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Optimization of cutting force of turning of AISI 1018 mild carbon steel using RSM

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ABSTRACT

With passage of time technologically advanced machines have been developed. But the problem of the tool wear and cutting force for a particular machining process remains to be improved. So, to avoid or to cope-up with this problem it is necessary to find the best combination of machining parameters for obtaining optimum cutting force. In this work the optimization of cutting force for a given combination is done in a useful and easy way. Three factors are selected that affect the optimizing parameters in case of turning. These factors are optimized to get the optimum cutting force. This is achieved by employing response surface methodology and signal to noise ratio calculation. One factor is varied by keeping the other two constant at same range. Through the response surface methodology 2D and 3D graphs are obtained and optimization is achieved. The S/N ratio is done to find out which factor has the most influence on the output that is cutting force.

Keywords: *Cutting Force; Depth of cut; Spindle speed; Feed; RSM; DOE; S/N ratio; ANNOVA*

I. INTRODUCTION

Turning is the most effective method for forming any work piece, because through turning we can easily remove unwanted material. It is used to remove rust, improve shape near to tolerance limit, improve surface finish, and many more. Turning encloses different metals for machining such as alloy steel, carbon steel, cast iron, stainless steel, aluminum, copper, magnesium, zinc. Machining process involves some parameters which affects machining. These are spindle speed, depth of cut, feed etc. these parameters are called independent factors whereas some dependent factors are cutting force, surface finish, tool wear, tool life etc. which are needed to be minimized or maximized depending on the type of factors. Here cutting force is optimized with respect to the independent factors within a given range.

In this research work the optimization of cutting force is done theoretically using response surface methodology. The S/N ratio calculation is done for finding out the most effective parameters for cutting force.

II. DESIGN & ANALYSIS

This method is designed by taking a given range of independent parameters from a HMT 22 lathe. The parameters are spindle speed, depth of cut, and feed. Here, three levels are taken for each parameter and Design of Experiments (DOE) is applied on it. This is a structured method which is used to identify various relationships between input and output. One of the DOE methods is RSM. The three levels obtained are fed into factorial combination in which we obtain 27 combinations of the parameters. Here optimization is done using AISI 1018 mild carbon steel.

Table-1: Attribution levels of cutting parameters for cutting force-

Control parameters	Unit	Symbol	Level1 (low)	Level2 (medium)	Level3 (high)
Spindle speed	rpm	N	40	102	192
Feed rate	mm/rev	f	0.04	0.05	0.06
Depth of cut	mm	d	0.5	1	1.5

(A) RESPONSE SURFACE METHODOLOGY

RSM is a method developed by Box and Wilson in the early 1950's. It is used for establishing relationships between various input and output variables.
For n number of measurable input variables, the response surface can be given as –

$Y = f(x_1, x_2, x_3, x_4 \ldots x_n) + \varepsilon$ -----------(1)

Where, $x_1 \ldots x_n$ are the independent input parameters and ε is the random error.
Y is the output or response variable which has to be optimized.

In a turning operation with three input variables, the response function can be written as –

$Y = f(x_1, x_2, x_3) + \varepsilon$ ----------- (2)

Where, $x_1 = \log d$, $x_2 = \log f$, and $x_3 = \log N$. $Y = \log F_C$ and ε is the random error.

RSM is mostly applied through multiple regression models. For example, the first order or linear multiple regression model can be used –
$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$ ----------- (3)
For better approximation, interaction terms can be included –

$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon$ ----------- (4)

The second order or quadratic regression model includes the square terms in addition to the terms above –

$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon$ --- (5)

In this case equation 5 is used to have the response surfaces in the design expert software.

(B) SUMMARY OF TURNING PARAMETERS AND FORMULAS

N= rotational speed of the work piece in rpm
f=feed in mm/rev or in/rev
V_C=cutting speed of work piece in m/min or ft/min
=π D N/1000 or ω R [Since, ω = 2ΠN/60]
D= diameter of work piece in mm
ω = angular velocity rev/sec or rad/sec
R = radius of the job
d = depth of cut in mm or in
MRR = Material removal rate in mm^3/sec or in^3/min
= V_C*f*d
P=Power in hp or in lb/min or joule/sec or watt
= E*MRR
E=specific energy consumption
T=Torque in lb-in or N-m
=P/2ΠN
F_C=Cutting force in N or lb
=T/R

Table -2: Approximate range of energy requirements in cutting operations at the drive motor of the machine tool (for dull tools multiply by 1.25) –

Material	Specific energy (E)	
	w-s/mm^3	hp-min/in^3
Aluminum alloys	0.4 - 1	0.15-0.4
Cast irons	1.1-5.4	0.4-2
Copper alloys	1.4-3.2	0.5-1.2
High-temperature alloys	3.2-8	1.2-3

Magnesium alloys	0.3-0.6	0.1-0.2
Nickel alloys	4.8-6.7	1.8-2.5
Refractory alloys	3-9	1.1-3.5
Stainless steels	2-5	0.8-1.9
Steels	2-9	0.7-3.4
Titanium alloys	2-5	0.7-2

(C) CALCULATION OF CUTTING FORCE (F_C)

Cutting force is the tangential force exerted by the tool. Here specific energy (E) of steels ranges from 0.7 - 3.4 hp min/in^3 as per table 4 so an approx medium value is selected of about 1.47 from the range. It is easier to calculate power in hp that's why the values are transferred from mm3/sec to in^3/min.

SET 1:

$N_1 = 40$ rpm

$f_1 = 0.04$ mm/rev

$d_1 = 0.5$ mm

Cutting speed = $V_{C1} = \omega_1 R = [(40*2\pi)/60]*7.5 = 31.4$ mm/sec

$MRR_1 = V_{C1} * f_1 * d_1$

$= (\pi * D * N_1) * f_1 * d_1$

$= 31.4 * 0.04 * 0.5$

$= 0.628$ mm3/sec

$= 0.0023$ in^3/min

Power (P_1) = E * MRR_1 = 1.47 * 0.0023 = 0.0034 hp

Specific energy (E) of steels ranges from 0.7 - 3.4 hp min/in^3 as per table 4 so an approx medium value is selected of about 1.47 from the range. It is easier to calculate power in hp that's why the values are transferred from mm3/sec to in^3/min.

Power (P_1) = 0.0034 * 396000 = 1346.4 in lb/min

Torque (T_1) = $P_1/2\pi N_1$ = (1346.4)/ (2*π * 40) = 5.36 lb-min

Cutting Force (F_{C1}) = T_1/R = 5.36/0.2953 = 18.1510 lb = 80.7358 N

Other sets can similarly be calculated following this process. The calculated cutting force for different combinations is shown in table 3.

Table- 3: Calculated cutting forces for the respective combination-

Serial no.	Factorial combination			Cutting forces (F_C)
	Spindle speed (N)	Feed(f)	Depth of cut (d)	
1	40	0.04	0.5	80.7358 N
2	102	0.04	0.5	80.8262 N
3	192	0.04	0.5	81.3383 N
4	40	0.05	0.5	101.371 N
5	102	0.05	0.5	101.368 N
6	192	0.05	0.5	101.385 N
7	40	0.06	0.5	122.120 N
8	102	0.06	0.5	121.645 N
9	192	0.06	0.5	121.661 N
10	40	0.04	1	162.134 N
11	102	0.04	1	162.224 N
12	192	0.04	1	162.217 N
13	40	0.05	1	202.682 N

14	102	0.05	1	202.743N
15	192	0.05	1	202.773 N
16	40	0.06	1	243.216 N
17	102	0.06	1	243.532 N
18	192	0.06	1	243.325 N
19	40	0.04	1.5	243.186 N
20	102	0.04	1.5	243.288 N
21	192	0.04	1.5	243.322 N
22	40	0.05	1.5	304.027 N
23	102	0.05	1.5	304.110 N
24	192	0.05	1.5	304.157 N
25	40	0.06	1.5	364.833 N
26	102	0.06	1.5	364.933 N
27	192	0.06	1.5	364.987 N

(D) **SIGNAL-TO-NOISE RATIO(S/N)**

The S/N ratio calculation is done for finding out the most effective parameters for cutting force.

Calculating S/N ratio for smaller is better for cutting force, the equation is,

$S/N\ (Y_i) = -10 \log (\sum (X_i^2)/n)$

Where Y_i = S/N ration for respective result

X_i = Cutting force for each combination = 1 to 27

n = No. of results for each combination for combination no. i

Table- 4: Calculated S/N ratio for the respective combination-

Serial no.	Factorial combination			Cutting forces (F_C)	S/N ratio (Y_i)
	Spindle speed (N)	Feed (f)	Depth of cut (d)		
1	40	0.04	0.5	80.7358 N	-38.141
2	102	0.04	0.5	80.8262 N	- 38.15
3	192	0.04	0.5	81.3383 N	-38.20
4	40	0.05	0.5	101.3710N	-40.11
5	102	0.05	0.5	101.3686N	-40.11
6	192	0.05	0.5	101.3852N	-40.11
7	40	0.06	0.5	122.1204N	-41.73
8	102	0.06	0.5	121.6459N	-41.70
9	192	0.06	0.5	121.6610N	-41.70

10	40	0.04	1	162.1343N	-44.19
11	102	0.04	1	162.2247N	-44.20
12	192	0.04	1	162.2172N	-44.20
13	40	0.05	1	202.6829N	-46.13
14	102	0.05	1	202.7432N	-46.13
15	192	0.05	1	202.7734N	-46.14
16	40	0.06	1	243.2165N	-47.71
17	102	0.06	1	243.5329N	-47.73
18	192	0.06	1	243.3250N	-47.72
19	40	0.04	1.5	243.1864N	-47.71
20	102	0.04	1.5	243.2889N	-47.72
21	192	0.04	1.5	243.3220N	- 47.72
22	40	0.05	1.5	304.0275N	- 49.65
23	102	0.05	1.5	304.1103N	- 49.66
24	192	0.05	1.5	304.1570N	- 49.66
25	40	0.06	1.5	364.8339N	- 51.24
26	102	0.06	1.5	364.9333N	- 51.24
27	192	0.06	1.5	364.9875N	- 51.24

Table- 5: Calculated overall mean S/N ratio –

Level	Average S/N ratio by factor level			Overall mean of S/N ratio (Y_O)
Low	Feed(f) Depth of cut (d) Spindle speed (N)			-45.1875
	-43.3627	-39.9993	-45.1853	
Medium	-45.3058	-46.0213	-45.1856	
High	-46.8941	-49.5419	-45.1917	
Delta = larger – smaller	3.5314	9.5426	0.0064	
Rank	2	1	3	

Here rank 1, 2, 3 indicates that depth of cut is the most influencing factor for cutting force followed by feed and spindle speed.

III. RESULTS & DISCUSSIONS

Analysis of the effects of parameters on cutting force is done in design expert software, using response surface methodology by the theoretical and results obtained earlier.

(A) **ANNOVA**

The analysis of variance (ANOVA) was used to study the significance and effect of the cutting parameters on the response variables i.e. cutting force.

Table- 6: ANNOVA for cutting force-

Source	Sum o squares	df	Mean square	c	p-value	
Model	2.195E+05	6	36582.49	2.225E+06	< 0.0001	significant
A-depth of cut	1.839E+05	1	1.839E+05	1.119E+07	< 0.0001	
B-feed	29512.58	1	29512.58	1.795E+06	< 0.0001	
C-spindle speed	0.0411	1	0.0411	2.50	0.1295	
AB	4897.71	1	4897.71	2.979E+05	< 0.0001	
AC	0.0032	1	0.0032	0.1917	0.6662	
BC	0.0889	1	0.0889	5.41	0.0307	
Residual	0.3288	20	0.0164			
Cor Total	2.195E+05	26				

From Table 6, we can see that the P-Value for the model is 0.0001 which is lesser than the significance value of 0.05. Hence, the model is significant. Feed and depth of cut is found to be the most influential parameters affecting the cutting force with low P-value among all three parameters.

Table-7: Estimated Coded Regression Coefficients for cutting force-

Factor	Co-efficient estimate	df	Standard error	95% CI low	95% CI high	VIF
Intercept	202.75	1	0.0247	202.70	202.80	
A-depth of cut	101.36	1	0.0303	101.29	101.42	1.01
B-feed	40.60	1	0.0303	40.54	40.67	1.01
C-spindle speed	0.0475	1	0.0301	-0.0152	0.1102	1.0000
AB	20.20	1	0.0370	20.13	20.28	1.0000
AC	0.0161	1	0.0368	-0.0607	0.0929	1.01
BC	-0.0856	1	0.0368	-0.1624	-0.0088	1.01

Table -8: Fit statistics of cutting force

Std. Dev.	0.1282	R^2	1.0000
Mean	202.75	Adjusted R^2	1.0000
C.V. %	0.0632	Predicted R^2	1.0000
		Adeq Precision	4351.0264

Regression Equation in Un-coded Units for cutting force:

cutting force = -1.63891 +0.637870 depth of cut +33.04753 feed + 0.005833 spindle speed +4040.50667 depth of cut * feed + 0.000424 depth of cut * spindle speed – 0.112632 feed * spindle speed.

(B) EFFECTS OF DEPTH OF CUT, FEED AND SPINDLE SPEED ON CUTTING FORCE

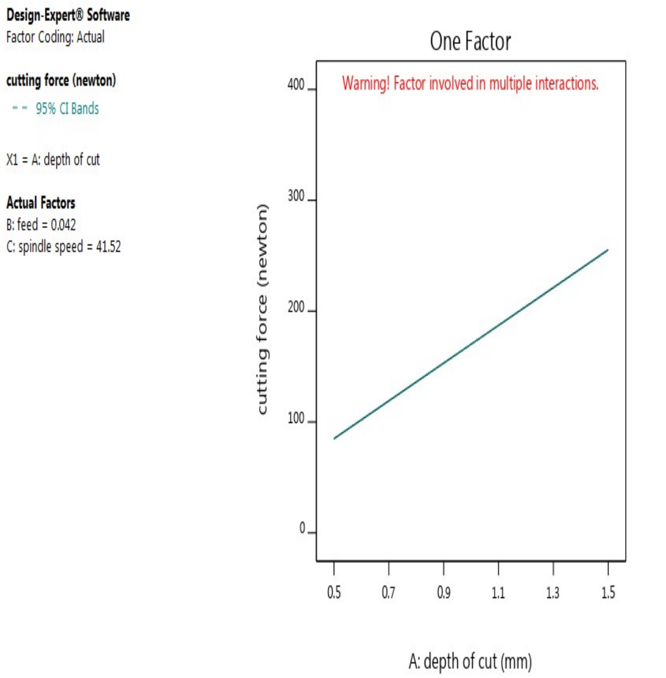

Fig-1 Variation of cutting force with depth of cut

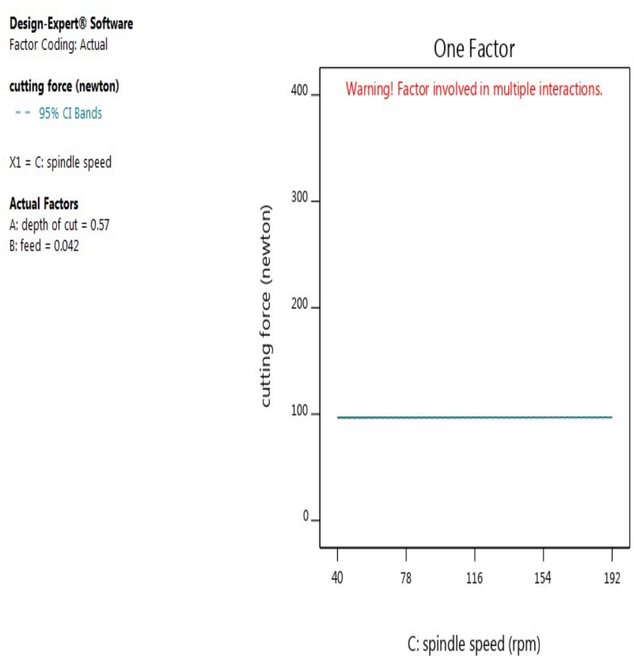

Fig-2 Variation of cutting force with spindle speed

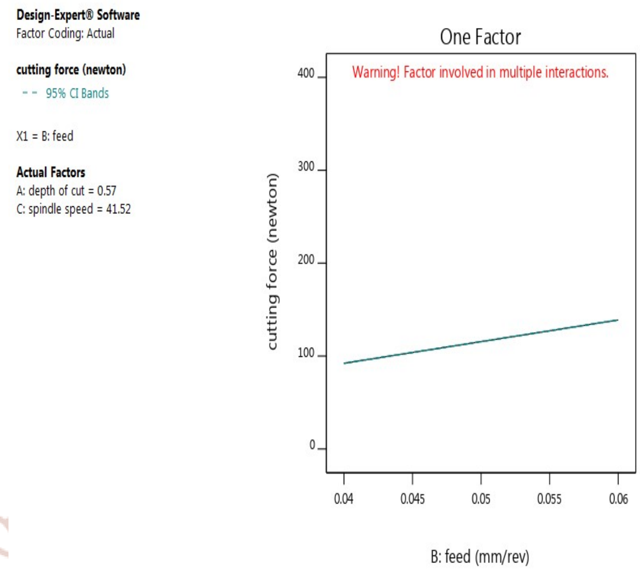

Fig-3 Variation of cutting force with feed

The graphs show that the most effective parameter is depth of cut.

(D) VARIATION S/N RATIO WITH DEPTH OF CUT, FEED AND SPINDLE SPEED FOR CUTTING FORCE

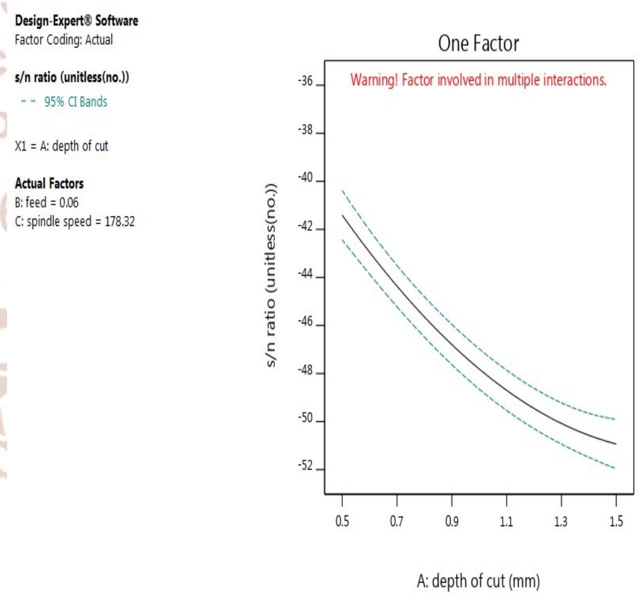

Fig-4 Variation of mean S/N ratio with depth of cut

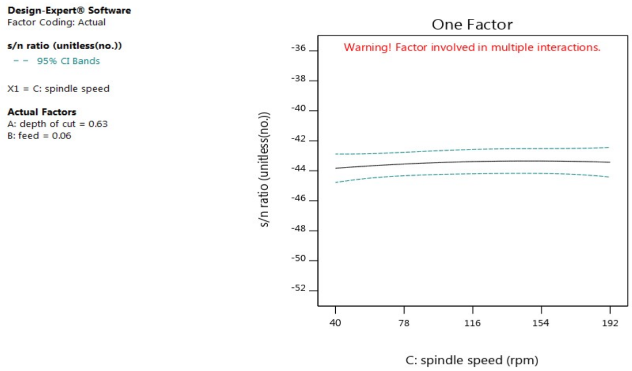

Fig-5 Variation of mean S/N ratio with spindle speed

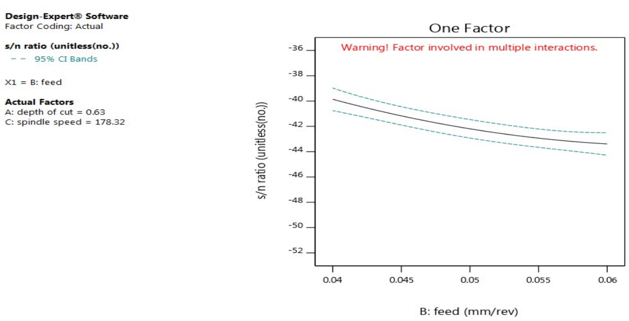

Fig-6 Variation of mean S/N ratio with feed

The above graphs show the validation of the S/N ratio calculation and prove that the most effective parameter is depth of cut.

(E) RESPONSE SURFACES ANALYSIS

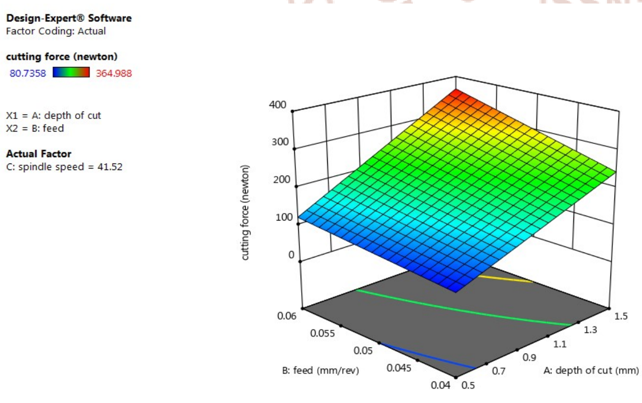

Fig-7 Effect of depth of cut and feed rate on cutting force

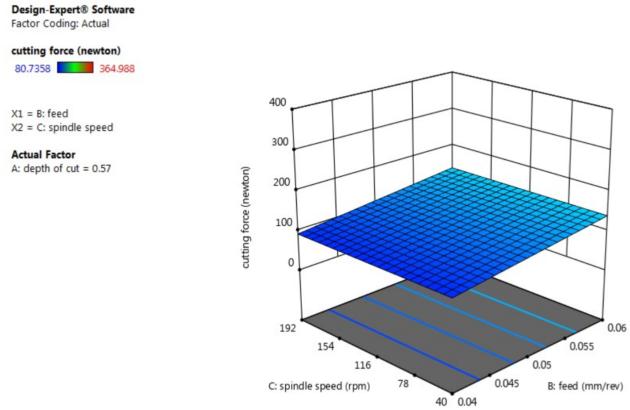

Fig-8 Effect of spindle speed and feed rate on cutting force

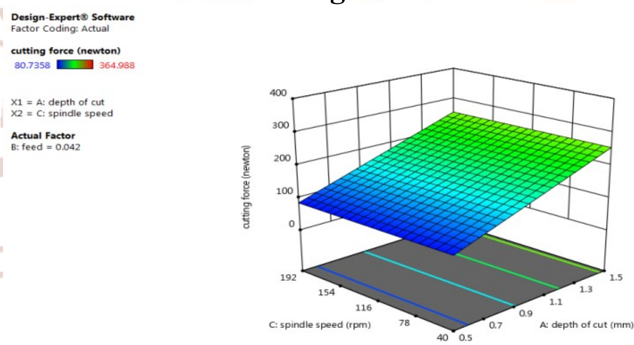

Fig-9 Effect of depth of cut and spindle speed on cutting force

The graphs interpret that cutting force increases with increasing depth of cut and varies approx linearly with feed. It is also clear from the S/N ratio calculation that the main parameter which effect cutting force is depth of cut.

(F) OPTIMIZATION

The desirability function is used as a decision support tool which is to identify the process parameters that are resulting in the near-optimum settings for process responses. The optimization is done in design expert software version 11.

Table- 9: Constraints for optimization of machining parameters –

Condition	Goal	Upperlimit	Lower limit
Depth of cut(mm)	In range	0.5	1.5
Feed (mm/rev)	In range	0.04	0.06
Spindle speed (rpm)	In range	40	192
Cutting force (N)	Minimize	80.7358	364.9875
Machining time (T_C)	Minimize	1.21	10.49

Table- 10: Response optimization for cutting force –

Number	depth of cut	Feed	spindle speed	cutting force	Desirability	
1	0.500	0.040	40.000	80.874	1.000	
2	0.500	0.040	41.296	80.876	1.000	Selected
3	0.500	0.040	43.217	80.880	0.999	
4	0.500	0.040	45.653	80.882	0.999	
5	0.500	0.040	46.998	80.885	0.999	
6	0.500	0.040	48.706	80.887	0.999	
7	0.500	0.040	50.577	80.890	0.999	

The optimum cutting parameters obtained in table 10 are as follows:

1) Spindle speed = 41.296 rpm
2) Feed rate = 0.04 mm/rev
3) Depth of cut = 0.5 mm

The optimized cutting force (F_C) = 80.876, with a Composite Desirability = 1.000

IV. CONCLUSION

From the above research work it can be concluded that the cutting force in case of turning can be improved when operated under optimum combination of the influencing parameters. Here the optimum combinations of the parameters for best cutting force are given above. Regression equation obtained here by software can be used to find one parameter when the other two are known so as to get the best cutting force within the range and is also used to obtain graphs. ANNOVA is also done to check the accuracy by R^2 value. From the S/N ratio the importance of one factor with respect to others can be obtained.

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