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Design optimization of cutting parameters for turning operations based on the Taguchi method

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Abstract

In this study, the Taguchi method, a powerful tool to design optimization for quality, is used to find the optimal cutting parameters for turning operations. An orthogonal array, the signal-to-noise (S/N) ratio, and the analysis of variance (ANOVA) are employed to investigate the cutting characteristics of S45C steel bars using tungsten carbide cutting tools. Through this study, not only can the optimal cutting parameters for turning operations be obtained, but also the main cutting parameters that affect the cutting performance in turning operations can be found. Experimental results are provided to confirm the effectiveness of this approach. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Taguchi method; Optimization; Turning; Tool life; Surface roughness

1. Introduction

In a turning operation, it is an important task to select cutting parameters for achieving high cutting performance. Usually, the desired cutting parameters are determined based on experience or by use of a handbook. However, this does not ensure that the selected cutting parameters have optimal or near optimal cutting performance for a particular machine and environment. To select the cutting parameters properly, several mathematical models [1–6] based on statistical regression techniques or neural computing have been constructed to establish the relationship between the cutting performance and the 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 using this modern approach. Furthermore, a large number of cutting experiments has to be performed and analyzed in order to build the mathematical models. Thus the required model buildings is very costly in terms of time and materials. In this paper, an alternative approach based on the Taguchi method [7–9] is used to determine the desired cutting parameters more efficiency.

Basically, the Taguchi method is a powerful tool for the design of high quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. The methodology is valuable when the design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system performance to sources of variation. In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a world-wide range of industries and nations [10].

In the following, the Taguchi method is introduced first. The experimental details of using the Taguchi method to determine and analyze the optimal cutting parameters are described next. The optimal cutting parameters with regard to performance indexes such as tool life and surface roughness are considered. Finally, the paper concludes with a summary of this study and future work.

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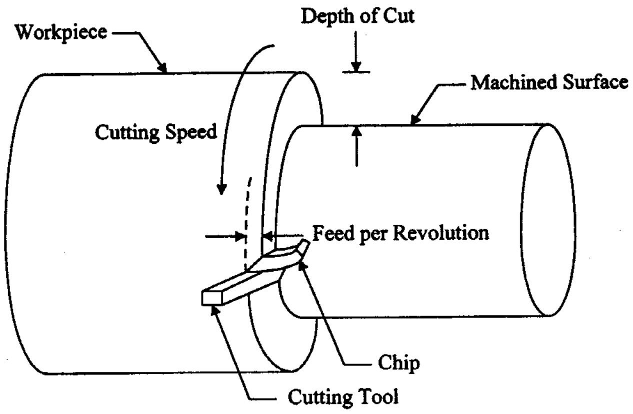

Fig. 1. Basic turning operation

2. Description of the Taguchi method

Taguchi is the developer of the Taguchi method [7]. He proposed that engineering optimization of a process or product should be carried out in a three-step approach, i.e. system design, parameter design, and tolerance design. In system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design, this design including the product design stage and the process design stage. In the product design stage, the selection of materials, components, tentative product parameter values, etc., are involved. As to the process design stage, the analysis of processing sequences, the selections of production equipment, tentative process parameter values, etc., are involved. Since system design is an initial functional design, it may be far from optimum in terms of quality and cost. Following on from system design is parameter design. The objective of parameter design is to optimize the settings of the process parameter values for improving quality characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variation in the environmental conditions and other noise factors. Finally, tolerance design is used to determine and analyze tolerances around the optimal settings recommend by the parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not meet the required performance, and involves tightening tolerances on the product parameters or process parameters for which variations result in a large negative influence on the required product performance. Typically, tightening tolerances means purchasing better-grade materials, components, or machinery, which increases cost. However based on the above discussion, parameter design is the key step in the Taguchi method to achieving high quality without increasing cost. To obtain high cutting performance in turning, the parameter design proposed by the Taguchi method is adopted in this paper.

Basically, experimental design methods [11] were developed originally by Fisher [12]. However, classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out when the number of the process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N

Table 2
Experimental layout using an L_9 orthogonal array

Experiment No.	Cutting parameter level			
	A	B	C	D
	Cutting speed	Feed rate	Depth of cut	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	

Table 1
Cutting parameters and their levels

Symbol	Cutting parameter	Unit	Level 1	Level 2	Level 3
A	Cutting speed	m min^{-1}	135	210[a]	285
B	Feed rate	mm rev^{-1}	0.08	0.20[a]	0.32
C	Dept of cut	mm	0.6	1.1[a]	1.6

[a] Initial cutting parameters.

Table 3
Experimental results for tool life and S/N ratio

Experiment No.	Cutting speed (m min^{-1})	Feed rate (mm rev^{-1})	Depth of cut (mm)	Tool life (s)	S/N ratio (dB)
1	135	0.08	0.6	2645	68.45
2	135	0.20	1.1	2060	66.28
3	135	0.32	1.6	1733	64.78
4	210	0.08	1.6	1310	62.35
5	210	0.20	0.6	1198	61.57
6	210	0.32	1.1	734	57.31
7	285	0.08	1.1	854	58.63
8	285	0.20	1.6	765	57.67
9	285	0.32	0.6	216	46.69

Table 4
S/N response table for tool life

Symbol	Cutting parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max-min
A	Cutting speed	66.50	60.41	54.33	12.17
B	Feed rate	63.14	61.84	56.26	6.88
C	Depth of cut	58.90	60.74	61.60	2.70

The total mean S/N ratio = 60.41 dB.

analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

To summarize, the parameter design of the Taguchi method includes the following steps: (1) identification of the quality characteristics and selection of design parameters to be evaluated; (2) determination of the number of levels for the design parameters and possible interactions between the design parameters; (3) selection of the appropriate orthogonal array and assignment of design parameters to the orthogonal array; (4) conducting of the experiments based on the arrangement of the orthogonal array; (5) analysis of the experimental results using the S/N and ANOVA analyses; (6) selection of the optimal levels of design parameters; and (7) verification of the optimal design parameters through the confirmation experiment. Therefore, three objectives can be achieved through the parameter design of the Taguchi method, i.e: (1) determination of the optimal design parameters for a process or a product; (2) estimation of each design parameter to the contribution of the quality characteristics; and (3) prediction of the quality characteristics based on the optimal design parameters.

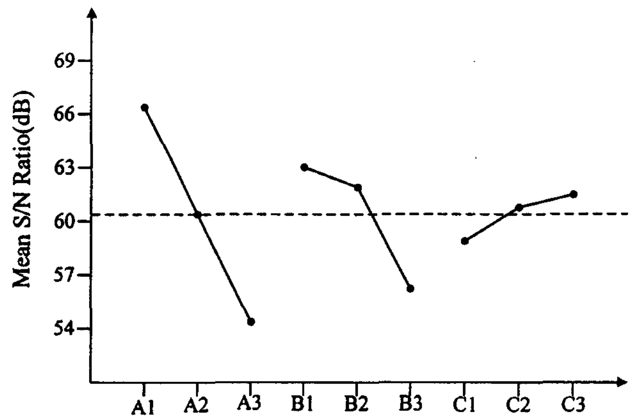

Fig. 2. S/N graph for tool life.

3. The turning process experiment

Turning is a very important machining process in which a single-point cutting tool removes material from the surface of a rotating cylindrical workpiece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried out on a lathe that provides the power to turn the workpiece at a given rotational speed and to feed the cutting tool at a specified rate and depth of cut. Therefore, three cutting parameters, i.e. cutting speed, feed rate, and depth of cut, need to be determined in a turning operation (Fig.

Table 5
Experimental results for surface roughness and S/N ratio

Experiment No.	Cutting speed (m min^{-1})	Feed rate mm rev^{-1})	Depth of cut (mm)	Surface roughness (μm)	S/N ratio (dB)
1	135	0.08	0.6	1.24	−1.86
2	135	0.20	1.1	1.92	−5.67
3	135	0.32	1.6	9.44	−19.50
4	210	0.08	1.6	2.64	−8.44
5	210	0.20	0.6	4.51	−13.09
6	210	0.32	1.1	7.49	−17.49
7	285	0.08	1.1	0.91	0.84
8	285	0.20	1.6	4.18	−12.43
9	285	0.32	0.6	9.70	−19.73

Table 6
S/N response table for surface roughness

Symbol	Cutting parameter	Mean S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max-min
A	Cutting speed	−9.01	−13.00	−10.44	3.99
B	Feed rate	−3.15	−10.40	−18.91	15.75
C	Depth of cut	−11.56	−7.44	−13.46	6.02

1). Since turning operations are accomplished using a cutting tool, the high forces and temperature during machining create a very harsh environment for the cutting tool. Therefore, tool life is an important index to evaluate cutting performance in a turning operation. In addition, the purpose of turning operations is to produce a low surface roughness of the machined workpiece. Therefore, surface roughness is another important index to evaluate cutting performance. Basically, tool life and surface roughness correlated strongly with cutting parameters such as cutting speed, feed rate, and depth of cut [13,14]. Proper selection of the cutting parameters can secure longer tool life and better surface roughness. Hence, design optimization of the cutting parameters based on the Taguchi method is adopted to improve the tool life and the surface roughness in a turning operation.

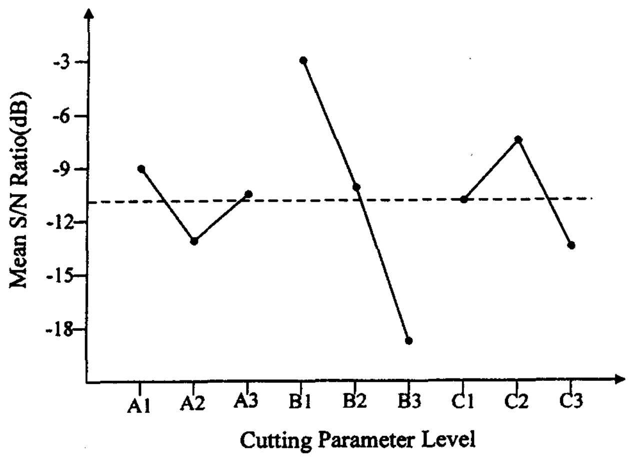

Fig. 3. S/N graph for surface roughness.

3.1. Selection of the cutting parameters and their levels

The cutting experiments were carried out on an engine lathe using tungsten carbide with the grade of P-10 for the machining of S45C steel bars. The initial cutting parameters were as follows: cutting speed 210 m min^{-1}; feed rate 0.20 mm rev^{-1}; and depth of cut 1.1 mm. The feasible space for the cutting parameters was defined by varying the cutting speed in the range 135–285 m min^{-1}, the feed rate in the range 0.08–0.32 mm rev^{-1}, and the depth of cut in the range 0.6–1.6 mm. In the cutting parameter design, three levels of the cutting parameters were selected, shown in Table 1.

3.2. Cutting performance measure

The tool life is defined as the elapsed period of cutting time when the average flank wear land V_B of the tool is equal to 0.3 mm or the maximum flank wear land V_{Bmax} is equal to 0.6 mm. This tool life criterion is recommended by the International Standard Organization (ISO). In the experiments, the flank wear land was measured using a tool microscope (Isoma). The machined surface roughness was measured by a 3D-Hommelewerk profile meter. The average surface roughness R_a, which is the most widely used surface finish parameter in industry, was selected for this study, being the arithmetic average of the absolute value of the

Table 7
Results of the analysis of variance for tool life

Symbol	Cutting parameter	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)
A	Cutting speed	2	222.17	111.08	12.36	66.98
B	Feed rate	2	80.19	40.09	4.46	24.17
C	Depth of cut	2	11.38	5.69	0.63	3.43
Error		2	17.97	8.98		5.72
Total		8	331.71			100

Table 8
Results of the ANOVA for surface roughness

Symbol	Cutting parameter	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)
A	Cutting speed	2	24.56	12.28	25.82	5.39
B	Feed rate	2	373.12	186.56	392.24	81.93
C	Depth of cut	2	56.75	28.38	59.67	12.46
Error		2	0.95	0.48		0.21
Total		8	455.39			100

heights of roughness irregularities from the mean value measured within a sampling length of 8 mm.

4. Design and analysis of cutting parameters

In this section, the use of an orthogonal array to reduce the number of cutting experiments for design optimization of the cutting parameters is reported. Results of the cutting experiments are studied using the S/N and ANOVA analyses. Based on the results of the S/N and ANOVA analyses, optimal settings of the cutting parameters for tool life and surface roughness are obtained and verified.

4.1. 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 2. 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.

4.2. Analysis of the S/N ratio

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (S.D.) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the S.D. Taguchi uses the S/N ratio to measure the quality characteristic

Table 9
Results of the confirmation experiment for tool life

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2	A1B1C3	A1B1C3
Tool life (s)	1059	2890	2604
S/N ratio (dB)	60.50	69.22	68.17

Improvement of S/N ratio = 7.68 dB.

Table 10
Results of the confirmation experiment for surface roughness

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2	A1B1C2	A1B1C2
Surface roughness (μm)	2.754	0.79	1.084
S/N ratio (dB)	−8.80	2.03	−0.70

Improvement of S/N ratio = 8.10 dB.

deviating from the desired value. The S/N ratio η is defined as

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

where M.S.D. is the mean-square deviation for the output characteristic.

As mentioned earlier, there are three categories of quality characteristics, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the-better. To obtain optimal cutting performance, the-higher-the-better quality characteristic for tool life must be taken. The mean-square deviation (M.S.D.) for the-higher-the-better quality characteristic can be expressed as:

$$\text{M.S.D.} = \frac{1}{m} \sum_{i=1}^{m} \frac{1}{T_i^2} \quad (2)$$

where m is the number of tests and T_i is the value of tool life and the i th test.

Table 3 shows the experimental results for tool life and the corresponding S/N ratio using Eqs. (1) and (2). 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 cutting speed 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 tool life (Table 4). In addition, the total mean S/N ratio for the nine experiments is also calculated and listed in Table 4. Fig. 2 shows the S/N response graph for tool life. As shown in Eqs. (1) and (2), the greater is the S/N ratio, the smaller is the variance of tool life around the desired (the-higher-the-better) value. However, the relative importance amongst the cutting parameters for tool life 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.

On the other hand, the-lower-the-better quality characteristics for surface roughness should be taken for obtaining optimal cutting performance. The M.S.D. for the the-lower-the-better quality characteristic can be expressed as:

$$\text{M.S.D.} = \frac{1}{M} \sum_{i=1}^{m} S_i^2 \quad (3)$$

where S_i is the value of surface roughness for the i th test.

Table 5 shows the experimental results for surface roughness and the corresponding S/N ratio using Eqs. (1) and (3). The S/N response table and S/N response graph for surface roughness are shown in Table 6 and Fig. 3. Regardless of the-lower-the-better of the 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)).

4.3. Analysis of variance

The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the quality characteristic. This is to accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SS_T from the total mean S/N ratio η_m can be calculated as:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \quad (4)$$

where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the i th experiment.

The total sum of spared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each design parameter and the sum of squared error SS_e. The percentage contribution ρ by each of the design parameters in the total sum of squared deviations SS_T is a ratio of the sum of squared deviations SS_d due to each design parameter to the total sum of squared deviations SS_T.

Statistically, there is a tool called an F test named after Fisher [12] to see which design parameters have a significant effect on the quality characteristic. In performing the F test, the mean of squared deviations SS_m due to each design parameter needs to be calculated. The mean of squared deviations SS_m is equal to the sum of squared deviations SS_d divided by the number of degrees of freedom associated with the design parameter. Then, the F value for each design parameter is simply the ratio of the mean of squared deviations SS_m to the mean of squared error. Usually, when $F > 4$, it means that the change of the design parameter has a significant effect on the quality characteristic.

Table 7 shows the results of ANOVA for tool life. It can be found that cutting speed and feed rate are the significant cutting parameters for affecting tool life. The change of the depth of cut in the range given in Table 1 has an insignificant effect on tool life. Therefore, based on the S/N and ANOVA analyses, the optimal cutting parameters for tool life are the cutting speed at level 1, the feed rate at level 1, and the depth of cut at level 3. Table 8 shows the results of ANOVA for surface roughness. Cutting speed, feed rate, and depth of cut are the significant cutting parameters for affecting surface roughness. However, the contribution order of the cutting parameters for surface roughness is feed rate, then depth of cut, and then cutting speed. The optimal cutting parameters for surface roughness are the cutting speed at level 1, the feed rate at level 1, and the depth of cut at level 2.

4.4. Confirmation tests

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 $\hat{\eta}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o} (\bar{\eta}_i - \eta_m) \tag{5}$$

where η_m is the total mean S/N ratio, $\bar{\eta}_i$ is the mean S/N ratio at the optimal level, 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 tool life can then be obtained and the corresponding tool life can also be calculated by using Eqs. (1) and (2). Table 9 shows the comparison of the predicted tool life with the actual tool life using the optimal cutting parameters, good agreement between the predicted and actual tool life being observed. The increase of the S/N ratio from the initial cutting parameters to the optimal cutting parameters is 7.68 dB, which means also that the tool life is increased by about 2.5 times. Table 10 shows the comparison of the predicted surface roughness with the actual surface roughness using the optimal cutting parameters, where a predicted surface roughness consistent with the actual surface roughness is noted. The increase of the S/N ratio from the initial cutting parameters to the optimal cutting parameters is 8.10 dB and therefore the surface roughness value is improved by about 2.5 times. In other words, the experiment results confirm the prior design and analysis for optimizing the cutting parameters. Tool life and surface roughness in turning operations are greatly improved through the approach.

5. Concluding remarks

This paper has discussed an application of the Taguchi method for optimizing the cutting parameters in turning operations. As shown in this study, the Taguchi method provides a systematic and efficient methodology for the design optimization of the cutting parameters with far less effect than would be required for most optimization techniques. It has been shown that tool life and surface roughness can be improved significantly for turning operations. The confirmation experiments were conducted to verify the optimal cutting parameters. The improvement of tool life and surface roughness from the initial cutting parameters to the optimal cutting parameters is about 250%.

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