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Optimizing the process parameters of machinability through the Taguchi Technique

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Abstract: CNC machine tool is widely used by manufacturing engineers and production personnel to quickly and effectively set up manufacturing processes for new products. This study discusses an investigation into the use of Taguchi Parameter Design methodology for study of CNC turning operation for surface roughness as a response variable. The Taguchi parameter design method is an efficient experimental method in which a response variable can be study, using fewer experimental runs than a factorial design method. The control parameters for this operation included: spindle speed, feed rate, depth of cut, and tool nose radius. A total of 27 experimental runs were conducted using an orthogonal array, and the ideal combination of controllable factor levels was determined for the surface roughness and signal-to-noise ratio. A confirmation run was used to verify the results, which indicated that this method was both efficient and effective in determining the best turning parameters for the surface roughness.

Keywords: Turning operation, Surface Roughness, Machining Parameter, Software Qualitek 4, Taguchi Technique, Mild Steel.

INTRODUCTION

Metal cutting is one of the most important methods of removing unwanted material in the production of mechanical component. The usual conception of cutting suggests clearing the substance apart with a thin knife or wedge. When metal is cut the action is rather different and although the tool will always be wedge shaped in the cutting area and the cutting edge should always be sharp the wedge angle will be far too great for it to be considered knife shaped. Consequently a shearing action takes place when the work moves against the tool.

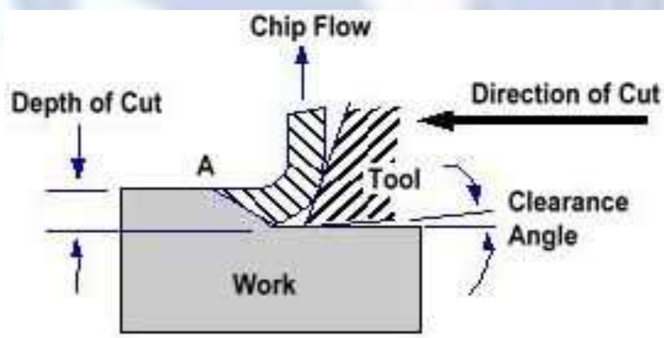

Fig: 1 Basic Metal Cutting Theory

Figure 1 shows a tool being moved against a fixed work piece. When the cut is in progress the chip presses heavily on the top face of the tool and continuous shearing takes place across the shear plane AB. Although this figure shows a tool working in the horizontal plane with the work piece stationary, the same action takes place with the work piece revolving and the tool stationary.

FUNDAMENTAL MACHINING PARAMETERS

The major operating parameters to be specified in turning are the Cutting speed (V)'. Feed rate (f_r), Depth of cut (d) and Tool nose radius(r). For all metal-cutting processes, "speeds and feeds" are important parameters.

a) Cutting speed (V):

The speed is the cutting speed, which is a measure of the part cut surface speed relative to the (here, stationary) tool. It is the largest of the relative velocities of cutting tool or work piece. In drilling and milling, it is the speed of the cutting tool. In Turning, it is given by the surface speed of the work piece. Speed is a velocity unit, which is typically listed in terms of feet/min, inches/min, meters/second, or meters/min.

b) Feed (f_r):

It is movement of the tool per revolution. In turning, it is the distance the tool travels in one revolution of the work piece. Feed (Labeled on the figure 2 as f_r), is the amount of material removed for each revolution or per pass of the tool over the work piece. Feed is measured in units of length/revolution, length/pass, length/tooth, length/time, or other. The term “feed” is used to describe the distance the tool moves per revolution of the work piece and depends largely on the surface finish required. For roughing out a soft material a feed of up to 0.25 mm per revolution may be used. With tougher materials this should be reduced to a maximum of 0.10 mm/rev.

c) Depth of cut (d):

The depth of cut (DOC) (Labeled on the figure 2 as d.), represents the third parameter for metal cutting for turning, depth of cut (DOC) is the depth that the tool is plunged into the surface. The DOC is half of the difference in the diameters Da and Db, the initial and final diameters, respectively. It is the distance the cutting tool penetrates into the work piece. For example, it is given by: d = (Da-Db)/2.

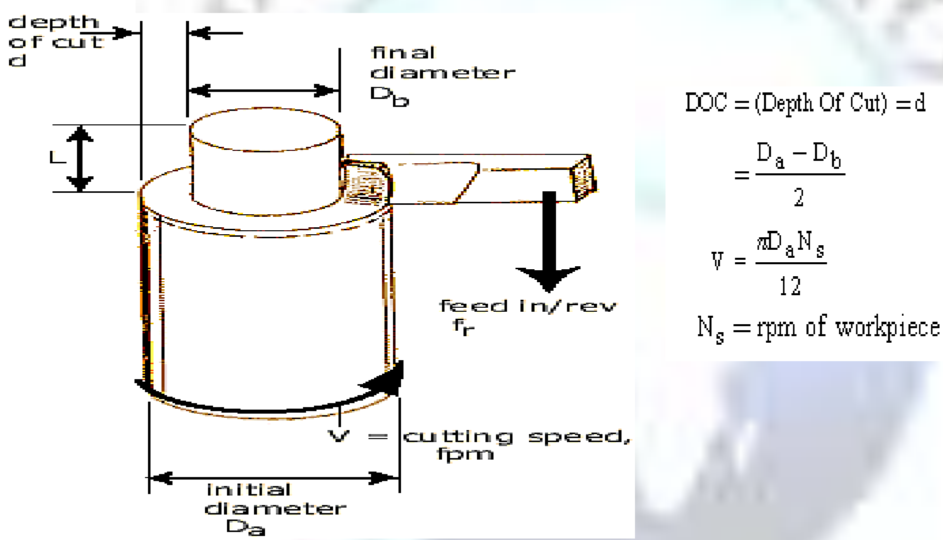

Fig 2: Geometry of fundamental machining parameters

The Taguchi method is a well-known technique that provides a systematic and efficient methodology for process optimization and this is a powerful tool for the design of high quality systems. Taguchi approach to design of experiments in easy to adopt and apply for users with limited knowledge of statistics, hence gained wide popularity in the engineering and scientific community. This is an engineering methodology for obtaining product and process condition, which are minimally sensitive to the various causes of variation, and which produce high-quality products with low development and manufacturing costs. Signal to noise ratio and orthogonal array are two major tools used in robu design.
For the maximum material removal rate, the solution is “Larger is better” and S/N ratio is determined according to the following equation:

$$\frac{S}{N} = -10\log_{10}\{\frac{1}{n}\sum\frac{1}{y^2}\}$$

Where, S/N = Signal to Noise Ratio, n = No. of Measurements, y = Measured Value The influence of each control factor can be more clearly presented with response graphs. Optimal cutting conditions of control factors can be very easily determined from S/N response graphs, too. Parameters design is the key step in Taguchi method to achieve reliable results without increasing the experimental costs.

LIST OF HARDWARE AND THEIR SPECIFICATIONS

1. CNC lathe
2. Surface roughness measurement device
3. Cutting tool inserts

1) CNC Lathe:

LMWRIGI 15 A50 CNC Lathe
Spindle speed range: 1,000 rpm minimum, 3500 rpm maximum
Feed rate range: 0.0025 –100 mm per rev
Least input movement increment: X 0.001mm, Z 0.025 mm

Fig 3: LMWRIGI 15 A50 CNC Lathe

2) Surface roughness measurement device:

Mitutoy Surftest SJ- 400 surface texture measuring instrument
Measures Ra in µm
Maximum traversing length: 50.00 mm
Horizontal traversing speed: 3.0 mm/min
Roughness average, Ra: 30-100% of the full scale ±2%

Fig 4: Mitutoyo Surftest SJ- 400

3) Cutting tool inserts:

Tools tipped with TiAIN-TiCN (Titanium Aluminium Nitride-Titanium Carbo Nitride) by PVD (Physical Vapor Deposition) only are highly advisable for machining that contain no more than 7% silicon. Tool used during experimentation are shown in figure 5 Different types of tool used in CNC machining are shown in figure three inserts of different nose radius mention below are used during experimentation D -55^0 Diamonds.

1. (0.2 mm nose radius)
2. (0.3 mm nose radius)
3. (0.4 mm nose radius

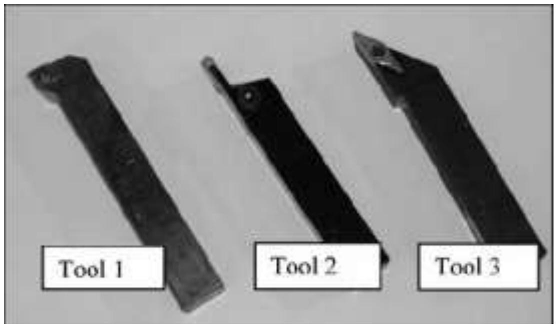

Fig. 5: (Tool 1 for facing, Tool 2 for parting and Tool 3 for turning)

WORK MATERIAL

Traditional machining operations such as turning, milling, boring, tapping, sawing etc. are easily performed on M.S. The machines that are used can be the same as for use with steel, however optimum machining conditions such as rotational speeds and feed rates can only be achieved on machines designed.

Taguchi Orthogonal Array

If there is an experiment having 3 factors which have three values, then total number of experiment is 27. Then results of all experiment will give 100 accurate results. In comparison to above method the Taguchi orthogonal array make list of nine experiments in a particular order which cover all factors. Those nine experiments will give 99.96% accurate result. By using this method number of experiments reduced to 9 instead of 27 with almost same accuracy.

Process Parameter

Table 1: Parameters, codes, and level values used for the orthogonal Array

Parameter	Code	Level 1	Level 2	Level 3
Control factors				
Spindle speed (rpm)	A	1,500	2,250	3,000
Feed rate (mm/rev)	B	0.1	0.2	0.3
Depth of cut (mm)	C	0.2	0.4	0.6
Tool radius (mm)	D	0.2	0.3	0.4

Design of Experiment

Taguchi's designs aimed to allow greater understanding of variation than did many of the traditional designs. Taguchi contended that conventional sampling is inadequate here as there is no way of obtaining a random sample of future conditions. Taguchi proposed extending each experiment with an "outer array" or orthogonal array should simulate the random environment in which the experiment would function.

Experimentation

The whole experimentation is divided into different steps. All the steps are discussed in detail below:

a) Preparation of Job

After doing initial turning on workpiece the diameter is reduced to 10 mm. Workpiece is cut into equal part of length 60mm and measured initial weight of all jobs.

b) Maximum Limits of Operating Parameters

There are three machining parameters i.e. Spindle speed, Feed rate, Depth of cut. Different experiments are done by varying one parameter and keeping other two fixed so maximum value of each parameter was obtained. Operating range is found by experimenting with top spindle speed and taking the lower levels of other parameters. A combination of all three parameters is found beyond which tool or job fails.

Taguchi Orthogonal Array

Taguchi orthogonal array is designed with three levels of turning parameters with the help of software Minitab 15. Each three level parameter has 2 degree of freedom (DOF) (Number of level – 1), the total DOF required for three parameters each at three levels is 8[=4x (3-1)]. As per Taguchi's method the total DOF of the OA must be greater than or equal to the total DOF required for the experimentation. So an L_9 OA (a standard 3- level OA) having 8(=9-1) degree of freedom was selected for the present analysis. The standardized Taguchi-based experimental design used in this study was an L_9 (3_4) orthogonal array, as described shown in below table 2.

Table 2: The basic Taguchi L_9 (3_4) orthogonal array

Run	Control factors and levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

This basic design uses up to four control factors, each with three levels. A total of nine runs must be carried out, using the combination of levels for each control factor (A through D).The addition of noise factors is optional, and requires each run to be conducted once for each combination of noise factor. The selected parameters, discussed in the introduction, are listed in table 1, along with their applicable codes and values for use in the Taguchi model. The control and noise factors are independent variables, and the response variable is the dependent variable. The control factors are the basic, controlled parameters used in a turning operation. The noise factors are often uncontrolled variables in machine shops which may affect the surface roughness of a turning operation. The selected factors were considered because that could be controlled in an experimental setup.

A modified orthogonal array, table 3 was created using the basic Taguchi orthogonal array and the selected parameters from table 1. In this array, the basic array with the control factors are shown as the inner control factor array and the added repetitions the outer noise array.

Table 3: Modified Taguchi L_9 (3^4) orthogonal array

Inner Control Factor Array				Outer Control Factor Array		
SpindleSpeed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Tool Radius (mm)	Y1	Y2	Y3
1500	0.1	0.2	0.2	1.35	1.85	1.52
1500	0.2	0.4	0.3	3.36	3.12	3.46
1500	0.3	0.6	0.4	4.07	3.47	3.13
2250	0.1	0.4	0.4	1.2	1.13	0.83
2250	0.2	0.6	0.2	3.97	4.47	4.6
2250	0.3	0.2	0.3	5.47	5.92	5.34
3000	0.1	0.6	0.3	1.16	1.04	1.17
3000	0.2	0.2	0.4	1.21	2.65	1.4
3000	0.3	0.4	0.2	6.16	5.97	5.94

Also indicated here is the required repetition for each run for each combination of noise factors and different measurement are Y1, Y2, Y3, .All of the experimental are repeated three times.

EXPERIMENTATION AND DATA COLLECTION

The next step is to design the matrix experiment and define the data analysis procedure. The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply three times (if outer array is not used) or according to the outer array (if used). Randomizations were carried for to reduce bias in the experiment. The spindle speed, feed rate, and depth of cut parameters were programmed into the CNC program. The tool inserts were changed as needed to obtain the prescribed radius, and to alternate between the in each set. The surface roughness measurement process included the use of a Talysurf 10, as well as all the necessary hardware to align the stylus motion perpendicular to the axis of the turned part during the measurement. The maximum surface roughness measurement (maximum R_a) of each cut was recorded for analysis.

The results of the surface roughness measurements R_a (μm) of each sample are shown in table 3, along with the additional parameters of the expanded orthogonal array. The individual surface roughness measurements are noted in the array. A final column has been added to this array, to indicate the signal-to-noise (S/ N) ratio, calculated as follows:

$$\eta = -10\log\left[\frac{1}{n}\left(\sum y_i^2\right)\right]$$

Where η is the S/N ratio,

- y_i are the individual surface roughness measurements in columns Y1 through Y3, and
- nis the number of repetitions; in this case, n=3.

DATA ANALYSIS

The experiment was planned by using the parametric approach of the Taguchi method. A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc. In the present investigation, following methods are used.

1. ANOVA for raw data & S/N data
2. Optimum Condition and Performance
3. Plot of average response curves & Variation Reduction

Analysis of Raw Data and S/N Ratios:

Table 4 shows the result of the analysis of variance (ANOVA) for surface roughness height Ra. The analysis of variance was carried out for a 95% confidence level. The main purpose of the analysis of variance is to investigate the influence of design parameters on optimal surface finish by indicating the parameters that significantly affect the quality characteristics of the machined surfaces. This analysis provides the relative contribution of machining parameters in controlling the response of machining performance criteria i.e. surface roughness height Ra during turning. Table 4 shows that the spindle speed (P=4.233%), feed (P=72.994%), depth of cut (P=0.13%) and tool nose radius (P=22.641%) are responsible and have some influence on surface roughness height Ra. The influence of feed (P=72.994%) and tool nose radius (P=22.641%) are the most significant as according literature review. And the influence of spindle speed (P=4.233%), is significant and depth of cut (P=0.13%) is less influencing factors compare to other on the surface roughness height Ra during turning.

Table 4: ANOVA table for responded raw data

SOURCE	Sum of Sq.	DOF	Variance	Percentage	Pure Sum
Spindle Speed	11.62	2	5.81	4.233	11.62
Feed rate	200.34	2	100.17	72.994	200.34
Depth of Cut	0.358	2	0.179	0.13	0.358
Tool nose Radius	62.141	2	31.07	22.641	62.141
Error	0	0	0	0	0
Total	274.61	8		100	

The high variance for each run also seems to indicate that the noise factors affected the resulting surface roughness values of the samples. The Ra (mean response variable) effect table under the array in Table 5 indicates the mean of the response variable means for each level of each control factor. This specifies the mean surface roughness value that each level of each control factor produced during this experiment. The S/N effect table under the array in Table 6 indicates the mean of the S/N values for each level of each control factor Table 5 and Table 6 shows average effect response for the raw data and effect response table for S/N ratio.

Table 5: Average effect response table for the S/N data

LEVEL	Spindle speed	Feed	Depth of cut	Tool nose radius
L1	6.817	1.744	7.774	10.948
L2	9.299	8.053	7.888	7.621
L3	6.966	13.284	7.42	4.513
Max-Min	2.482	5.231	0.468	6.435
Rank	3	2	4	1

Table 6: Optimum Condition & Performance

Factor	Description	Level	Contribution
Spindle speed	2000	2	1.604
Feed	0.22	3	5.59
Depth of cut	0.6	2	0.194
Tool nose radius	0.2	1	3.253

Plot of average response curves & Variation Reduction

Since we are looking for the mean and variance of the surface roughness values to be as small as possible, the ideal S/N effects should be as large as possible. This can be shown graphically as well; Fig. 6,7, 8 and 9 shows plots of the response and S/N ratio effects from Table 5 and 6. These graphs reveal the level to be chosen for the ideal cutting parameters (the level with the highest point on the graph), as well as the relative effect each parameter has on the S/N ratio (the general slope of the line). As seen in the response and S/N ratio effects graphs all four parameters had at least some effect on the surface roughness and S/N ratios in this study. The feed rate and tool nose radius are shown to have a strong effect on surface roughness and their S/N ratios, which was expected from the literature review. The spindle speed and depth of cut had a smaller effect, as evidenced by the shallow slope of the lines. The effect of spindle speed appears to be nonlinear, with the middle level being the least desirable for surface roughness.

The S/N ratio and Ra effects data plotted in these graphs can be used to determine the optimal set of parameters from this experimental design. The graphs indicate the levels at which the S/N ratio and Ra effects are at their optimal magnitudes; that is, the S/N ratio effect is at its highest magnitude, and the Ra effect is at its lowest magnitude. However, since a confirmation run was required for this experiment, a single level must be chosen. Since the spindle speed affects the linear speed of the feed rate (which is in mm\rev), a higher spindle speed was chosen to maximize productivity. Additionally, selecting the level based on the S/N ratio is ideal, since the S/N ratio effect can be considered as resulting in the best response given the noise in the system. The optimized levels of each of the other three parameters were included in the confirmation run. As seen in Table 5, the selected spindle speed was at level 2 (2000 rpm), the optimal feed rate was at level 3 (0.22mm\rev), the optimal depth of cut was at level 2 (0.6 mm), and the optimal tool nose radius was at level 1 (0.2 mm). The final confirmation run would be used to verify that this combination was ideal.

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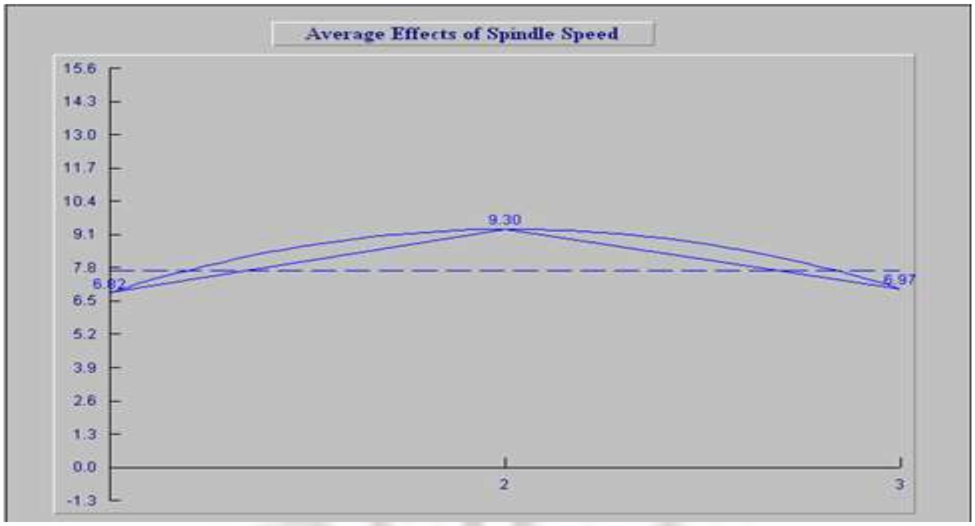

Figure 6: Response and S/N ratio effects for spindle speed

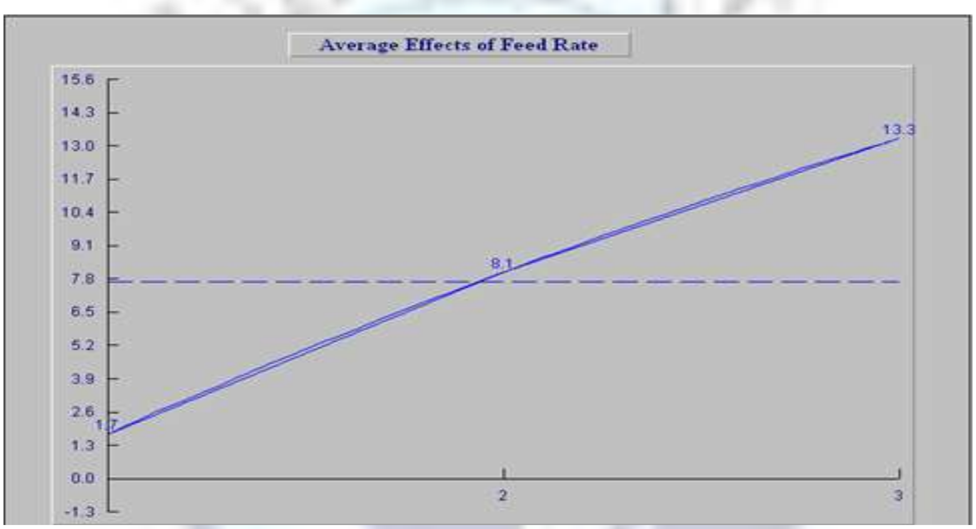

Figure 7: Response and S/N ratio effects Feed rate

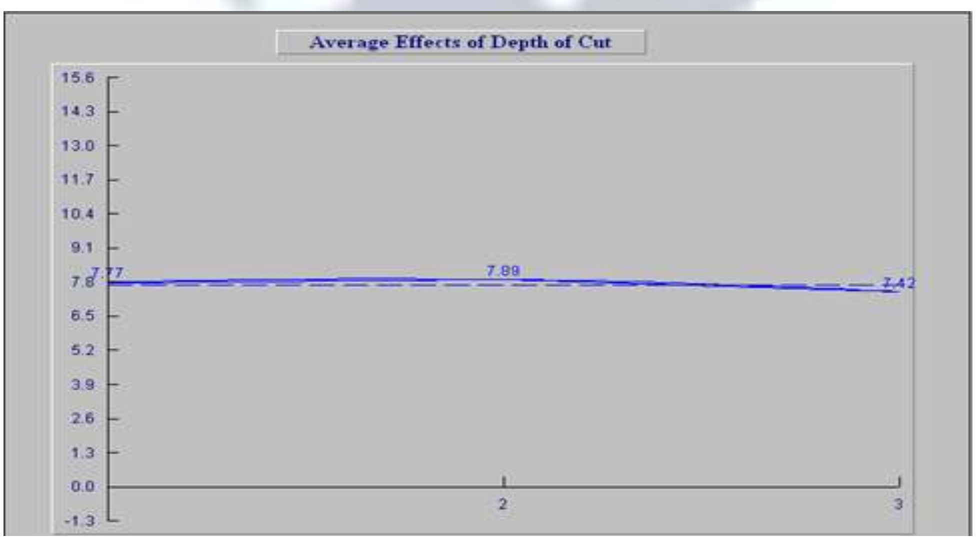

Figure 8: Response and S/N ratio effects for depth of cut

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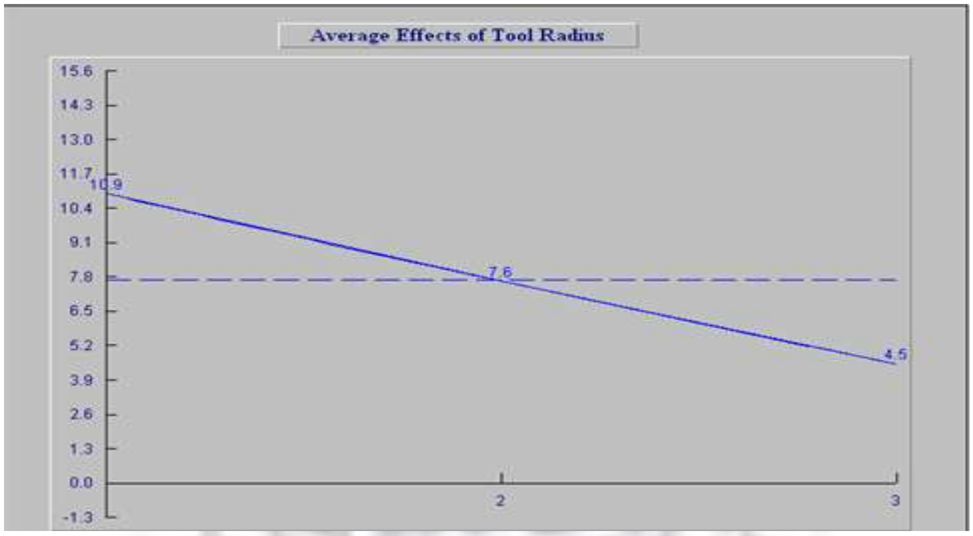

Figure 9: Response and S/N ratio effect Tool nose radius

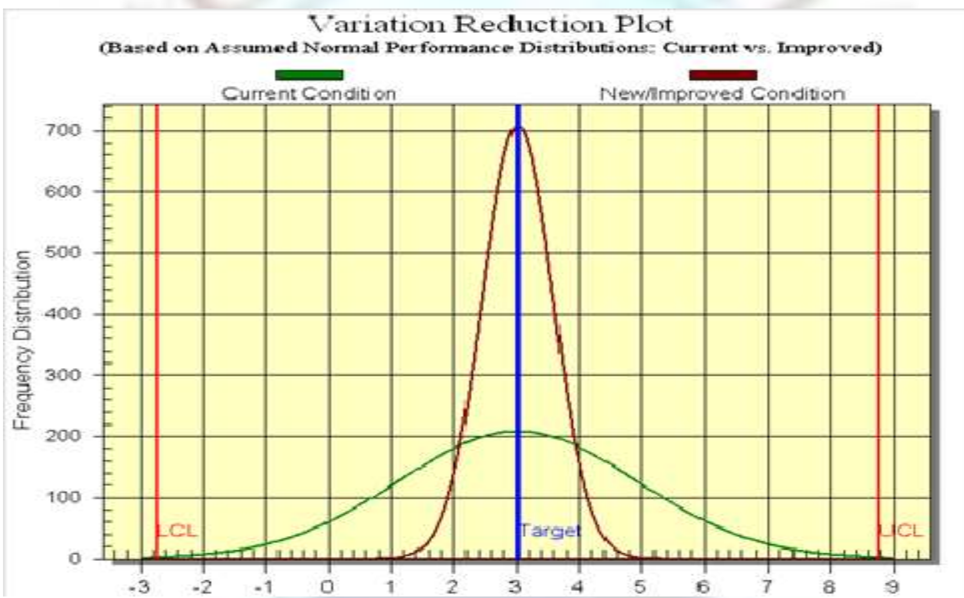

Fig 10: Variation Reduction Plot

CONCLUSION

This study presented an efficient method for determining the optimal turning operation parameters for surface finish under varying conditions through the use of the Taguchi parameter design process. This process was applied using a specific set of control and noise parameters, and a response variable of surface roughness. The present study can be concluded in the following steps:

1. Taguchi design of experiment technique can be very efficiently used in the optimization of machining parameters in metal cutting processes.
2. Optimum parameter setting for surface roughness is obtained at a cutting speed of 2400rpm, feed rate 40mm/min. and depth of cut 0.5mm.
3. Formulation of equation is done with the help of which surface roughness can be predicted.
   $Ra = - 1.14 + 0.160\ S + 0.976\ F + 0.228\ D$
4. Contour and surface plots obtained through this study can be used as standard for selecting parameters for target surface finish.

SCOPE FOR FUTURE WORK

The machining variables are divided into three main categories. These are tool variables, work piece variables and set-up variables. Tool variables includes tool material, nose radius, tool wear, tool geometry, tool vibration, machine tool rigidity, and tool overhang etc. Work piece variables include work piece material, hardness, length and diameter etc. Set-up variables include cutting speed, feed rate, depth of cut etc. In the present work set-up and & tool variables are considered. Work piece variables can also be optimized by using Taguchi design of experiment. There is also scope for considering more factors levels, interactions to optimize a selected set of parameters. A comparison between different optimization techniques can also be studied to check which optimization technique is better.

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