Optimization of cutting parameters for surface roughness in turning of studs manufactured from AISI 5140 steel using the Taguchi method

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This study focuses on optimizing cutting parameters based on the Taguchi method to minimize surface roughness in turning of studs manufactured from AISI 5140 steel. The Taguchi method, which is a powerful tool for designing optimized quality, is used to find the optimum surface roughness in turning operations. Rotational speed, feed rate and depth of cut were considered as control factors for the surface roughness, and L9 orthogonal array was determined for experiment trials. An orthogonal array, a signal-to-noise ratio, and an analysis of variance were employed to investigate the surface roughness characteristics of AISI 5140 steel. Minimum surface roughness was obtained at 2000 rpm rotational speed, 0.2 mm × rev^{-1} feed rate and 0.5 mm depth of cut. Optimal surface roughness was calculated as 1.70 µm by using optimal level of design parameters. Confirmation test showed that Taguchi method can be used precisely for optimizing the cutting parameters in turning of AISI 5140 steel. Through this study, it is possible to not only obtained the optimum surface roughness for turning operations, but also the main cutting parameters affecting the performance of turning operations. The developed model can be used in the metal machining industries in order to determine the optimum cutting parameters for minimum surface roughness.

Article Information

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Keywords
Surface roughness, turning, steel, analysis of variance, Taguchi method

The surface quality is an important parameter to evaluate the productivity of machine tools as well as machined components. Hence, achieving the desired surface quality is of great importance for the functional behavior of the mechanical parts. Surface quality is generally associated with surface roughness. The surface roughness of machined parts is known to have considerable effect on some properties such as wear resistance and fatigue strength [1]. Turning is one of the most important material removal processes that has been widely used in today's chip based manufacturing industry. Steel components used in manufacturing industries such as automotive, construction, food, textile and space craft keep improving progressively. It is for this reason that researches have been investigated machinability of steels. They have been developed mathematical models to predict the surface roughness in terms of various process parameters during turning [2-15].

In this study, effects of cutting parameters (rotational speed, feed rate and depth of cut) on the surface roughness of AISI 5140 steel were experimentally investigated by using Taguchi design method. An orthogonal array, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) were employed to analyze the effect of cutting parameters.

Experimental procedure

The materials used in the experiments were commercially available AISI 5140 steel widely used in bolt, nut and stud fabrication. Chemical composition of the workpiece material is given in Table 1. In

Table 1: Chemical composition of AISI 5140 (wt.-%)

C	Si	Mn	P	S	Cr	Ni	Cu	Fe
0.436	0.331	0.831	0.011	0.007	1.111	0.025	0.075	97.129

this study, studs were used as specimen for machining test. Schematic representation of the testing specimen is shown in Figure 1. The cutting experiments were carried out using a DOOSAN PUMA 240 industrial type of CNC lathe with cutting fluid. DNMG 150608 – SM 4225 SANDVIK carbide insert (α = 8°, γ = 14°, r = 0.4 mm) was used for the machining of AISI 5140 steel studs. The surface hardness of studs was measured as 40 ± 2 HR_C after heat treatment process (austenitized at 850 °C for one hour and quenched in oil, and then tempered at 600 °C for one hour and cooled in air) as described in Figure 2.

Input parameters of the models are rotational speed (A), feed rate (B) and depth of cut (C). Output parameter of the models is the corresponding surface roughness Ra. The range of each parameter was coded in three levels. Control factors and their levels are given in Table 2. Three replications of each cutting condition were conducted resulting in a total of 27 tests. A MITUTOYO SJ201 type surface roughness tester was used for measuring surface roughness. Each workpiece was measured three times for statistical reasons, and the arithmetic mean of the measured values was given in Table 3.

Results and data analysis

Analysis of the S/N ratio. In the Taguchi method, the term "signal (S)" represents the desirable value for the output characteristic and the term "noise (N)" represents the undesirable value for the output characteristic. There are several S/N ratios available depending on the type of characteristic: lower-is-better, nominal-is-the-best and higher-is-better [16, 17]. The smaller the S/N ratios, the better the result when we consider tool wear, surface roughness and cutting force. In the present study, the lower-the-better quality characteristic was selected for the surface roughness. The loss function of the-lower-the-better quality characteristics can be expressed as:

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

with η: S/N ratio, n: number of tests and y_i: experimental value of the ith experiment.

The average test results for the surface roughness were transformed into a signal-to-noise (S/N) ratio by using Equation (1) and is given in Table 3. The mean S/N ratio for each level of the cutting parameters is calculated and listed in Table 4. The graphic of mean of S/N ratios versus factor levels is shown in the Figures 3a to 3c. The dashed line indicated in this figure is the total mean value of S/N ratios. Based on Taguchi prediction that the larger difference between value of S/N ratios will have a more significant effect on surface roughness. Thus, it can be concluded that increasing the feed rate will increase the surface

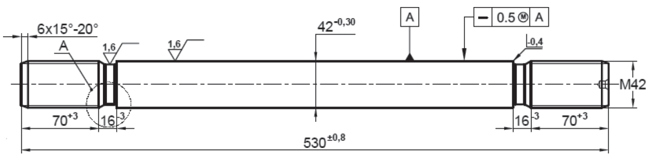


Figure 1: Schematic illustration of the testing specimen dimensions (mm)

Symbol	Factors	Level 1	Level 2	Level 3
A	Rotational speed (rpm)	1600	1800	2000
B	Feed rate (mm × rev^{-1})	0.20	0.30	0.40
C	Depth of cut (mm)	0.5	1	1.5

Table 2: Cutting parameters and their levels

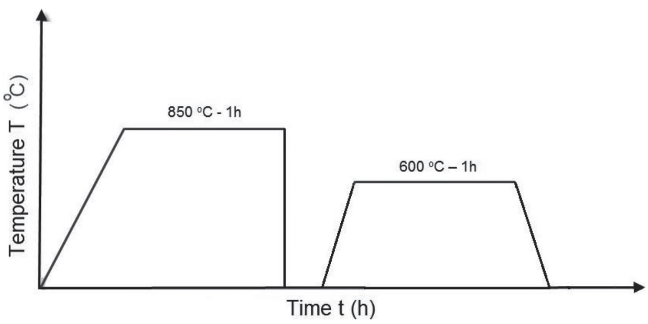
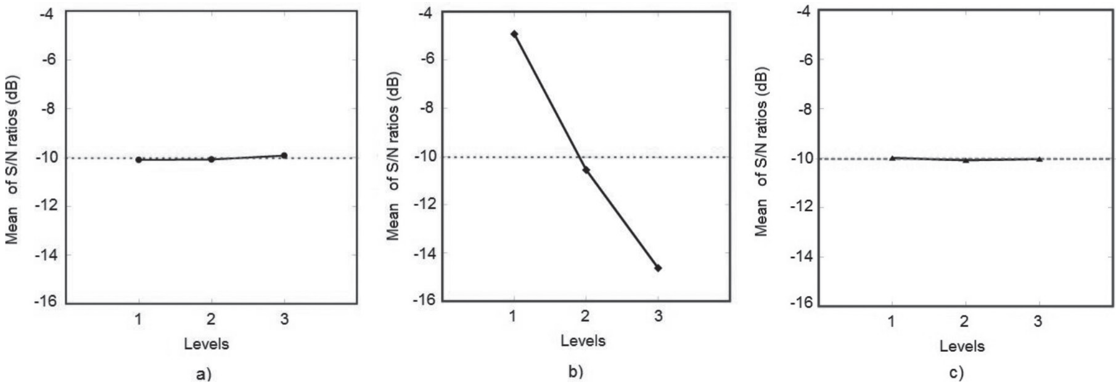


Figure 2: Thermal scheme of the heat treatment process employed in the present work

Trial No.	A (rpm)	B (mm × rev^{-1})	C (mm)	Ra (µm)	S/N (dB)
1	1600	0.2	0.5	1.78	-5.00
2	1600	0.3	1	3.42	-10.68
3	1600	0.4	1.5	5.39	-14.63
4	1800	0.2	1	1.77	-4.95
5	1800	0.3	1.5	3.41	-10.65
6	1800	0.4	0.5	5.40	-14.64
7	2000	0.2	1.5	1.74	-4.81
8	2000	0.3	0.5	3.29	-10.34
9	2000	0.4	1	5.37	-14.60

Table 3: L_9 orthogonal array, experimental results and S/N ratios for R_a

Figure 3: Graphic of mean S/N ratios versus factor levels, a) effect of rotational speed, b) effect of feed rate, c) effect of cut depth



roughness significantly. Thus, it is seen in Figure 3 and Table 4 that the third level of A factor, the first level of B factor and first level of C factor are higher and therefore, the combination of parameters is $A_3B_1C_1$. Consequently, the optimum cutting condition parameters for the turning of the AISI 5140 steel were determined as 2000 rpm for the rotational speed, 0.2 mm × rev^{-1} for the feed rate and 0.5 mm for the depth of cut.

Analysis of variance (ANOVA). The purpose of the analysis of variance (ANOVA) is to investigate which control parameters significantly affect the quality characteristic [16, 17]. ANOVA was used to analyze the effects of rotational speed, feed rate and depth of cut on surface roughness. ANOVA results are illustrated in Table 5.

Statistically, there is a tool called F test to see which control factors have significant effect on the quality characteristic. In the analysis, F ratio is a ratio of mean square error (MS) to residual, and is traditionally used to determine the significance of a factor. The significance of control factors is determined by comparing F value of each control factor and $F_{0.05}$ value from table. The F ratio corresponding to 95 % confidence level in calculation of process parameters is $F_{0.05,2,8} = 4.46$. The P value reports the significance level (suitable and unsuitable) which is listed in Table 5. Significance level (α) was selected as 0.05. The value of p is less than 0.05 which indicates that control factor is considered to be statistically significant. The percentage contributions of each control factor were used to measure corresponding effects on the quality characteristic. It was calculated by using the total sum of squared deviations (SS_T) from the total mean S/N ratio and the sum of squared deviations (SS_d) for each control factor and error. Contribution percent (%) is also defined as the significance rate of process parameters on the surface roughness. It can be observed from Table 5 that feed rate affects the surface roughness by 99.90 % for AISI 5140 steel. The rotational speed and the depth of cut do not have statistical and physical significance regarding surface roughness, because test $F < F_{0.05,\ 2.8} = 4.46$ as shown in Table 5. From Table 5, it can be realized that the feed rate factor (99.90 %) has statistical and physical significance on the surface roughness for AISI 5140 steel. The factor rotational speed (0.0385 %) does not have statistical and physical significance on the surface roughness, because test F is smaller than $F_{0.05}$. The factor depth of cut (0.0075 %) does not have statistical and physical significance on the surface roughness, because test F is smaller than $F_{0.05}$. Statistical results indicate that the surface is significantly influenced (at 95 % confidence level) by the feed rate. An increase in the feed rate increases surface roughness value.

Confirmation test. The confirmation test was performed to verify experimental conclusions using optimal level of design parameters. The estimated value of S/N ratio can be calculated by Equation (2). Table 6 shows the comparison of the initial, actual and predicted surface roughness values. As shown in Table 6, there is a good agreement between predicted and actual surface roughness values.

$$\hat{\eta} = \eta_m + \sum_{i=1}^{j} (\eta_i - \eta_m) \tag{2}$$

with $\hat{\eta}$: estimated value of S/N ratio, η_m: total mean of S/N ratio, η_i: mean of S/N ratio and j: number of the main design parameters that affect the quality characteristic.

The predicted optimal surface roughness Rap was calculated by Equation (3) by considering individual effects of the factors ($A_3B_1C_1$) and their levels. According to Equation (3), optimal surface roughness was computed as 1.70 µm. Percentage error (%) was determined as 5.02 for the actual surface roughness and as 5.54 for the S/N ratio.

$$Ra_p = T_{Ra} + (A_3 - T_{Ra}) + (B_1 - T_{Ra}) + (C_1 - T_{Ra}) \tag{3}$$

with T_{Ra}: surface roughness total mean value.

In practice, the quality losses between initial and optimal combination for surface roughness are calculated by Equation (4). The quality loss of surface roughness was calculated as 27.4 %.

$$\frac{L_{opt}(y)}{L_{ini}(y)} = \left[\frac{1}{2}\right]^{\Delta_\eta/3} \tag{4}$$

with $L_{opt}(y)$and $L_{ini}(y)$: optimal and initial combinations, respectively, and Δ_η: difference between S/N ratios of optimal and initial combinations.

Conclusions

This paper discusses an application of the Taguchi method for investigating the effects of cutting parameters on the surface roughness in the turning of AISI 5140 steel. As shown in this study, the Taguchi method provides a systematic and efficient methodology for the design optimization of the cutting parameters with a minimum number of trials. In the turning processes, cutting conditions have different values of rotational speed, feed rate and depth of cut. The level of importance of the cutting parameters on the surface roughness is determined by using ANOVA. The optimal combination of experimental parameters for each factor was found as $A_3B_1C_1$. The best combination of cutting parameters to optimize the problem in order to achieve minimum roughness was obtained by using 2000 rpm rotational speed, 0.2 mm × rev^{-1}

	SS	Df	MS	F ratio	p value	Contribution (%)
A	7.622E-003	2	3.811E-003	2.83	0.2608	0.0385
B	19.77	2	9.89	7354.02	0.0001	99.90
C	1.489E-003	2	7.444E-003	0.55	0.6436	0.0075
Error	0.011	2	1.344E-003			0.055
Total	19.79	8	0.013			100

Table 5: ANOVA results for R_a

Level	A	B	C
1	-10.10	-4.92	-9.99
2	-10.08	-10.56	-10.08
3	-9.92	-14.62	-10.03
Δ	0.18	9.7	0.09

Table 4: Mean S/N ratios of control factors

	Initial combination	Optimal combination		Error (%)
		Experiment	prediction	
Level	$A_2B_2C_3$	$A_3B_1C_1$	$A_3B_1C_1$	
R_a (µm)	3.41	1.79	1.70	5.02
S/N (dB)	-10.65	-5.05	-4.77	5.54

Table 6: Comparison of the initial and optimal combination results

feed rate and 0.5 mm depth of cut. It was found that the feed rate (99.90 %) has a significant effect on the surface roughness. The rotational speed and the depth of cut have no significant effect on the surface roughness. The quality loss was calculated at the optimal conditions as 27.4 %. Thereby, the quality losses for the surface roughness were reduced to 72.6 % by using the Taguchi method. Surface roughness for the optimal combination was calculated as 1.70 µm. Based on the confirmation experiment results, the surface roughness decreased by 1.91 times.

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Abstract

Optimierung der Schneidparameter bezüglich der Oberflächenrauheit beim Drehen von Bolzen aus dem Stahl 5140 mittels des Taguchi-Verfahrens. Die diesem Beitrag zugrunde liegenden Studie fokussiert sich auf die Optimierung der Schneidparameter beim Drehen von Bolzen aus einem Stahl des Typs AISI 5140. Hierzu wurde das Taguchi-Verfahren, das ein leistungsfähiges Werkzeug zur Designoptimierung darstellt, angewandt. Hierbei wurden die Rotationsgeschwindigkeit, die Vorschubrate und die Schnitttiefe als Kontrollfaktoren für die Oberflächenrauheit berücksichtigt und das orthogonale L9-Array für die Experimente bestimmt. Es wurden der Signal-Rausch-Abstand und die Varianzanalyse angewandt, um die Oberflächencharakteristika des Stahls AISI 5140 zu untersuchen. Die minimale Oberflächenrauheit ergab sich für eine Rotationsgeschwindigkeit von 2000 U × min^{-1}, eine Vorschubrate von 0,2 mm × U^{-1} und eine Schnitttiefe von 0,5 mm. Die optimale Oberflächenrauheit wurde mit 1,70 µm berechnet, indem die optimalen Niveaus der Designparameter ausgewählt wurden. Die Validierungstests zeigten, dass das Taguchi-Verfahren für die präzise Optimierung der Schneidparameter beim Drehen des Stahls AISI 5140 verwendet werden kann. Durch eine solche Studie lässt sich nicht nur die optimale Oberflächenrauheit für die Drehvorgänge ermitteln, sondern es lassen sich auch die Hauptparameter, die die Performance der Drehvorgänge beeinflussen, bestimmen. Das hier entwickelte Modell kann in der metallverarbeitenden Industrie eingesetzt werden, um die optimalen Schneidparameter für eine minimale Oberflächenrauheit zu ermitteln.

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DOI 10.3139/120.110968
Materials Testing
59 (2017) 1, pages 77-80

ISSN 0025-5300

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