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Multiperformance Optimization in Turning of Free-Machining Steel Using Taguchi Method and Utility Concept

V.N. Gaitonde, S.R. Karnik, and J. Paulo Davim

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This article presents the application of Taguchi method and the utility concept for optimizing the machining parameters in turning of free-machining steel using a cemented carbide tool. A set of optimal process parameters, such as feed rate, cutting speed, and depth of cut on two multiple performance characteristics, namely, surface roughness and metal removal rate (MRR) is developed. The experiments were planned as per L_9 orthogonal array. The optimal level of the process parameters was determined through the analysis of means (ANOM). The relative importance among the process parameters was identified through the analysis of variance (ANOVA). The ANOVA results indicated that the most significant process parameter is cutting speed followed by depth of cut that affect the optimization of multiple performance characteristics. The confirmation tests with optimal levels of machining parameters were carried out to illustrate the effectiveness of Taguchi optimization method. The optimization results revealed that a combination of higher levels of cutting speed and depth of cut along with feed rate in the medium level is essential in order to simultaneously minimize the surface roughness and to maximize the MRR.

Keywords cemented carbide tool, free-machining steel, metal removal rate, surface roughness, Taguchi method, turning, utility concept

1. Introduction

The surface quality is an important parameter for evaluating the productivity of machine tools and the machined parts. Hence, the desired surface quality is to be achieved for the functional behavior of the mechanical parts (Ref 1). The surface roughness is the index of product quality and has an influence on several properties, such as fatigue strength, coefficient of friction, lubrication, corrosion resistance, and wear resistance of the machined components (Ref 2). Nowadays, in the manufacturing industry, special attention is paid to dimensional accuracy and surface finish. Thus, measuring and characterizing of the surface finish is considered to be the predictor of the machining performance (Ref 3).

Turning is the primary operation in most of the production processes that produces the components, which have critical features requiring specific surface finish. In the manufacturing industry, the cutting conditions continue to be chosen solely on the basis of handbook values/manufacturer recommendations/operators experience in order to achieve the best possible surface finish. Due to an inadequate knowledge of the complexity and parameters affecting the surface finish in turning operation, an improper decision may cause high manufacturing costs and low product quality. Further, the metal removal rate (MRR) plays an important role in turning operation and high MRR is invariably preferred. Hence, the proper selection of cutting tools and process parameters is an important criterion for achieving high surface quality and high MRR in the machining process (Ref 4).

The optimization of process parameters requires a systematic methodological approach by using experimental methods and mathematical/statistical models. Taguchi method is used to optimize the performance characteristics of process parameters, which is proved to be a powerful tool that differs from traditional practices (Ref 5, 6). This approach can economically satisfy the needs of problem solving and design optimization with less number of experiments without the need for process model developments. Thus, it is possible to reduce time and cost for the experimental investigations. The original Taguchi method is designed to optimize a single performance characteristic (Ref 7-9). However, most of the products have multiple performance characteristics, and hence, there is a need to obtain a single optimal process parameters setting, which can be used to produce products with optimum or near optimum characteristics as a whole. Many researchers have suggested different modifications to the original Taguchi method for multiresponse optimization (Ref 10).

Davim (Ref 11) developed linear regression models to predict average surface roughness (R_a) and maximum peak to valley height (R_t) by conducting experiments on free-machining steel based on Taguchi L_{27} orthogonal array. The predicted values of surface roughness parameters were compared with

V.N. Gaitonde, Department of Industrial and Production Engineering, B. V. B. College of Engineering and Technology, Hubli 580 031, Karnataka, India; **S.R. Karnik**, Department of Electrical and Electronics Engineering, B. V. B. College of Engineering and Technology, Hubli 580 031, Karnataka, India; and **J. Paulo Davim**, Department of Mechanical Engineering, University of Aveiro, Campus Santiago, 3810-193 Aveiro, Portugal. Contact e-mails: gaitondevn@yahoo.co.in, karniksr@yahoo.com and pdavim@ua.pt

corresponding values computed using theoretical models. However, as per authors' knowledge, no work has been reported in the literature on simultaneous optimization of surface roughness and MRR in turning of 9SMnPb28k (DIN) free-machining steel. Hence, an attempt has been made in this article, which discusses the application of Taguchi method and the utility concept for multi-objective turning process optimization. The utility concept (Ref 12) employs the weighting factors to each of the signal to noise (S/N) ratios of the performance characteristics to obtain a multiresponse S/N ratio for each trial of an orthogonal array. In the present investigation, Taguchi technique using utility concept has been employed for determining the best combination values of cutting parameters, namely, feed rate, cutting speed, and depth of cut in order to minimize the surface roughness, as well as to maximize the MRR simultaneously in turning of free-machining steel, 9SMnPb28k (DIN) using cemented carbide tools.

2. Methodology

2.1 Taguchi Approach

An orthogonal array is a major tool used in the Taguchi design, which is used to study several design parameters by means of a single quality characteristic. The purpose of conducting an orthogonal experiment is to determine the optimum level for each controllable parameter and to establish the relative significance of individual parameters in terms of their main effects on the response. The conventional method involves one variable at a time, while keeping the other parameters at fixed levels. This method is generally time consuming and requires a considerable number of experiments to be performed. For example, if there are k factors with l levels defined for each of the factors, then it is necessary to carry out l^k number of experiments. On the other hand, the matrix experiments using orthogonal arrays enable to study the effect of several factors simultaneously with reduced number of experiments. Depending on the number of process parameters and setting levels, a suitable array is selected (Ref 5, 6). Each column of the orthogonal array designates a process parameter and its setting levels in each experiment and each row designates an experiment with the level of different process parameters in that experiment. Taguchi suggests S/N ratio, which is a logarithmic function of desired response, serves as the objective function for optimization (Ref 5, 6), The S/N ratio is used to measure the performance characteristics and the significant process parameters through analysis of variance (ANOVA).

2.2 Taguchi Approach with Utility Concept

In order to optimize the multiple responses, Taguchi design is not applied directly, as each performance characteristic may not have the same measurement unit. Hence, the evaluations of various characteristics should be combined to give a composite index. Such a composite index represents the utility of a product. The overall utility of a product is the sum of utilities of each of the performance quality characteristics (Ref 12).

If X_i is a measure of effectiveness of an attribute i and there are n attributes evaluating the outcome space, then the overall utility function is given by:

$$U(X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} U_i(X_i) \quad \text{(Eq 1)}$$

where, $U_i(X_i)$ is the utility of the ith attribute. Depending upon the requirements, the attributes may be given priorities and weights. Hence, the weighted form of Eq 1 is:

$$U(X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} w_i U_i(X_i) \quad \text{(Eq 2)}$$

where,

$$\sum_{i=1}^{n} w_i = 1 \quad \text{(Eq 3)}$$

and w_i is the weight assigned to attribute i.

3. Experimental Procedure

3.1 Plan of Experiments

In the present work, three parameters, namely, feed rate, cutting speed, and depth of cut are considered and the ranges of the parameters were selected based on the earlier investigation carried out by Davim (Ref 11). The parameters identified in the present study are multilevel factors and their outcome effects are not linearly related; and hence, it has been decided to use three-level tests for the cutting parameters. The identified process parameters and their levels are presented in Table 1.

Taguchi optimization begins with the selection of orthogonal array with distinct number of levels defined for each of the parameters, feed rate, cutting speed, and depth of cut. The minimum number of trials in the orthogonal array is given by:

$$N_{\min} = (l - 1)k + 1 \quad \text{(Eq 4)}$$

where, k = number of factors = 3 and l = number of levels = 3. This gives $N_{\min}$ = 7; and hence, according to Taguchi design concept L_9 orthogonal array has been selected. Thus, only 9 experiments are required to study the entire turning process parameter space using L_9 orthogonal array. The L_9 orthogonal array for the present study is illustrated in Table 2.

3.2 Materials and Processes

The work material used in the present study is 9SMnPb28k (DIN) free-machining steel. The length to diameter ratio of the workpiece is kept approximately as 2:1. '*TPUN 160308 P10 (ISO)*' type cemented carbide inserts were used throughout the investigation. The geometry of the cutting tool insert is as follows: rake angle: +6°; clearance angle: 5°; edge major tool cutting: 60°; cutting edge inclination angle: 0°; included angle: 60°; and corner radius: 0.8 mm. Experiments were performed

Table 1 Process parameters and their levels

Parameter	Code	Unit	Level 1	Level 2	Level 3
Feed rate	A	mm/rev	0.10	0.16	0.25
Cutting speed	B	m/min	71	141	283
Depth of cut	C	mm	0.50	0.75	1.00

Table 2 L_9 orthogonal array along with the responses and computed values of multiresponse S/N ratio

Trial no.	Levels of process parameters A	B	C	Response R_a, μm	MRR, cm^3/min	S/N ratio, dB η_1 for R_a	η_2 for MRR	η
1	1	1	1	3.52	3.55	−10.9309	11.0046	0.0369
2	1	2	2	2.08	10.575	−6.3613	20.4856	7.0622
3	1	3	3	0.75	28.3	2.4988	29.0357	15.7673
4	2	1	2	3.71	8.52	−11.3875	18.6088	3.6107
5	2	2	3	1.97	22.56	−5.8893	27.0668	10.5887
6	2	3	1	1.17	22.64	−1.3637	27.0975	12.8669
7	3	1	3	4.9	17.75	−13.8039	24.9840	5.5900
8	3	2	1	3.31	17.625	−10.3966	24.9226	7.2630
9	3	3	2	2.54	53.0625	−8.0967	34.4958	13.1995

as per orthogonal array on a conventional lathe with a 6 kW power. Trials were carried out at random to avoid systematic errors.

The average surface roughness (R_a), which is commonly used in the manufacturing industry, is considered for the present investigation. R_a is the arithmetic value of the departure of profile from the centerline along sampling length. The surface roughness measurements (three measurements) were made over the turning surfaces using stylus instrument (according to ISO 4287/1 and DIN 4762). The surface roughness was measured at three equally spaced locations around the circumference of the workpiece. The measurements on turning surfaces were made by a '*Hommelwerke T1000*' profilometer (one measurement) with a cut off of 0.8 mm and a precision 0.01 μm and with a '*Perthometer S6 P*' profilometer (two measurements) with a cut-off of 0.8 mm and a precision 0.01 μm. The value used is the average of three measurements of each surface. The average values of R_a are given in Table 2.

4. Analysis of Results and Discussion

In the present study of turning process optimization, the objective is to minimize the surface roughness and to maximize the MRR.

The MRR is calculated from the following equation:

$$\text{MRR} = fvd \ (\text{cm}^3/\text{min}) \quad \text{(Eq 5)}$$

where, f is feed rate in mm/rev; v is cutting speed in m/min; d is depth of cut in mm.

The computed values of MRR for each trial of an orthogonal array are summarized in Table 2.

Taguchi design uses S/N ratio instead of mean value to interpret the trial results data into a value for the evaluation characteristic in the optimum setting analysis (Ref 5), because S/N ratio can reflect both mean and variation of the performance characteristics. In the present investigation, Taguchi parameter design with the utility concept has been introduced for optimizing the multiple performance characteristics (R_a and MRR). Here, R_a is to be minimized and MRR to be maximized. Hence, "*smaller the better type*" characteristic for R_a and "*larger the better type*" characteristic for MRR have been selected. The S/N ratio associated with the responses, R_a and MRR are given as (Ref 5, 6):

$$\eta_1 = -10 \log_{10}[R_a^2] \quad \text{(Eq 6)}$$

$$\eta_1 = -10 \log_{10}\left[\frac{1}{\text{MRR}^2}\right] \quad \text{(Eq 7)}$$

In the utility concept, the multiresponse S/N ratio is given by (Ref 12):

$$\eta = w_1\,\eta_1 + w_2\,\eta_2 \quad \text{(Eq 8)}$$

where, w_1 and w_2 are the weighting factors associated with S/N ratio for each of the responses R_a and MRR, respectively. These weighting factors are decided based on the priorities among the various responses to be simultaneously optimized.

In the present investigation, weighting factors of 0.5 for each of the responses is considered, which gives equal priorities to both R_a and MRR for simultaneous optimization. The computed values of S/N ratio for each response and the multiresponse S/N ratio for each trial in the orthogonal array are given in Table 2.

4.1 Analysis of Interaction Effects of Parameters on Multiple Performance Characteristics

The plots of two factor interaction effects on multiresponse S/N ratio of multiple characteristics are generated using *MINITAB* statistical software (Ref 13). Figure 1 shows the interaction effect of cutting speed and feed rate. It can be observed from Fig. 1 that there exists a considerable interaction effect of cutting speed variation on multiresponse S/N ratio of performance characteristics for any given value of feed rate. On the other hand, for any given cutting speed, the effect of feed rate variation on multiresponse S/N ratio is comparatively less. Further, when the cutting speed is high (283 m/min), the interaction effect due to feed rate is less as compared to the interaction effect when the cutting speed is either at low level (71 m/min) or at medium level (141 m/min). The interaction effect due to feed rate and depth of cut is exhibited in Fig. 2 and it seen that the degree of mutual interaction between the feed rate and depth of cut on multiresponse S/N ratio is more. Figure 3 illustrates the interaction effect due to depth of cut and cutting speed. The effect of variations of depth of cut on multiresponse S/N ratio of performance characteristics is less when the cutting speed is high (283 m/min) as compared to the depth of cut variations when the cutting speed is either at low level

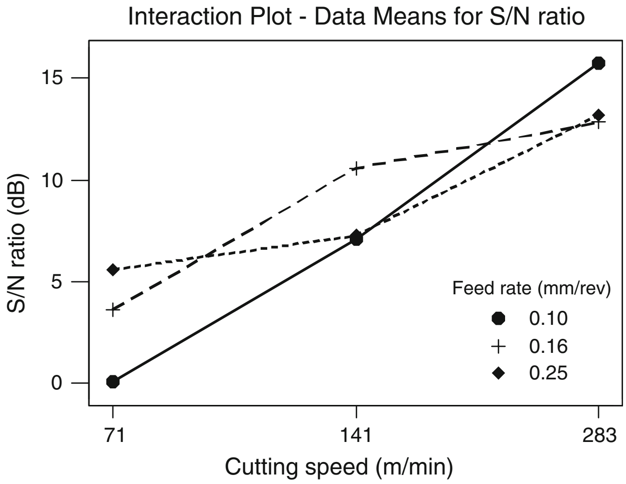

Fig. 1 Interaction effect plot of feed rate and cutting speed on multiresponse S/N ratio of performance characteristics

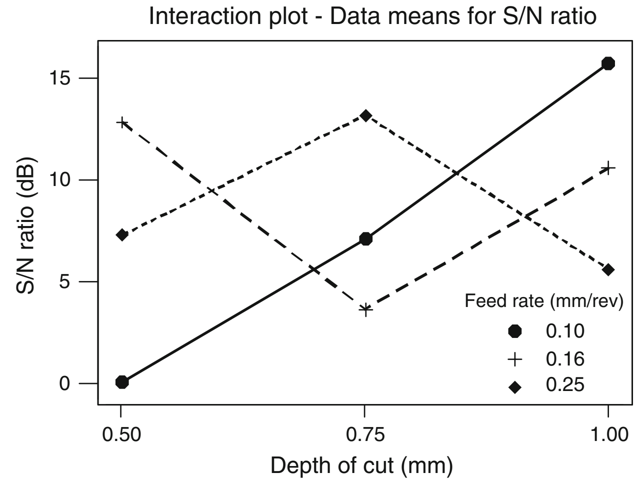

Fig. 2 Interaction effect plot of feed rate and depth of cut on multiresponse S/N ratio of performance characteristics

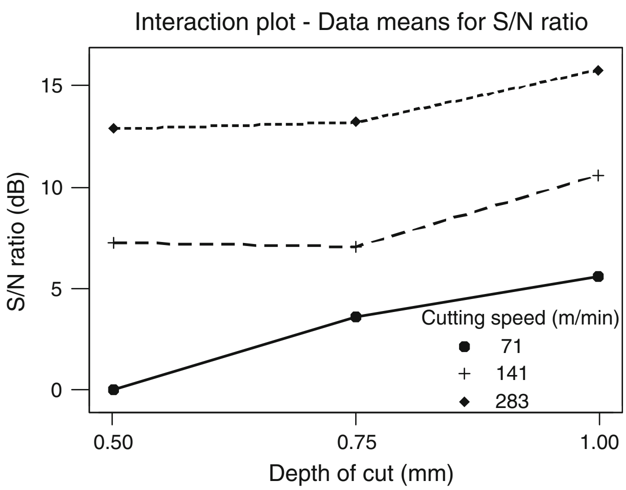

Fig. 3 Interaction effect plot of cutting speed and depth of cut on multiresponse S/N ratio of performance characteristics

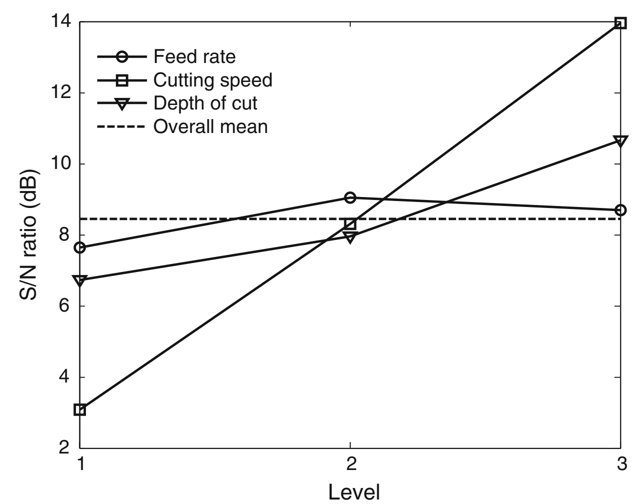

Fig. 4 Response graph of control parameters

(71 m/min) or at medium level (141 m/min). Further, the degree of interaction effect of cutting speed variations is almost same for all the values of depth of cut as seen in Fig. 3. Hence, from the above discussion, it can be concluded that the interaction effect is minimal either due to feed rate or due to depth of cut when the cutting speed is high (283 m/min).

4.2 Analysis of Means

The analysis of means (ANOM) is used to determine the optimal process parametric settings and it is the process of estimating the main effects of each parameter (Ref 5). The effect of a parameter level is the deviation it causes from the overall mean response. The overall mean of η associated with nine trials is computed as:

$$m = \frac{1}{9}\sum_{k=1}^{9} \eta_k \qquad \text{(Eq 9)}$$

The effect of a process parameter level i for parameter j is:

$$(m)_{i,j} = \frac{1}{l}\sum_{i=1}^{l} (\eta_i)_j \qquad \text{(Eq 10)}$$

The optimum level of a process parameter is the level, which gives the highest S/N ratio. The maximization of multiresponse S/N ratio for the optimal level associated with each process parameter is:

$$j_{i,\text{opt}} = \max\{(m)_{i,j}\} \quad \text{for} \quad j = f, v, d;\ i = 1, 2, 3 \qquad \text{(Eq 11)}$$

The ANOM result for multiresponse S/N ratio is represented in the response graph (Fig. 4). Thus, for the optimal process parameter setting for the present investigation is A2, B3 and C3. Hence, the best combination values for achieving minimum surface roughness and maximum MRR are:

- Feed rate: 0.16 mm/rev
- Cutting speed: 283 m/min
- Depth of cut: 1 mm.

However, the relative contribution of each process parameter on multiple performance characteristics is determined through ANOVA that enables more accurate determination of the optimal process parameter levels (Ref 5, 6).

4.3 Analysis of Variance

The ANOVA is a computational technique, which is used to estimate the relative significance of each process parameter in terms of percent contribution on the overall response (Ref 5, 6). The ANOVA is also required for estimating the variance of error for the effects and confidence interval of the prediction error. The ANOVA table contains the degrees of freedom, sum of squares, mean square and percentage contribution. The parameters with higher percentage contribution are ranked higher in terms of importance in the experiment and also have significant effects in controlling the overall response.

Table 3 illustrates the results of ANOVA performed on multiple performance characteristics. It is clearly observed in ANOVA table that the cutting speed has major contribution (86.05%) in optimizing the multiple performance characteristics followed by depth of cut (11.75%). However, feed rate does not have any significant effect in optimization. Further, it is also seen that the ANOVA has resulted in around 0.65% of error contribution, indicating that the interaction effects of the process parameters are negligible for simultaneously minimizing the surface roughness and maximizing the MRR.

4.4 Verification Test of Optimal Result

The verification experiment is the final step in Taguchi design. Since the optimum condition of parameter levels was not included in the main experiment, an indirect method was chosen to predict the multiple characteristics. The predicted optimum value of S/N ratio (η_{opt}) is determined as (Ref 5):

$$\eta_{opt} = m + \sum_{j=1}^{p} [(m_{i,j})_{max} - m] \qquad \text{(Eq 12)}$$

where, $(m_{i,j})_{max}$ is the S/N ratio of optimum level i of parameter j and p is the number of main design parameters that affect the multiple performance. The predicted S/N ratio for the optimum parameter levels (A2, B3 and C3) is 16.7297 dB.

The validation experiment was conducted according to the optimal process parameter levels (A2, B3 and C3). Two trials were conducted and the corresponding surface roughness values were measured. The average value of surface roughness is 1.19 µm and the computed value of MRR for the optimal parameter setting is 45.28 cm^3/min. The multiresponse S/N ratio for the confirmation experiment is 15.8036 dB.

In order to judge the closeness of observed value of S/N ratio with that of the predicted value, the confidence interval value of η_{opt} for the optimum process parameter level combination at 95% band is determined. The CI is given by (Ref 6):

$$\mathrm{CI} = \sqrt{F_{(1,\upsilon_e)} V_e \left(\frac{1}{n_{eff}} + \frac{1}{n_{ver}} \right)} \qquad \text{(Eq 13)}$$

where, υ_e is the degrees of freedom for error = 2, $F_{(1,\upsilon_e)}$ is the F value for 95% confidence interval = 18.51, V_e is the variance of error = 0.6698, $n_{eff} = \frac{N}{1+\upsilon}$; N = Total trial number = 9, v = Degrees of freedom of p process parameters = 6, n_{ver} is the validation test trial number = 2.

In the present study, the prediction error i.e. the difference between η_{opt} and η_{obs} is 0.9261 dB, which is within the CI value of ±3.9802 dB, and hence, justifying the adequacy of the additivity of the model. Thus, the optimal process parameter level combination for simultaneously minimizing the roughness and maximizing MRR is A2, B3 and C3.

Table 3 Summary of ANOVA

Parameter	Degrees of freedom	Sum of squares	Mean square	Percentage contribution
Feed rate (A)	2	3.2022	1.6011	1.55
Cutting speed (B)	2	177.1708	88.5854	86.05
Depth of cut (C)	2	24.1850	12.0925	11.75
Error	2	1.3396	0.6698	0.65
Total	8	205.8976	25.7372	100

4.5 Discussion

From the results of ANOM, it is found that the combinations required for simultaneously optimizing the surface roughness (R_a) and material removal rate (MRR) in turning of free-machining steel are, feed rate (*f*) at medium level and the cutting speed (*v*) and depth of cut (*d*) at higher levels. As observed from Eq 5, the higher values of feed rate, cutting speed and depth of cut are required to maximize the material removal rate. However, the surface roughness increases with an increase in feed rate, as the surface roughness being proportional to the square of the feed rate. Hence, a trade off is necessary for feed rate values for simultaneous optimization. This also agrees with the previous investigations carried out by several researchers during machining of different grades of steels. Yang and Tarng (Ref 7), in their study reported a similar observation in machining of S45C steel using tungsten carbide cutting tool. It was reported by Tosun and Ozler (Ref 14) that, the lower values of feed rate, cutting speed and depth of cut are necessary to reduce the surface roughness in hot turning operations of high manganese steel using M20 sintered carbide tool. Ozel et al. (Ref 15) found that surface roughness increases with feed rate during hard turning of AISI H13 steel using cubic boron nitride (CBN) inserts. On the other hand, Singh and Rao (Ref 16), in their experimental investigation of hard turning of AISI 52100 bearing steel using mixed ceramic inserts, reported that surface roughness increases with cutting speed for a given depth of cut.

From the above discussion, it is clear that most of the work reported earlier is mainly concentrated on the optimization of single performance characteristic. It is worth mentioning here that the optimal combination of feed rate, cutting speed and depth of cut required to minimize the surface roughness may not be the same for maximizing the material rate. The proposed utility concept in this study finds a trade-off combination of feed rate, cutting speed and depth of cut suitable for simultaneously optimizing both the performance characteristics.

5. Conclusions

The application of Taguchi approach with utility concept has been employed to determine the best combination values of cutting parameters, such as feed rate, cutting speed, and depth of cut for simultaneously minimizing the surface roughness and maximizing the material removal rate during turning of free-machining steel using cemented carbide tool. The experiments were planned as per L_9 orthogonal array. The optimal process parameter levels were obtained through ANOM and the percent contribution of each process parameter in optimizing the multiple performances was determined through ANOVA. From the analysis of experimental results using S/N ratio and ANOVA the following conclusions are drawn from the current investigation within the ranges of the process parameters selected.

- The results of ANOM indicate that a combination of higher levels of cutting speed and depth of cut along with feed rate in the medium level is necessary for simultaneously minimizing the surface roughness and maximizing the MRR.
- The results of ANOVA clearly indicate that the cutting speed is the most significant parameter followed by depth of cut. On the other hand, the feed rate does not have any significant effect in optimizing the multiple performances.
- The ANOVA also resulted in around 0.65% of error, indicating that the interaction effects of process parameters on optimization of multiple performances are negligible.
- The utility concept is found to be very simple and useful for simultaneous optimization of several performance characteristics.

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