable value for the output characteristic. In this study ‘Smaller is Better’ characteristic is used for calculation of S/N ratio and mean for getting the optimized cutting forces.

$$\frac{S}{N}_{(\text{Smaller})} = -10 \log\left[\sum_{i=1}^{n} \frac{y_i^{\,2}}{n}\right] \tag{1}$$

where, y_i : Value of force component of dataset *i*.
n : number of experiments.
Taguchi analysis for cutting forces (F_f, F_c and F_r) versus rake angle, approach angle and feed rate results S/N ratio and mean values are given in Table 4.

Table 4(a). S/N ratio for F_f.Table 4(b). S/N ratio for F_c.Table 4(c). S/N ratio for F_r.

Level	*α*	*K*	*f*
1	-41.39	-42.6	-42.35
2	-43.33	-42.08	-42.05
3	-42.51	-41.83	-41.42
4	-41.17	-41.89	-42.58
Delta	2.17	0.77	1.16
Rank	1	3	2

Level	*α*	*k*	*f*
1	-48.53	-47.28	-47.23
2	-48.87	-47.11	-46.86
3	-47.42	-47.94	-48.39
4	-46.76	-49.25	-49.10
Delta	2.11	2.15	2.24
rank	3	2	1

Level	*α*	*k*	*f*
1	-41.06	-31.67	-33.82
2	-37.11	-34.49	-34.68
3	-33.96	-37.92	-38.93
4	-34.81	-42.86	-39.51
Delta	7.10	11.18	5.68
rank	2	1	3

The rank is determined based on influencing level of the corresponding parameter on the respective cutting force (F_f, F_c and F_r). The main effects plots for S/N ratio are shown in Fig. 3.

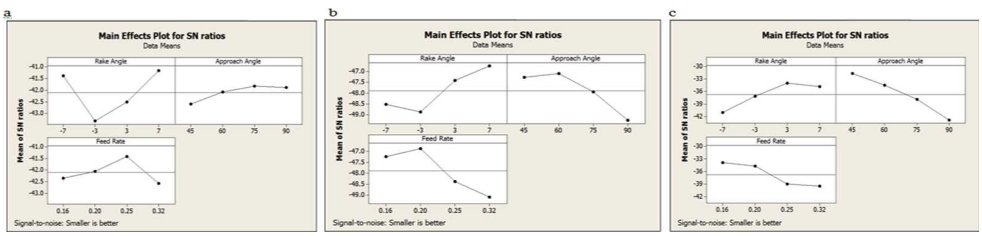

Fig. 3 (a)Main effects plot of S/N ratio for F_f; (b)Main effects plot of S/N ratio for F_c; (c)Main effects plot of S/N ratio for F_r.

The main effect plot for feed force S/N ratio graph shows that the optimum values of influencing factors in their rank order. According to SN ratio analysis the maximum point is the optimum influencing level of the cutting factor on corresponding cutting force. The values optimum cutting factors for feed force, cutting force and radial force are

Cutting force (F_f):Rake angle (α) = 7^0, Feed rate (f) = 0.25 mm andApproach angle (k) = 75^0.

Cutting force (F_c):Feed rate = 0.20 mm, Approach angle = 60^0 andRake angle = 7^0.

Radial force (F_r):Approach angle = 45^0,Rake angle = 3^0 and Feed rate = 0.16 mm.

4.2. *Analysis of Variance (ANOVA)*

The experimental data obtained have been subjected to ANOVA test. ANOVA is used for the single response; therefore the tests are conducted separately for each component of cutting forces(Haci SAGLAM et al., 2011). The model for the cutting forcesis evaluated by the 95% confidence level(Douglas C et al., 2001), this indicates that the obtained models are considered to be statistically significant and the terms in the model have a significant effect on the responses. The ANOVA results for experimental data are given in Table 3.

Table 5(a). ANOVA results for F_f.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
α	3	3292	3292	1097	0.61	0.631
k	3	361	362	121	0.07	0.975
f	3	1027	1027	342	0.19	0.899
Error	6	10731	10731	1789		
Total	15	15412				

S = 42.2907 R-Sq = 30.37% R-Sq(adj) = 0.00%

Table 5(b). ANOVA results for F_c.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
α	3	10794	10794	3598	1.64	0.277
k	3	10918	10918	3639	1.66	0.273
f	3	13395	13395	4465	2.03	0.211
Error	6	13166	13166	2194		
Total	15	48274				

S = 46.8437 R-Sq = 72.73% R-Sq(adj) = 31.82%

Table 5(c). ANOVA results for F_r.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
α	3	20812.2	20812.2	6937.4	12.86	0.005
k	3	34307.2	34307.2	11435.7	21.20	0.001
f	3	15747.7	15747.7	5249.2	9.73	0.010
Error	6	3236.9	3236.9	539.5		
Total	15	74103.9				

S = 23.2267 R-Sq = 95.63% R-Sq(adj) = 89.08%

On the observation of p values, the significant difference of most effecting factors is identified. From ANOVA probability test (p test), if $p>0.05$ then there is no significant difference and if $p<0.05$ then there is a significant difference from their group.

The ANOVA test results that factors of feed force are having p values 0.631, 0.975, 0.899 (> 0.05); hence there is no significant difference. Similarly cutting force factors are having p values 0.277, 0.273, 0.211 (>0.05), so these factors are also not showing any significant difference. But the p values of radial force factors are 0.005, 0.001, 0.010 (<0.05); there is significant difference from this group.

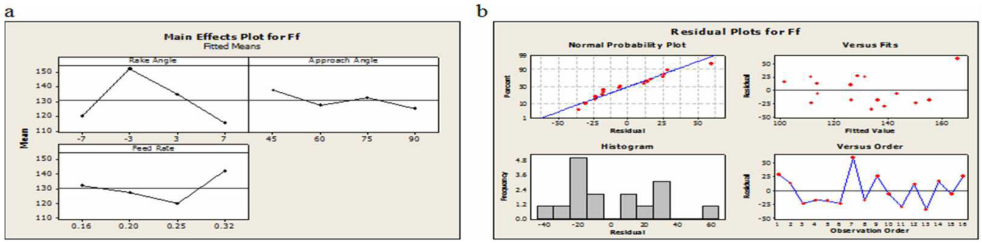

Fig. 4 (a) Main effects plot for F_f ; (b) Residual plots for F_f.

The normality plot of the residuals above shows that the residuals follow a normal distribution. Both plot of residuals versus fitted values and plot of residuals versus run order do not show any pattern. Thus, both constant variance and independence assumptions are satisfied. The main effects plot and interaction plot for Feed force (F_f) are shown in Fig 4.

From the ANOVA results tableadjusted sum of squares (Adj SS) and their total sum of squares (SS) on each individual response or cutting force, which can help in finding out of the percentage of influence values of the factors; to evaluate the significance of the corresponding factors. The Percentage of influence equation is given by

$$\%\text{ of influence} = \frac{\text{Adj SS}}{\text{Total SS}} \times 100 \quad (2)$$

The most effective factor on F_f is rake angle, on $F_c$is feed rate and for F_r is approach angle. According to ANOVA statistical significant analysis these factors are most influencing on cutting forces hence these are considered to be non-significant. The percentage of influence charts, on cutting forces are shown in Fig 5.

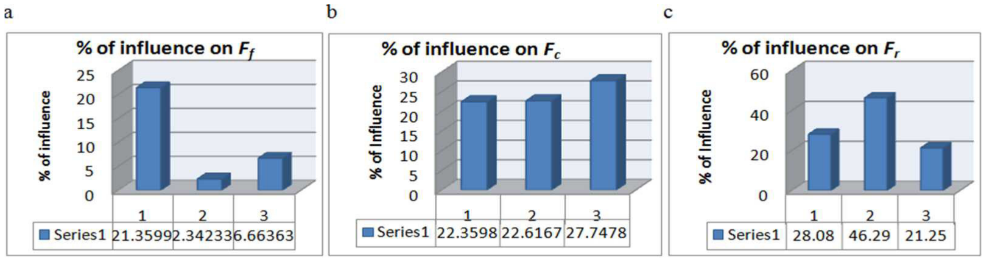

Fig 5. (a) % of influence chart on F_f ; (b) % of influence chart on F_c; (c) % of influence chart on F_r.

5. Fuzzy Inference System (FIS) and Fuzzy Sets

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves the following elements: Membership Functions, Logical Operations, and If-THEN Rules(Pham, D. T et al., 2001).Fuzzy sets and logic is a discipline that has proved itself successful in automated reasoning of expert systems(Hashmi, K et al., 2003).In recent past, fuzzy logic has found high degree of applicability in development of expert systems.

For the current research work, the knowledge from the experimental data, Taguchi analysis, and ANOVA results are used for its development.The set of fuzzy rules defines a fuzzy estimation surface. The accuracy of interpolation depends on the number of membership functions, their position, their shape and the rules used to express the relationships between these membership functions. Here Mamdani max-min interference for interference mechanism and centre of gravity (Centroid) defuzzier formula method for defuzzification are used, because these operators assure a linear interpolation of output between the rules. The structure of fuzzy system is shown in Fig 6.

Fig. 6 Structure of fuzzy rule based inference system.

5.1. *Fuzzy sets*

After obtaining the data from experiments, the experimented range of input and output variables were divided into fuzzy sets as linguistic variable in the next step. These membership functions helped converting to numeric variables into linguistic terms. Four fuzzy sets are designed for eachinput (α, k and f) and output(F_f, F_c and F_r) variables. For the entire input variables, equally distributed curve 'triangular' membership function fuzzy sets are utilized. For the entire output variables, equally distributed curve 'guass' membership function fuzzy sets are utilized. The linguistic terms used in input fuzzy sets are 'Low', 'High', 'NLow', 'NHigh', 'Below middle' and 'Above middle'.The values of input factors and corresponding linguistic terms are summarized in Table 6.
The details of the fuzzy sets, membership functions and ranges of input and out parameters are shown in Fig. 7 and 8 respectively.

Table 6.Expressions used in fuzzy sets of F_f, F_c and F_r.

α	MF name	k	MF name	f	MF name
-7	NHigh	45	Low	0.16	Low
-3	NLow	60	Below middle	0.20	Below middle
3	Low	75	Above middle	0.25	Above middle
7	High	90	High	0.32	High

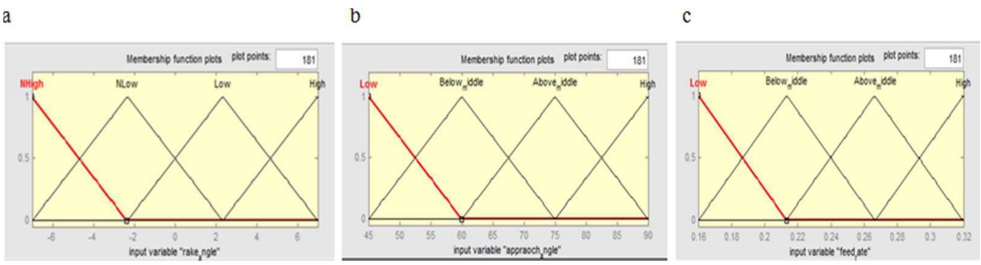

Fig. 7 (a) Membership function for rake angle; (b) Membership function for approach angle; (c) Membership function for feed rate.

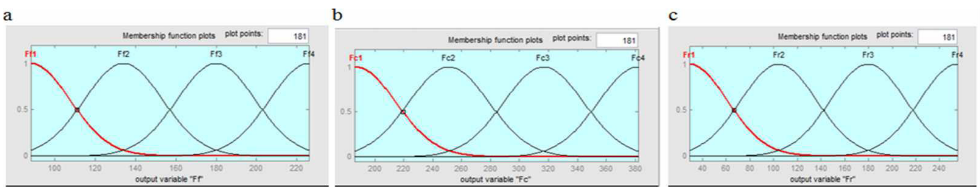

Fig. 8 (a) Membership function for F_f; (b) Membership function for F_c; (c) Membership function for F_r.

5.2. *Fuzzy rules*

The relationship between inputs and output in a fuzzy system is characterized by set of linguistic statements which are called fuzzy rules(Hashmi, K et al., 2003). The number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets for each input variable. In this research work, there are 16 possible rules. Expressions and the abbreviation details of these fuzzy sets, giving minimum values of estimation error, are provided in Table 6 and 7.

Table 7. Fuzzy rules

S.No	α	k	f	F_f	F_c	F_r
1	NHigh	Low	Low	Ff2	Fc2	Fr1
2	NHigh	Below middle	Below middle	Ff2	Fc2	Fr2
3	NHigh	Above middle	Above middle	Ff1	Fc2	Fr3
4	NHigh	High	High	Ff1	Fc3	Fr4
5	NLow	Low	Below middle	Ff2	Fc1	Fr1
6	NLow	Below middle	Low	Ff2	Fc1	Fr1
7	NLow	Above middle	High	Ff4	Fc4	Fr2
8	NLow	High	Above middle	Ff2	Fc3	Fr3
9	Low	Low	Above middle	Ff2	Fc2	Fr1
10	Low	Below middle	High	Ff2	Fc2	Fr1
11	Low	Above middle	Low	Ff1	Fc1	Fr1
12	Low	High	Below middle	Ff2	Fc2	Fr2
13	High	Low	High	Ff1	Fc1	Fr1
14	High	Below middle	Above middle	Ff2	Fc1	Fr1
15	High	Above middle	Below middle	Ff1	Fc1	Fr1
16	High	High	Low	Ff2	Fc2	Fr2

The membership function of system could be obtained by using Mamdani max-min interference as max=1 in MATLAB R2012a (7.14.0.739). The values of feed force (F_f), cutting force (F_c) and radial force (F_r) for α= -7^0, k = 90^{0}and f=0.25 mm/rev were obtained as 157 kgf, 284 kgf and 142 kgf, respectively.

5.3. *Testing and Comparison*

For the purpose of testing and comparison of expert systems cylindrical turning experiments were done upon work-pieces at constant cutting speed and depth of cut, using turning cutting tools having different inclined and approaching angles. The cutting force components were measured at four different feed rates. In order to compare the estimated values of cutting forces from the fuzzy rule based system with the actual data achieved from experiments three of data set as sample were selected. The three data sets are the optimized results in taguchi experimental analysis. From the rule viewer the values for all the three cutting forces (F_f, F_c and F_r) are obtained by using experimental data set and shown in Table 8.

Table 8.Fuzzy results.

Input Factors			Fuzzy results		
α	*k*	*f*	F_f	F_c	F_r
-7	45	0.16	134	252	53.8
-7	60	0.2	135	252	105
-7	75	0.25	105	252	179
-7	90	0.32	103	316	230
-3	45	0.2	135	226	55.7
-3	60	0.16	134	209	54.7
-3	75	0.32	210	360	105
-3	90	0.25	135	316	179
3	45	0.25	135	252	56.3
3	60	0.32	134	252	54.7
3	75	0.16	104	209	54.7
3	90	0.2	135	252	105
7	45	0.32	103	208	53.8
7	60	0.25	135	210	56.3
7	75	0.2	104	210	55.7
7	90	0.16	134	252	105

Table 9. Comparison of fuzzy predicted values with experimental values for optimized input values.

Optimal combinations			Fuzzy values(F_{fv})			Experimental values(F_{ev})		
α	*k*	*f*	F_f	F_c	F_r	F_f	F_c	F_r
7	90	0.25	157	284	142	152	316	139
7	60	0.2	157	284	142	157	284	146
3	45	0.16	157	284	142	148	265	127
Prediction Error e_p(%)			4.67	4.33	4.67			
Accuracy (%)			95.33	95.67	95.33			

As seen in the Table 9, the prediction error of sample test is very close to training set data. The term prediction error (e_p) can be defined as follows:

$$e_p = \frac{1}{n}\left[\sum_{i=1}^{n}\left(F_{ev} - F_{fv}\right)\right] \quad (3)$$

If the cutting tools undergoes changing of tool geometry due to possible tool wear or tool breakage the abnormal increase in wear would be reported by increase in cutting force. This proves that fuzzy inference system technique incorporating cutting forces as major input can be used to diagnose tool wear states in tool condition monitoring systems.

6. Conclusions

In this paper the optimum levels of feed rate, rake angle and approach angle for optimum cutting forces in turning are identified using Taguchi Method.Analysis of variance (ANOVA) is also conducted to findthe order and percentage of influencing parameters on all cutting forces.

From the results of this work the following conclusions are drawn:

- Optimal conditions are identified for optimal values of F_f, F_c andF_r through Taguchi Method.
- ANOVA test results are examined, and observed that the order of influencing factor onFeed force (F_f) is rake angle, feed rate and approach angle on Cutting force (F_c) is feed rate, approach angle and rake angle on Radial force (F_r) Approach angle, rake angle and feed rate.
- On comparison of fuzzy results with actual experimental values for optimized data sets, the prediction error is found to be about 4.53 and percentage of accuracy is 95.44%.

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