International Journal of scientific research and management (IJSRM)
||Volume||4||Issue||06||Pages||4351-4354||2016||
Website: www.ijsrm.in ISSN (e): 2321-3418

Experimental Analysis of the Cutting Forces and Material Removal Rate during Dry Turning of En-36 Steel

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Abstract
In the present case study, an attempt has been made to investigate the effect of process parameters (cutting speed, feed rate and depth of cut) on axial force, radial force, main cutting force and material removal rate in dry turning of En-36 (655M13), using carbide cutting tool. The effects of the selected process parameters on performance characteristics/responses and subsequent optimal settings of the parameters have been accomplished using Taguchi's parameter design approach. The result shows that the optimal settings for minimum values of cutting forces are lower values of feed rate, depth of cut and cutting speed are required. For the higher values of material removal rate larger values of feed, depth of cut and cutting speed are desired. The results are further verified by conducting confirmation experiments.
Keywords: cutting forces, material removal rate, En-36(655M13) steel, Taguchi approach.

1. INTRODUCTION

Metal cutting process forms the basis of the engineering industry/organisation and is involved either directly or indirectly in the production of nearly every product of our modern civilization. The metal cutting industries in developing countries continue to suffer from a major drawback of not running the machine tools at their optimum operating conditions. The operating conditions continue to be chosen solely on the basis of the handbooks values and/or manufacturer recommendations and/or worker's experience. The literature survey has revealed that a little research has been conducted to obtain the optimal levels of cutting parameters and tool geometry that yield the best machining characteristics to difficult-to-machine materials. En-36 steel is one such material which is difficult-to-machine. Its typical applications are in manufacturing of machine tools and automobile parts such as shafts, cams and roller. It can be used in high duty bushing, heavy duty gear.

Antony [1] proposed the methodology to develop a simple and practical step by step approach for tackling multiple quality characteristics problem by Taguchi's quality loss function for identifying the significant factor/interaction effects and also for determining the optimal condition for the problem. Many researchers observed higher cutting forces during hard turning at low cutting speeds due to low temperature and built up edge (BUE) formation. The forces reduced with increase in cutting speed, which might be due to thermal softening of the work piece material due to higher cutting temperature at high speeds [2]-[4]. An ANOVA [3] showed that the feed rate had considerable effect on cutting force but for thrust force, it was negligible. Another study [5] shows that the selected process parameters – cutting speed, feed and depth of cut as well as the interaction between cutting speed and depth of cut significantly affect the mean and variance of cutting force.

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Nomenclature

v	Cutting speed (m/min.)
f	Feed (mm/rev.)
d	Depth of cut (mm)
F_x	Axial force (N)
F_y	Radial force (N)
F_z	Cutting force (N)
MRR	Material removal rate (g/sec.)

Lalwani [8] investigated the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces and surface roughness in finish hard turning of MDN 250 steel using coated ceramic tool. The machining experiments were conducted based on RSM and sequential approach using face centered central composite design.

It was reported by the researchers [9] that the cutting component of forces (F_z) is more sensible to the variations of the cutting conditions than the rest of components analysed during the study. Furthermore, tools with nose radius of 0.4 and 0.8 mm have similar behaviour from the point of view of the forces generated during machining at low feed rates. Suresh [10] used response methodology and genetic algorithm to determine machining parameters on surface roughness.

The objective of the work is to obtain an optimal setting of process/cutting parameters – cutting speed, feed and depth of cut to yield optimal cutting forces and material removal rate while machining En-36 steel with carbide cutting tool. The effects of the process/cutting parameters on cutting forces and material removal rate and the subsequent optimal settings of the parameters for obtaining their optimal values have been accomplished using Taguchi's parameter design approach.

2. PRESENT WORK

DOI: 10.18535/ijsrm/v4i6.18

Present work is an attempt to examine the effects of cutting parameters on the cutting forces and material removal rate. The turning of hardened En 36 steel was performed on heavy duty lathe machine (KL-510).

Table 1—Process parameters with their values

Factor	process parameters	level1	level2	level3
A	Cutting speed (m/min.)	88	114	135
B	Feed rate (mm/rev.)	0.16	0.24	0.32
C	Depth of cut (mm)	0.1	0.2	0.3

The range of process parameters selected is given in Table 1. Three levels of speed, feed and depth of cut were selected which are suitable for experiment. An L-9 orthogonal array was selected as per the Taguchi's design of experiments.

3. RESULTS AND DISCUSSION

Three specimens for each trial condition were prepared using randomization technique. Thus 27 specimens were turned and a customized dynamometer was used to measure the cutting forces. The cutting forces and material removal rate were measured for all 9 experiments and their mean values are shown in Table 2. The mean response refers to the average value of the performance characteristics for each parameter at different levels. The average values of cutting forces and material removal rate for each parameter at different levels are calculated and plotted in Figs. 1, 2, 3 and 4 respectively.

In this study, smaller-the-better and larger-the-better principle are considered to minimize cutting forces and to maximize MRR. The corresponding loss function is expressed as follow (Ross, 1988):

Smaller-the-better, S/N ratio = $-10\, log\ 1/n\ \Sigma\ y^2$ (1)

Larger–the-better, S/N ratio = $-10 \log 1/n\ \Sigma\ 1/ y^2$ (2)

Where n is the number of observations and y is the observed data.

It is evident from the Figs. 1, 2 and 3 that cutting forces are minimum at the first level of feed rate and the first level of depth of cut. Also it can be seen that lower cutting speed favours reduction of cutting forces. It is seen from Fig. 4 that larger value of feed and depth of cut are required for optimum value of the material removal rate. Also higher level of cutting speed gives better results for MRR.

The influence of process parameters for axial force as shown in Fig. 1 reveals that the effect of cutting speed in affecting the axial force is significantly larger followed by depth of cut and feed rate. While for radial force in Fig. 2 cutting speed significantly affects the radial force followed by depth of cut and feed rate. It can also be seen for the cutting force it is clear from the Fig. 3 that three factors (feed rate, depth of cut, cutting speed) are significant in affecting the response (Table 5).

Table 2. Experimentation and measured responses (mean value).

S.N.	v	f	d	F_X	F_Y	F_Z	mrr
1	88	0.16	0.1	91.52	50.66	160.18	0.165
2	88	0.24	0.2	120.95	71.91	241.90	0.812
3	88	0.32	0.3	171.62	94.80	300.74	1.212
4	114	0.16	0.2	179.79	101.33	323.62	1.036
5	114	0.24	0.3	205.94	124.22	395.53	1.185
6	114	0.32	0.1	156.91	94.80	313.81	1.045
7	135	0.16	0.3	212.47	137.29	415.15	2.245
8	135	0.24	0.1	173.25	111.14	339.97	1.802
9	135	0.32	0.2	205.94	125.85	398.80	2.114

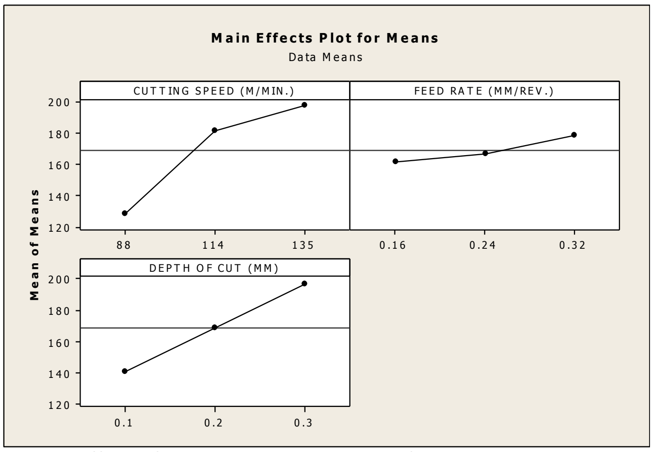

Fig.1—Effects of process parameters on axial force (raw data)

Fig.2—Effects of process parameters on radial force (raw data)

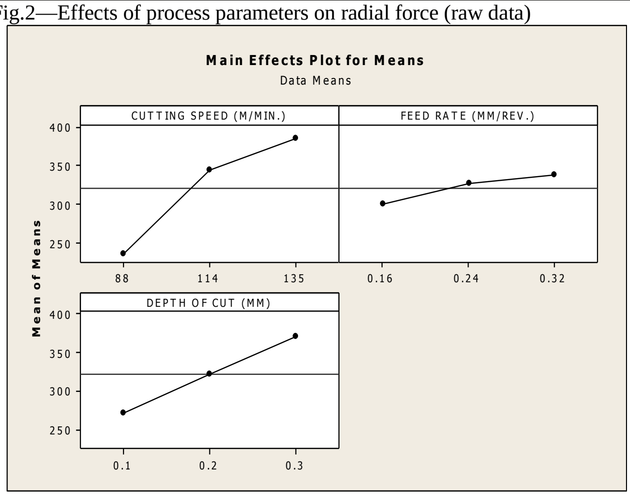

Fig. 3- Effects of process parameters on cutting force (raw data)

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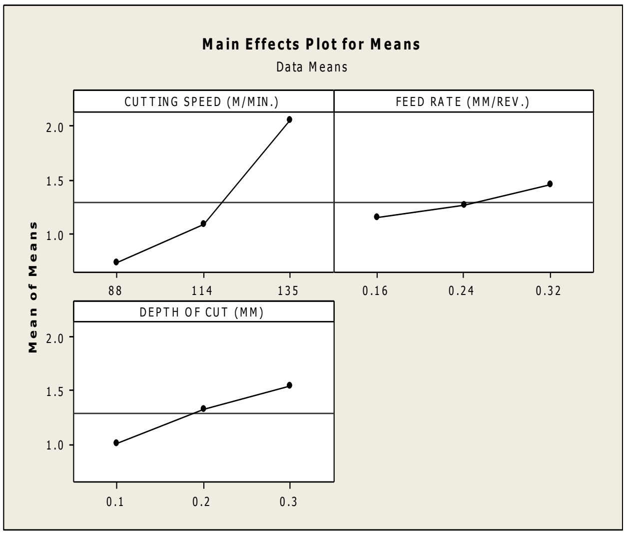

Figure 4: Effects of process parameters on MRR (raw data)

All the process parameters for material removal rate (Table 6) were found 'significant'. Cutting speed and depth of cut were found to be highest contributor for the selected range of cutting parameters (Fig. 4).

Table 3. ANOVA of data for axial force F_x

Source	df	SS	V	F	p-value
A	2	23542.2	11771.1	139.27	0.000*
B	2	1337.6	668.8	7.91	0.003*
C	2	14171.3	7085.7	83.34	0.000*
e	20	1690.4	84.5		
T	26	40741.5			

SS= sum of squares, V= variance, e =error, df = degree of freedom, $F_{(0.05:1;20)} = 4.35$,
* Significant at 95% confidence level

Table 4. ANOVA of data for radial force F_y

Source	df	SS	V	F	p-value
A	2	12710.2	6355.1	201.60	0.000*
B	2	358.1	179.1	5.68	0.011*
C	2	5006.8	2503.4	79.41	0.000*
e	20	630.5	31.5		
T	26	18705.5			

SS= sum of squares, V= variance, e =error, df = degree of freedom, $F_{(0.05:1;20)} = 4.35$,
* Significant at 95% confidence level

Table 5. ANOVA of data for cutting force F_z

Source	df	SS	V	F	p-value
A	2	109039	54520	1184.20	0.000*
B	2	6845	3423	74.34	0.000*
C	2	44243	22121	480.49	0.000*
e	20	921	46		
T	26	161048			

SS= sum of squares, V= variance, e =error, df = degree of freedom, $F_{(0.05:1;20)} = 4.35$,
* Significant at 95% confidence level

Table 6. ANOVA of data for material removal rate

Source	df	SS	V	F	p-value
A	2	8.4372	4.2186	333.93	0.000*
B	2	0.4355	0.2173	17.24	0.000*
C	2	1.3406	0.6703	53.06	0.000*
e	20	0.2527	0.0126		
T	26	10.4661			

SS= sum of squares, V= variance, e =error, df = degree of freedom, $F_{(0.05:1;20)} = 4.35$,
* Significant at 95% confidence level

The optimal settings of the process parameters and the predicted optimal values of the cutting forces and MRR are given in Table 7. The confidence interval for the predicted mean on a confirmation experiment can be calculated by using the following equation [11] and its value given in Table 8.

$$C.I. = \sqrt{F\alpha(1, fe)Ve[\frac{1}{Neff} + \frac{1}{R}]} \quad (3)$$

Where F_α (1, fe) = F ratio required for α, α = risk, f_e =error DOF, V_e =error variance

N_{eff} =effective no. of replication

$$= \frac{N}{1+[Total\ DOF\ associated\ in\ the\ estimate\ of\ mean]}$$

R = number of repetitions for confirmation experiment, N = total number of experiments

Table 7. Optimal settings and predicted optimal values of the responses.

Quality characteristics	optimal settings of process parameter	predicted optimal value of QC
Axial force	$A_1B_1C_1$	92.48 N
Radial force	$A_1B_1C_1$	51.76 N
Cutting force	$A_1B_1C_1$	163.14 N
MRR	$A_3B_3C_3$	2.477 g/sec.

Table 8. Predicted optimal range of performance characteristics

Quality characteristics	optimal settings of process parameter	CI of predicted optimal value of QC
Axial force	$A_1B_1C_1$	$77.72 < \mu_{AF} < 107.23$N
Radial force	$A_1B_1C_1$	$42.75 < \mu_{RF} < 60.77$ N
Cutting force	$A_1B_1C_1$	$152.25 < \mu_{CF} < 174.03$N
MRR	$A_3B_3C_3$	$2.297 < \mu_{MRR} < 2.657$g/sec.

4. CONFIRMATION EXPERIMENTS

The confirmation experiment is the final step in verifying the conclusions drawn based on Taguchi's parameter design approach. The optimum conditions are set for the significant factors and a selected number of tests are run under constant specified conditions. The average of the confirmation experiment results is compared with the anticipated average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental conclusions. Three confirmation experiments were conducted at the optimal settings of turning process parameters recommended by the investigation. The average value of axial force while turning En-36 steel was found to be 93.16 N, for radial force as 49.03 N and for cutting force was 161.82 N. Similarly, for material removal rate it was found to be 2.315 g/sec. These results are within the 95% confidence interval of the predicted optimal values of the selected machining characteristics. Hence, the optimal settings of the process parameters as predicted in the analysis can be implemented.

5. CONCLUSIONS

Cutting speed was found to be the most influential process parameter followed by depth of cut and feed rate affecting the cutting forces. Higher cutting speed gives the higher values of all three cutting forces. For the material removal rate, all the three factors are significant. Higher values of feed and depth of cut are required for the optimum values of material removal rate. The material removal increases with increase in cutting speed. The confirmation experiment shows that the results are within the 95% confidence interval of the predicted optimal values of the selected machining characteristics.

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