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Optimization of Machining Parameters in Steel Turning Operation by Taguchi Method

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Abstract

This work is optimization of machining parameters in steel turning operation by Taguchi method. In this study the experimental work was carried out by turning EN-31 steel alloy by using tungsten carbide inserts. There were three main purposes of this study. The first was to explain and demonstrate a systematic procedure of Taguchi parameter design and applying it to the data on turning. The second was to find out the optimal combination of process parameters based on S/N ratio and to know the significance of each parameter by performing ANOVA analysis. The third important aim was to find out the effect of lubricant temperature in steel tuning process on the response (i.e surface roughness). The cutting parameters namely feed rate, depth of cut, and lubricant temperature were varied to observe the effects on responses. The main conclusion drawn from this study is that better surface finish is obtained by applying cooled lubricant. Even with higher depth of cuts surface finish is improved if lubricant temperature is lowered.

Keywords: Taguchi design, turning, surface roughness, cutting force;

1. Introduction

In a turning operation, it is important to select cutting parameters so that high cutting performance can be achieved .Selection of desired cutting parameters by experience or using handbook does not ensure that the selected cutting parameters are optimal for a particular machine and environment. The effect of cutting parameters is reflected on surface roughness, surface texture and dimensional deviations of the

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product. Surface roughness, which is used to determine and to evaluate the quality of a product, is one of the major quality attributes of a turning product. Surface roughness is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost. It describes the geometry of the machined surfaces and combined with the surface texture. The mechanism behind the formation of surface roughness is very complicated and process dependent [1]. Nalbant et al [1] presented an application of the parameter design of the Taguchi method in the optimization of turning operations. To select the cutting parameters properly, several mathematical models [2] based on statistical regression or neural network techniques have been constructed to establish the relationship between the cutting performance and cutting parameters.. Then, an objective function with constraints is formulated to solve the optimal cutting parameters using optimization techniques. Therefore, considerable knowledge and experience are required for this approach. In this study, an alternative approach based on the Taguchi method [3-4] is used to determine the desired cutting parameters more efficiently. In the past, several optimization methods for turning operations have been documented [3-5]. It is shown by this study that the use of the parameter design of the Taguchi method can greatly simplify the optimization procedure for determining the optimal cutting parameters in turning operations. As a result, from the practical viewpoint, the parameter design of the Taguchi method seems to be the most suitable approach to determine the optimal cutting parameters for turning operations in a machine shop [6]. Montgomery [7] emphasizes that Taguchi's philosophy about quality engineering is broadly applicable .He considers three stages in a product's (or process's) development: system design, parameter design, and tolerance design. In system design, the engineer uses scientific and engineering principles to determine the basic configuration. In the parameter design stage, the specific values for the parameters are determined and usually the objective is to specify nominal values for the parameters in order to minimize variability transmitted from uncontrollable (or noise) variables .Tolerance design is used to determine the best tolerances for the parameters. Taguchi suggests analyzing variation using an appropriately chosen signal-to- noise ratio (S/N) .These signal-to-noise ratios are derived from the quadratic loss function , and three of them are considered " Standard" and widely applicable. They are: 1 Nominal the best, 2 Larger the better and 3 Smaller the better. Factor levels that maximize the appropriate S/N ratio are optimal.

In this study the experimental work was carried out by turning EN-31 steel alloy by using tungsten carbide inserts with minimum quantity lubrication. The reason for selecting EN-31 steel alloy as work material is that this alloy is widely used in the automotive industry for the parts made by turning operations such as roller bearing, ball bearing, spline shaft and shearing blades. There were three main purposes of this study. The first was to explain and demonstrate a systematic procedure of Taguchi parameter design in turning. The second was to find out the optimal combination of process parameters based on S/N ratio and to know the significance of each parameter by performing ANOVA analysis. The third important aim was to find out the effect of lubricant temperature using minimum quantity lubrication technique developed by Abhang et al [8] in tuning process on the response (surface roughness) and to control the chip tool interface temperature and to develop prediction models for surface roughness, when the lubricant temperature was varied. The cutting parameters namely feed rate, depth of cut, and lubricant temperature were varied to observe the effects on responses. Abhang et al [9] showed that the cutting speed has lesser impact on surface roughness in the studied range (39m/min to 189m/min) as compared to feed and depth of cut .So higher cutting speeds could be used to improve the productivity so we have selected 1200 rpm as cutting speed.

During machining, using a tool with small tool nose radius, the area of contact available for conduction between the tool and work piece is small compared with that with a higher tool nose radius. Hence, the reduction of the heat conduction area promotes local temperature rise along the cutting edge [10].The nose radius is also taken at such a value that the surface roughness is reported to be best [8, 10]. If the tool nose radius increases to 1.2mm (either three times ,compared to nose radius of 0.4 mm), the values of cutting temperatures, decreases (of approximately 21%) while machining with higher tool nose radius [10]. An experimental set up was designed and fabricated and calibrated in Mechanical

Engineering Department AMU, Aligarh, to measure the temperature on cutting tool and work piece junction during metal cutting on precision lathe (LMT, LTM 20 heavy duty lathe machine). The most important characteristics of boric acid for use as a lubricant are that it is readily available and cheap and environmentally safe. Abhang et al [11] reported that by increasing boric acid more than 10% boric acid with SAE-40 base oil does not give any improvement in performance. The same author [12] used the grey relational analysis technique and determined the optimum turning process parameters. Various turning parameters such as cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants were considered and optimized by the grey relational grades obtained from the grey relational analysis for multi-performance characteristics (chip-tool interface temperatures, main cutting force and tool wear rate).

2. Experimental conditions and planning of experiment

The experiments were performed as follows-Nine experiments were carried out with parameters at different levels (each repeated thrice). The experimental conditions so far discussed have been summarized below in the following Table

Table1. Experimental conditions

Machine Tool	10 hp. Lathe LTM20
Work material	EN-31 steel alloy, 500 mm in length and 60 mm Φ
tool holder	WIDAX, SCLCR12 FOGT3, and INDIA Lit.
Insert configurations	CNMA 120412, (diamond shape carbide insert) ($\alpha = 6^o$, $\gamma_0 = -6^o$, $\lambda = -6^o$, $Kr = 95^o$, $Єr = 80\ ^o$, $r = 1.2$ mm).
Cutting speed	1200rpm
nose radius	1.2mm
Environments	MQL (10% boric acid with SAE - 40 base oil)
Work material composition	EN-31 steel, (C=0.95 to 1.2%, Si=0.10 to .35%, MN=.30to0.75%, Cr=1.0 to 1.6%, C0=0.025%, S=.040 %, P=.04%)
Size (mm)	Diameter = 60 mm and length = 500 mm

2.1. Selection of the cutting parameters and their levels

The initial cutting parameters were as follows: feed rate, lubricant temperature and depth of cut. In the cutting parameter design, three levels of the cutting parameters were selected, shown in Table 1. Experimental set up has been shown in Fig.1.

Table 2. Cutting parameters and their levels

Symbol	Cutting parameter	Unit	Level 1	Level 2	Level 3
A	Feed rate	mm/rev	0.05	0.10[a]	0.15
B	Depth of cut	mm	0.2	0.4[a]	0.6
C	Lubricant temperature	°C	10	30[a]	50

a Initial cutting parameters

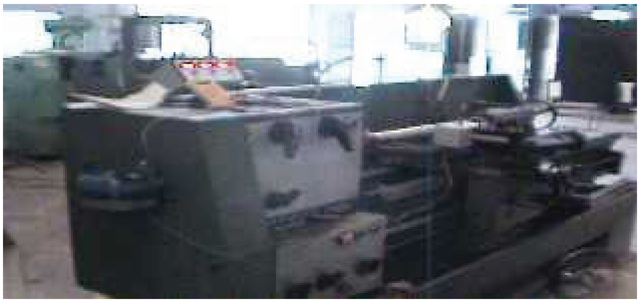

Fig.1. Experimental set up

2.2. Cutting performance measure

The surface roughness was measured on an optical microscope (Carl-zesis, Japan made lens factor is 0.89).The surface roughness was taken perpendicular to the turning direction. Cutting force is measured with the help of lathe tool dynamometer.

2.3. Orthogonal array experiment

To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between design parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level design parameter counts for two degrees of freedom. The degrees of freedom associated with the interaction between two design parameters are given by the product of the degrees of freedom for the two design parameters. In the present study, the interaction between the cutting parameters is neglected. Therefore, there are six degrees of freedom owing to there being three cutting parameters in the turning operations. Once the required degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the design parameters. In this study, an *L*9 orthogonal array with four columns and nine rows was used. This array has eight degrees of freedom and it can handle three-level design parameters. Each cutting parameter is assigned to a column, nine cutting-parameter combinations being available. Therefore, only nine experiments are required to study the entire parameter space using the L_9 orthogonal array. The experimental layout for the three cutting parameters using the L_9 orthogonal array is shown in Table 3. Since the L_9 orthogonal array has four columns, one column of the array is left empty for the error of experiments: orthogonality is not lost by letting one column of the array remain empty [2].

Table 3. Experimental layout using l_9 orthogonal array

	Cutting parameter level			
	A	B	C	D
Experiment No	Feed rate	Depth of cut	Lubricant temperature	Error
1	1	1	1	
2	1	2	2	
3	1	3	3	
4	2	1	3	

5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

2.4. Conducting experiments as per design.

The experiments were conducted as per the design explained above. The three cutting forces acting on a single point cutting tool are –feed force Fx, thrust force or cutting force Fy and radial force Fz acting in x, y, z directions respectively. The responses were recorded.

3. Results and discussion

3.1 .Analysis of surface roughness

Table IV shows the experimental results for surface roughness and the corresponding S/N ratios using. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio η is defined as

$$\eta = -10\log(M.S.D.) \tag{1}$$

There are three categories of quality characteristics, i.e. the-lower-the-better, the higher- the-better, and the-nominal-the-better. The mean-square deviation (M.S.D.) for the-higher-the-better quality characteristic can be expressed as:

$$M.S.D. = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{T_i^2} \tag{2}$$

Where m is the number of tests and Ti is the parameter. Lower the better quality characteristic for surface roughness and cutting forces should be taken for obtaining optimal cutting performance. The M.S.D for the lower the better quality characteristic can be expressed as:

$$M.S.D. = \frac{1}{M}\sum_{i=1}^{m}S_l^2 \tag{3}$$

Where, S_i is the value of the parameter for the i th tests. We have used lower the better quality characteristic formula.

Since the experimental design is orthogonal, it is then possible to separate out the effect of each cutting parameter at different levels. For example, the mean S/N ratio for the feed rate at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments 1–3, 4–6, and 7–9, respectively. The mean S/N ratio for each level of the other cutting parameters can be computed in the similar manner. The mean S/N ratio for each level of the cutting parameters is summarized and called the S /N response table for surface roughness (Table 5). In addition, the total mean S/N ratio for the nine experiments is also calculated and listed in table 5. Regardless of the-lower-the-better or the higher- the-better quality characteristic, the greater S/N ratio corresponds to the smaller variance of the output characteristic around the desired value (Eqs. (1) - (3). Fig.2 shows the S/N response graph for surface roughness. However, the relative importance amongst the cutting parameters for surface roughness still needs to be known so that optimal combinations of the cutting parameter levels can be determined more accurately. This will be discussed in the next section using the analysis of variance.

Table 4. Experimental results for surface roughness and s/n ratio

Experiment no	Feed rate (mm/rev)	D.O.C (mm)	Temperature of lubricant(°C)	Surface Roughness Ra(μm)	S/N ratio (dB)
1	0.05	0.2	10	9.28	-19.35
2	0.05	0.4	30	10.2	-20.17
3	0.05	0.6	50	10.68	-20.57
4	0.1	0.2	50	11.1	-20.91
5	0.1	0.4	10	9.42	-19.48
6	0.1	0.6	30	10.34	-20.29
7	0.15	0.2	30	10.78	-20.65
8	0.15	0.4	50	11.37	-21.12
9	0.15	0.6	10	10.09	-20.08

Table5. S/N response table for surface roughness

		Mean S/N ratio(dB)			
Symbol	Cutting parameter	Level 1	Level 2	Level 3	Max-Min
A	Feed rate	-20.03	-20.23	-20.62	0.59
B	Depth of cut	-20.3	-20.26	-20.313	0.053
C	Temperature of lubricant	-19.64	-20.37	-20.87	1.23

Total mean S/N ratio=-20.29dB

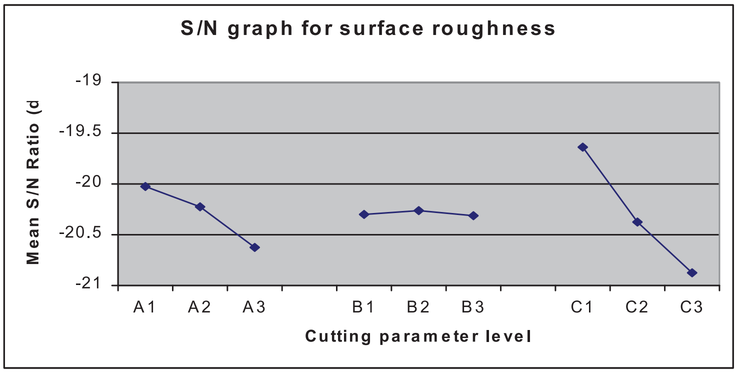

Fig. 2. S/N graph for surface roughness

Thus it can be clearly observed that A1B2C1 are the optimal levels of the design parameters for improved surface finish which implies feed rate at low level, depth of cut at medium level and lubricant temperature at low level combination gives the best surface finish within the specified range.

3.2. Confirmatory test.

Once the optimal level of the design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the design parameters. The estimated S/N ratio using the optimal level of the design parameters, the estimated S/N ratio $\hat{\eta}$ using the optimal level of design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{0}(\overline{\eta}_i - \eta_m) \tag{4}$$

$\overline{\eta}_i$ is the mean S/N ratio at optimal level, η_m is the total mean S/N ratio ,and *o* is the number of the main design parameters that affect the quality characteristic. The estimated S/N ratio using the optimal cutting parameters for surface roughness can then be obtained and the corresponding surface roughness can also be calculated by using Eqs. (1) and (4). Table 6 shows the comparison of the predicted surface roughness with the actual surface roughness using the optimal cutting parameters, good agreement between the predicted and actual surface roughness is being observed. The increase of the S/N ratio from the initial cutting parameters to the optimal cutting parameters is 1.84 dB. In other words, the experiment results confirm the prior design and analysis for optimizing the cutting parameters. Surface roughness in turning operations are greatly improved through the approach.

Table 6. Results of the confirmation experiment

	Initial cutting parameters	optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2	A1B2C1	A1B2C1
Surface roughness(μm)	11.76	9.28	9.51
S/N ratio (dB)	-21.41	-19.35	-19.57
Improvement of S/N ratio=1.84 dB			

Table 7. Results of Anova for surface roughness

Source	D.F	S.S	M.S	F value	P value	% contribution
Feed rate	1	0.7211	0.7211	34.175	0.002s	18.05
Depth of cut	1	0.0004	0.0004	0.0189	0.894ns	0.01
Lubricant temperature	1	3.1683	3.1683	150.156	0.000s	79.299
Residual error	5	0.1056	-	-	-	2.64
Total	8	3.9954	-	-	-	100

where‘s’ implies that the effect of the design parameter is significant and ‘ns’ implies that it is insignificant. It is clear from the ANOVA table that lubricant temperature is the most significant parameter for surface roughness. Among the three design parameters lubricant temperature contribution is the largest i.e 79.299 % followed by feed rate whose contribution is 18.05 % and then depth of cut 0.01 %. Thus within specified range effect of depth of cut on surface roughness is insignificant.

4. Conclusion

This paper has presented an application of the parameter design of the Taguchi method in the optimization of turning operations. The following conclusions can be drawn based on the experimental results of this study:

- Taguchi's robust orthogonal array design method is suitable to analyze the surface roughness (metal cutting), problem as described in this study.
- It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the machining parameters.
- The experimental results show that lubricant temperature and feed rate are the main parameters among the three controllable factors (feed rate, depth of cut and lubricant temperature) that influence surface roughness in turning EN-31 steel.
- In turning for minimum surface roughness, use of lower feed rate (0.05mm/rev), medium depth of cut (0.4mm) and low lubricant temperature (10°C) i.e. A1B2C1 are recommended to obtain better surface roughness for the specific test range. Thus the surface finish is better if cooled lubricant is applied.
- Deviations between actual and predicted S/N ratio of surface roughness is small.
  Thus to control turning process in terms of minimizing the surface roughness, lubricant temperature plays an important role. On decreasing the lubricant temperature the surface roughness decreases. Also surface finish deteriorates as the lubricant temperature increases within the specified range.
- Minimum surface roughness at optimum cutting parameters is 9.51 micron
  This research demonstrates how to use Taguchi parameter design for optimizing machining performance with minimum cost and time to industrial readers.

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