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Experimental Study and Identification of Optimal Cutting Parameters on Cutting Forces in Turning Using Taguchi Based Fuzzy Logic

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Abstract: *The cutting forces generated in turning are mainly influenced by speed, feed, depth of cut and tool geometry. The study of cutting forces for changes in tool geometry and feed rate using Taguchi Method and Fuzzy Logic is presented in this paper. Design of Experiments (DOE) helped in reducing the number of experiments to be performed. For an L16 orthogonal array DOE at different feed rates the turning experiments are performed on Aluminum rod with the HSS cutting tools by varying the tools of different rake angles at different approach angles and the values of responses (cutting forces) are tabulated. The analysis of the influence of feed rate and tool geometry on cutting forces is carried out by Taguchi and ANOVA methods and the optimal values of these factors are identified. A Taguchi based Fuzzy Logic system is developed using Taguchi experimental results. The cutting forces are estimated with the help of Fuzzy Logic system for the optimal values of feed rate and tool geometry. The prediction error is calculated for fuzzy results and is about 2.78 and the percentage of accuracy is 97.22%.*

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

I. Introduction

The quality is an emerging challenge of modern machining industries 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 is difficult task. The analysis of cutting forces is necessary for design and evaluation of machining parameters, tool design and calculation of power requirements etc. The cutting forces are mainly influenced by depth of cut and feed rate, respectively more than by cutting speed [1]. The cutting force components are very sensitive even for the smallest changes in the cutting process. Therefore, instead of calculating the cutting force theoretically, measuring them in process by dynamometers is preferred [2].

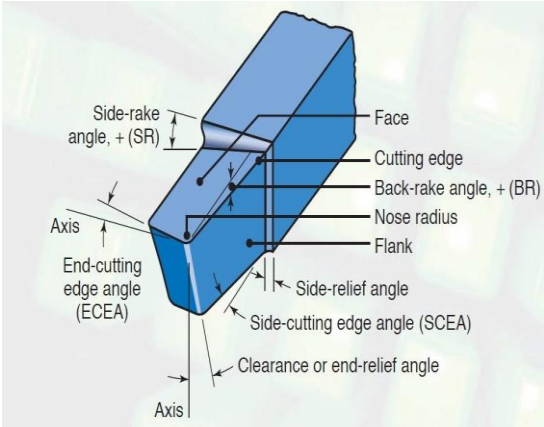
a. Feed rate

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 [3].

b. 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 [4]. 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.

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. When the tool is fed along a line at 90^0 to the axis of work-piece, namely cutting action is orthogonal [5]. In oblique cutting, approaching angle is $0^0<k<90^0$.The tool geometry is given in Fig1(a).



(a) (b)

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.

II. Input Factors and Taguchi Design of Experiments

The factors and their levels are summarized in Table 1.

Table 1: Factors and factor levels

Controllable factors	Symbol	Factor levels
Rake Angle (degree)	α	-5^0 5^0
Approach Angle (degree)	k	45^0 60^0 75^0 90^0
Feed rate (mm/rev)	f	0.16 0.20 0.25 0.32

For *three-factor Mixed-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 (Taguchi L16).

Exp. No.	*Rake Angle (α)*	*Approach Angle (k)*	*Feed Rate (f)*
1	-5	75	0.16
2	-5	75	0.20
3	-5	90	0.16
4	-5	90	0.20
5	-5	60	0.25
6	-5	60	0.32
7	-5	45	0.25
8	-5	45	0.32
9	5	75	0.16
10	5	75	0.20
11	5	90	0.16
12	5	90	0.20
13	5	60	0.25
14	5	60	0.32
15	5	45	0.25
16	5	45	0.32

III. Experimental Work

The turning experiments are performed according to Taguchi experimental design given in Table 2, on Aluminum work-piece of size Φ36x100 mm with different HSS cutting tools having different rake angles (-5^0 and 5^0) 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 on PSG A141 conventional lathe. The experimental setup is shown in Fig.2. All the turning experiments are conducted at a constant speed of v_c= 450 rev/min and depth of cut = 1 mm.

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

Cutting forces are measured with a *three-component compact force dynamometer* shown in Fig.3(b) and transferred from over serial port to the PC directly for further evaluation. The cutting forces namely feed force (F_f), Cutting force (F_c) and Radial force (F_r) are recorded in Table 3.

Table 3. Experimental data.

	Input Parameters			***Cutting forces***		
Exp. No.	***A***	***k***	***f***	F_f	F_c	F_r
1	-5	75	0.16	88	90	40
2	-5	75	0.20	108	120	50
3	-5	90	0.16	157	40	190
4	-5	90	0.20	127	60	230
5	-5	60	0.25	90	140	40
6	-5	60	0.32	100	160	50
7	-5	45	0.25	87	150	30
8	-5	45	0.32	112	160	50
9	5	75	0.16	98	100	210
10	5	75	0.20	108	110	210
11	5	90	0.16	98	30	150
12	5	90	0.20	110	50	180
13	5	60	0.25	118	140	130
14	5	60	0.32	157	160	140
15	5	45	0.25	122	150	90
16	5	45	0.32	127	170	100

IV. Analysis of Cutting Forces Using Taguchi And ANOVA

a. Taguchi Analysis

Taguchi has significant advantage in reduction of number of experiments to be performed to get necessary response functions at the stage of Design of Experiments (DOE). S/N ratio is used to measure the quality characteristic deviating from the desired value [6]. 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). Feed force (F_f)

Level	***α***	***k***	***f***
1	-40.55	-40.89	-40.61
2	-41.29	-41.11	-41.06
3	-42.51	-40.01	-40.26
4	-43.33	-41.66	-41.74
Delta	0.74	1.65	1.48
Rank	**3**	**1**	**2**

Table 4(b). Cutting force (F_c)

Level	***α***	***k***	***f***
1	-40.36	-43.93	-35.17
2	-39.94	-43.50	-37.99
3	-41.22	-40.37	-43.22
4	-41.17	-32.78	-44.21
Delta	0.42	11.15	9.05
Rank	**3**	**1**	**2**

Table 4(c). Radial force (F_r)

Level	***α***	***k***	***f***
1	-36.05	-35.65	-41.90
2	-43.23	-37.81	-43.19
3	-33.96	-39.73	-35.74
4	-34.81	-45.36	-37.72
Delta	7.18	9.71	7.45
rank	**3**	**1**	**2**

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 values optimum cutting factors for feed force, cutting force and radial force are given in below Table.5

Table 5 .Ranks of influencing cutting parameters on cutting forces.

Cutting force (F_f)			**Cutting force (F_c)**			**Radial force (F_r)**		
Rank	**Parameter**	**Value**	**Rank**	**Parameter**	**Value**	**Rank**	**Parameter**	**Value**
1	Rake angle	5^0	1	Feed rate	0.16	1	Approach angle	45^0
2	Approach angle	90^0	2	Approach angle	90^0	2	Rake angle	-5^0
3	Feed rate	0.32	3	Rake angle	5^0	3	Feed rate	0.25

The main effects plots for S/N ratio are shown in Fig. 3.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.

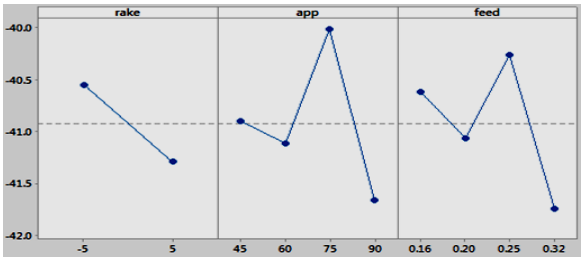


Fig. 3(a). The main effects plots for S/N ratio Vs F_f.

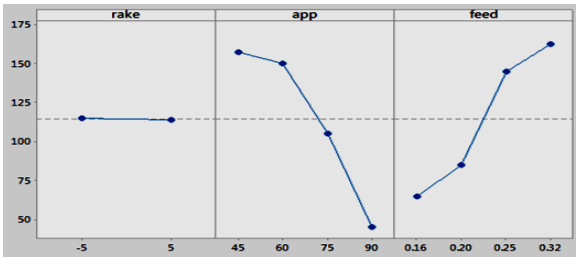


Fig. 3(b). The main effects plots for S/N ratio Vs F_c.

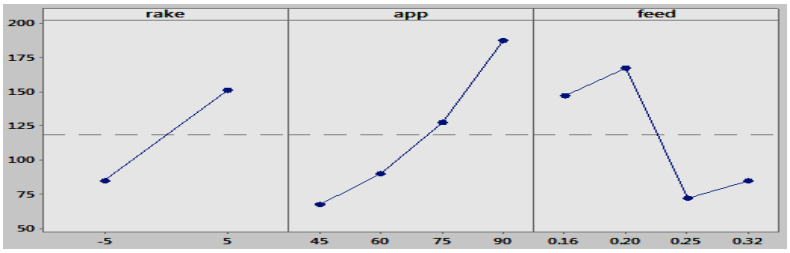


Fig. 3(c). The main effects plots for S/N ratio Versus F_r

b. Analysis of Variance (ANOVA)

ANOVA is used for the single response; therefore the tests are conducted separately for each component of cutting forces. The cutting forces are evaluated by the 95% confidence level, 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 = 22.3814 , R-Sq = 19.90**%**, R-Sq(adj) = 0.00%

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 = 12.3168, R-Sq = 95.06%, R-Sq(adj) = 93.27%

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 = 47.1639, Sq = 67.39% , R-Sq(adj) = 55.54%

p-test:

The p values helps in identification of the significant difference of most effecting factors. 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 results shown in Table 5, reveals that factors of feed force are having p values 0.457, 0.564 and 2.900 i.e, p > 0.05; hence there is no significant difference. Similarly cutting force factors are having p values 0.843 , 0.000 and 0.21 i.e, p > 0.05so these factors are also not showing any significant difference. But the p values of radial force factors are 0.017, 0.021, 0.034 (i.e, p < 0.05); there is significant difference from this group.

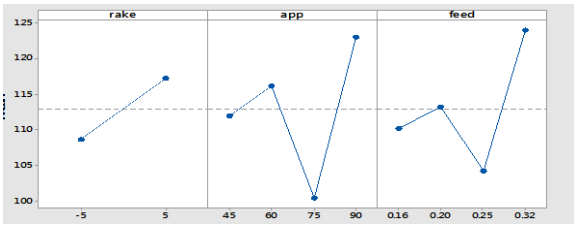


Fig. 4 (a) Main effects plot for F_f ;

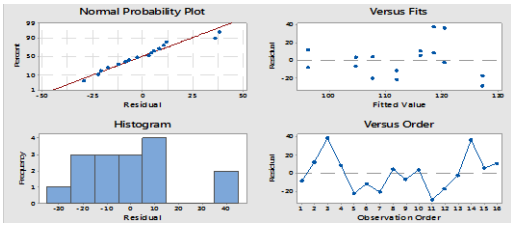


Fig. 4 (b) Residual plots for F_f.

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 table adjusted 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

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

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 by rake angle(1), Approach angle(2) and feed rate(3) are shown in Fig 5.

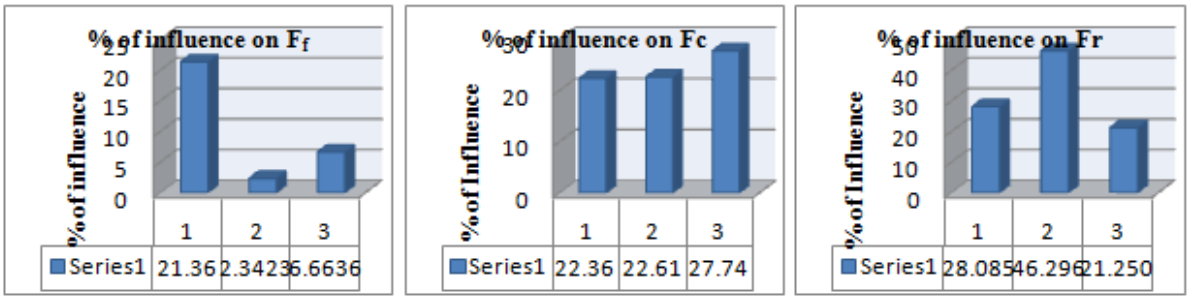


Fig 5. (a) % of influence chart on F_f ; (b) % of influence chart on F_c; (c) % of influence chart on F_r.

V. Taguchi Based Fuzzy Logic

Fuzzy Logic inference system involves in the process of mapping from a given input to an output using fuzzy logic. The process of fuzzy inference involves the following elements: Membership Functions, Logical Operations, and If-THEN Rules. Fuzzy sets and logic is a discipline that has proved itself successful in automated reasoning of expert systems [7]. The set of fuzzy rules defines a fuzzy estimation surface. The accuracy of interpolation depends on the number of Membership Functions (MF), 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.

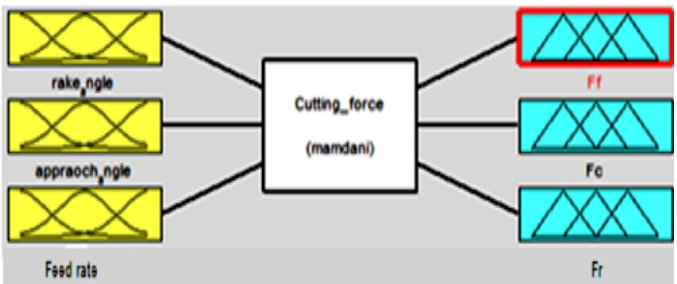


Fig. 6 Structure of fuzzy rule based inference system.

a. Fuzzy sets and Membership Functions (MF)

The 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 each input (α, k and f) and output(F_f, F_c and F_r) variables. For the input variables, equally distributed curve 'triangular' membership function and for the output variables, equally distributed curve 'guass' membership function fuzzy sets are utilized. The linguistic terms used in input fuzzy sets are 'Low', 'High', 'MLow', and 'MHigh'. The values of input factors and corresponding linguistic terms are summarized in Table 6.

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

α	MF name	*k*	MF name	*F*	MF name
-5	Low	45	Low	0.16	Low
		60	M Low	0.20	M Low
5	High	75	High	0.25	High
		90	M High	0.32	M High

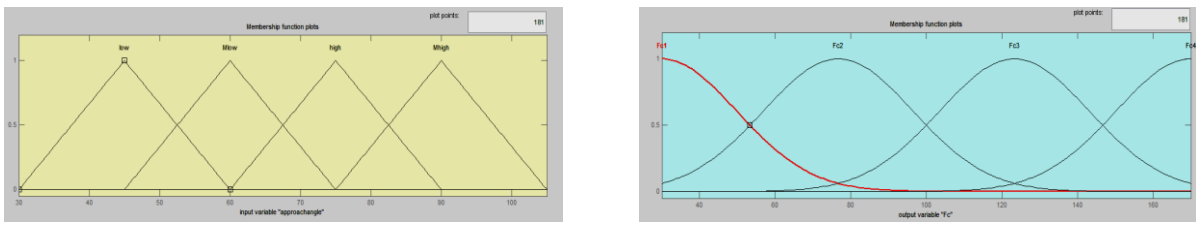


Fig. 7 (a) Membership functions for approach angle. (b) Membership functions for F_f.

b. Fuzzy rules

Table 7. Fuzzy rules

S.No	Rake angle(a)	Approach angles (k)	Feed rate (f)	Cutting forces		
				F_f	F_c	F_r
1	Low	High	Low	Fc2	Ff1	Fr1
2	Low	High	M low	Fc3	Ff2	Fr1
3	Low	M High	Low	Fc1	Ff4	Fr4
4	Low	M High	M low	Fc1	Ff3	Fr4
5	Low	M low	High	Fc1	Ff1	Fr1
6	Low	M low	M High	Fc4	Ff1	Fr1
7	Low	Low	High	Fc4	Ff2	Fr1
8	Low	Low	M High	Fc4	Ff1	Fr1
9	High	High	Low	Fc2	Ff2	Fr4
10	High	High	M low	Fc3	Ff1	Fr4
11	High	M High	Low	Fc1	Ff2	Fr4
12	High	M High	M low	Fc1	Ff2	Fr4
13	High	M low	High	Fc4	Ff2	Fr3
14	High	M low	M High	Fc4	Ff4	Fr3
15	High	Low	High	Fc4	Ff2	Fr2
16	High	Low	M High	Fc4	Ff3	Fr2

Table 8.Fuzzy results.

Input Factors			Fuzzy results		
α	k	F	F_f	F_c	F_r
-5	75	0.16	100	122	130
-5	75	0.20	77.1	94.7	52
-5	90	0.16	100	122	130
-5	90	0.20	45.4	150	208
-5	60	0.25	148	97.9	61
-5	60	0.32	155	94.7	52
-5	45	0.25	148	111	61
-5	45	0.32	155	94.7	52
5	75	0.16	100	122	130
5	75	0.20	77.1	111	208
5	90	0.16	100	122	130
5	90	0.20	45.4	111	208
5	60	0.25	148	111	162
5	60	0.32	155	150	162
5	45	0.25	148	111	98.2
5	45	0.32	155	134	97.3

The relationship between inputs and output in a fuzzy system is characterized by set of linguistic statements which are called fuzzy rules. The number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets for each input variable. Expressions and the abbreviation details of these fuzzy sets, giving minimum values of estimation error for 16 possible rules, are provided in Table 7.

The estimated values for all the three cutting forces (F_f, F_c and F_r) are obtained by the rule viewer and are shown in Table 8.

Note: *The optimal values of* ***feed force (F_f), cutting force (F_c) and radial force (F_r)*** *for $\alpha = -5^0$, $k = 45^0$ and f = 0.25 mm/rev, which are optimal cutting parameters of Taguchi analysis are* ***148kgf, 111 kgf and 61 kgf,*** *respectively.*

c. Testing and Comparison

In order to compare the estimated cutting forces from the fuzzy rule based system with the actual experimental data three sample data sets were selected (Optimal cutting parameters in Taguchi analysis). The *Prediction error (e_p)* test is conducted for selected datasets [8]. The results are shown in Table 9.

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

Table 9. Prediction error test results.

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
5	90	0.16	122	100	130	117	99	128
5	90	0.32	122	100	100	118	100	94
-5	45	0.25	111	148	61	105	144	64
Prediction Error e_p (%)			2.66	3.33	2.33			
Accuracy (%)			97.33	96.66	97.66			

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 logic technique incorporating cutting forces as major input can be used to diagnose tool wear states in tool condition monitoring systems.

VI. Conclusions

The optimal values of feed rate, rake angle and approach angle are identified for optimum cutting forces in turning using Taguchi Method. The percentage of influence of cutting parameters on cutting forces also determined with the help of Analysis of variance (ANOVA). From the results of this work the following conclusions are drawn:

- The Fuzzy Logic results the estimated values of cutting forces for designed model of experimental data set and the values of feed force (F_f), cutting force (F_c) and radial force (F_r) for α= -5^0, k = $45^0$and f=0.25 mm/rev were obtained as 148kgf, 111 kgf and 61kgf, respectively.

- On comparison of fuzzy results with actual experimental values for optimized data sets, the prediction error is found to be about 2.78 and percentage of accuracy is 97.22%.

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