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Investigating effects of cutting parameters on surface roughness machined by turning of C45 steel based on Taguchi methodology and ANOVA

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ABSTRACT

The present study investigates the effects of cutting parameters (cutting speed, feed rate, and depth of cut) on the roughness of the finished surface during turning C45 steel using CNC QUICK TURN 150 SG (Mazak, Japan) with carbide inserts WNMG431PP CA525 (Kyocera Precision Tools TAC08616). The experiment design was based on the Taguchi method. The results show that the feed rate significantly influences surface roughness; the cutting velocity is second in order, and the depth of cut is the weakest influence parameter on the surface roughness. The regression equation was proposed to predict the roughness of turned surfaces and its determination coefficient (R^2) of 0.9985. The prediction predicted by the regression models is compared to the experiment. The mean absolute and square error values are 6.73% and 0.85%. Hence, the model is reliable in estimating surface roughness.

1. INTRODUCTION

Engineers face practical problems in manufacturing, such as maximising manufacturing system performance using the available resources. The decisions made by manufacturing engineers are typically based not only on their experience during processing. Many of these phenomena are highly complex in machining and interact with many factors. Prior researchers have proposed conditions during machining and established cause-and-effect relationships between various factors and desired product characteristics.

Surface roughness is a widely used product quality index in most technical requirements for mechanical products. Achieving the desired surface quality is essential for the functional behaviour of parts. On the other hand, the surface roughness formation mechanism is process-dependent. The numerous uncontrollable factors influencing pertinent phenomena make a straightforward solution almost impossible. The most common strategy involves the selection of conservative process parameters, which neither guarantee the achievement of the desired surface finish nor attain high metal removal rates.

Surface roughness criteria are widely used in mechanical manufacturing engineering. Surface roughness can be represented by several parameters, including the arithmetical mean deviation of the assessed profile (R_a), the maximum height of the profile (R_z), the maximum profile valley depth (R_v), and the maximum profile peak height (R_p) (International Organization for Standardization, 2021). In most studies, R_a is most widely adopted to evaluate surface roughness quantitatively (Asiltürk and Akkuş, 2011; Hu et al., 2019; Chuangwen et al., 2018; Zhang et al., 2023).

Manufacturing parts by turning is one of the most fundamental machining operations. Numerous parameters, such as cutting speed, feed rate, depth of cut, workpiece material, etc., influence the turning process's surface finish. Several research works have been established in the field of mechanical manufacturing engineering. Asiltürk and Akkuş (2011) concluded that the feed rate and the depth of cut are two factors that significantly affect the surface roughness. Selvam and Senthil (2016) reported that nose radius has a more significant influence on surface roughness. Meanwhile, the feed rate, spindle speed, and depth of cut have been reported to affect the surface roughness insignificantly. Taha et al. (2010) investigated the effect of spindle speed, feed, and depth of cut on the surface roughness of EN24 steel during turning using TiC-coated tungsten carbide inserts. Philip Selvaraj et al. (2014) studied the effects of cutting speed and feed rate on surface roughness, cutting force, and tool wear in the dry turning of two nitrogen-alloyed duplex stainless steel grades. Manna and Salodkar (2008) reported the procedure for obtaining the optimized machining conditions for turning operations, considering the unit cost of production as an objective function. Wambua et al. (2023) studied the dry turning of mild steel of AISI 1080 in the universal lathe machine using high-speed steel with right-hand cutting tools, in which the experiments were designed using the Taguchi method with three variables (concluding cutting speed, depth of cut, and clearance angle) and each with four levels. The result showed that the clearance angle significantly affected the surface roughness; the depth of cut was recognized as the most critical factor contributing to material removal rate.

The present study investigates the effects of cutting parameters, concluding cutting speed, feed rate, and depth of cut on the roughness of the finished surface when turning C45 steel.

2. MATERIALS AND METHOD

C45 steels are widely used in mechanical machining. Hence, the specimens for testing are made of C45 steels. The chemical composition of the tested material is listed in Table 1. Before testing, specimens were machined to obtain geometry and dimensions, as shown in Figure 1.

Turning tests use CNC QUICK TURN 150 SG (Mazak, Japan, purchased in 2021, and the machine has undergone the manufacturer's periodic maintenance since 2023). The experimental work used carbide inserts WNMG431PP CA525 (Kyocera Precision Tools TAC08616) and a double clamp-type MTJNR 2525M16 (Mitsubishi Material Co.) tool holder. Surface roughness is measured using roughness tester HANDYSURF+35 (ACCRETECH).

Table 2 shows the cutting parameters values. The selected values are within the permissible range suggested by the manufacturer (Kyocera Precision Tools). The matrix of the Taguchi experiment design is shown in Table 3. Each experiment was measured three times, and the surface roughness presented was the average of the successive measurements. The cooling lubricant was used during the turning process. Table 4 shows the average surface roughness of each experiment.

To evaluate the effect of cutting parameters on the response (R_a), not only is the response for means calculated, but an Analysis of Variance (ANOVA) is also performed.

Table 1. Chemical composition of C45 steel

No.	Elements	wt%
1	C	0.45
2	Si	0.40
3	Mn	0.60
4	Cr	0.25
5	Mo	0.10
6	Ni	0.25
7	P	0.04
8	S	0.04
9	Fe	Rest

Table 2. Cutting parameters

Cutting parameters	Code value	Value at the level -1	0	1
v (m/min)	x_1	100	175	250
f (mm/r)	x_2	0.04	0.16	0.28
t (mm)	x_3	0.20	0.50	0.80

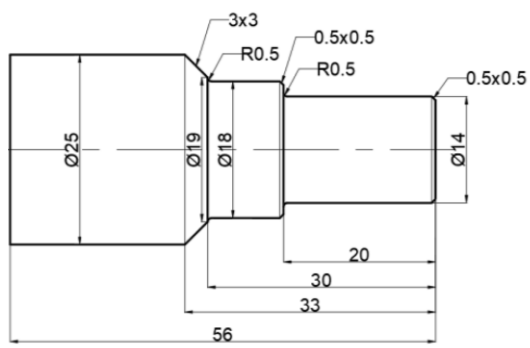

Figure 1. Specimen geometry and dimension

(Length and diameter dimensions have the same tolerance of $\pm$ 0,1*;* R_a *of machining surfaces is not larger than 2.5)*

Table 3. Experimental matrix

Trial	Cutting parameters *v* (m/min)	*f* (mm/r)	*t* (mm)
1	-1	-1	-1
2	-1	0	0
3	-1	1	1
4	0	-1	0
5	0	0	1
6	0	1	-1
7	1	-1	1
8	1	0	-1
9	1	1	0

Table 4. Experimental matrix and average-measurement values of R_a

Trial	Cutting parameters *v* (m/min)	*f* (mm/r)	*t* (mm)	R_a µm
1	-1	-1	-1	2.682
2	-1	0	0	1.639
3	-1	1	1	3.453
4	0	-1	0	0.345
5	0	0	1	1.663
6	0	1	-1	3.336
7	1	-1	1	0.913
8	1	0	-1	1.553
9	1	1	0	3.369

3. RESULTS AND DISCUSSION

3.1. Taguchi technique

Surface roughness (R_a) was considered an output response, and the category of quality characteristics was selected as "smaller the better". The Signal to Noise (S/N) Ratio for the response was calculated using Equation (1).

$$S/N\ (dB) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} R_{a_i}^2\right) \quad (1)$$

where $i = 1, 2, \dots, n$ $(n = 3)$ and R_{a_i} is the response value for each experimental condition.

The S/N ratio measures the process's performance characteristics, helps reduce its variance, and prevents deviation from the target value. Average S/N ratios were computed for one level of each cutting parameter to evaluate the effects of each cutting parameter on the surface roughness. The effects of cutting parameters on surface roughness were ranked based on the maximum and minimum average S/N ratio values. The main effects analysis is used to study the trend of the effects of each factor on the response. All details of average S/N ratios and means are shown in Table 5 and Table 6. Figures 3 and 4 show the S/N ratio and the main effects plots for surface roughness.

The results shown in Table 5 and Table 6 revealed that the feed rate significantly influences surface roughness; the cutting velocity is second in order, and the depth of cut is the weakest influence parameter on the surface roughness. Similar conclusions are also revealed in Figure 2 and Figure 3, which are consistent with those given in previous studies (Asiltürk & Akkuş, 2011; Lalwani et al., 2008). According to the S/N ratio plot shown in Figure 3 and the main effect plot shown in Figure 4, the minimum value of surface roughness is obtained with the first level of feed rate ($f = 0.04$ mm/r) and the second level of cutting velocity ($v = 175$ m/min) and depth of cut ($t = 0.5$ mm).

Table 5. Response table for signal-to-noise ratios (smaller is better)

Level	Cutting parameter *v*	*f*	*t*
-1	-7,875	0,488	-7,619
0	-1,880	-4,178	-1,866
1	-4,528	-10,593	-4,797
Delta	5,995	11,081	5,753
Rank	2	1	3

Table 6. Response table for means

Level	Cutting parameter *v*	*f*	*t*
-1	2,591	1,313	2,524
0	1,781	1,618	1,784
1	1,945	3,386	2,010
Delta	0,810	2,073	0,739
Rank	2	1	3

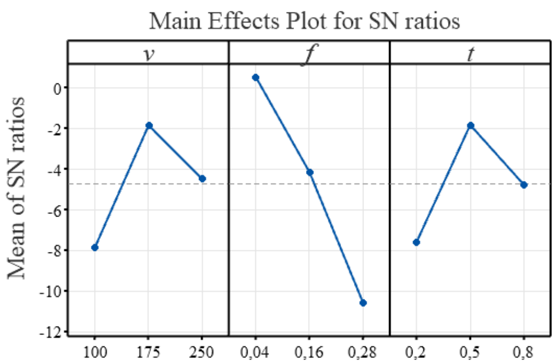

Figure 3. S/N ratio plot for surface roughness

Figure 4. Main effects plot for surface roughness

3.2. ANOVA

ANOVA is also conducted to investigate the degree of cutting parameters that influence surface roughness, R_a. The data shown in Table 4 was analyzed and graphically expressed in Figure 5 to check whether the surface roughness values follow a normal distribution. The graphical results in Figure 5 show that the experimental data are distributed along the limit line and reference lines. Note that, the P-value is more significant than 0.05, which means the data follow the normal distribution.

ANOVA is adopted based on the experimental data shown in Table 4, and the ANOVA result is shown in Table 7. According to the P-values of cutting parameters shown in Table 7, they are smaller than the critical value (0.05); it is concluded that these cutting parameters significantly affect the surface roughness. Based on the P-values of cutting parameters, the speed rate has the smallest P-value (0.007), the cutting velocity has a P-value of 0.008, and the P-value of the depth of cut has the highest value with 0.011. It is hence evaluated that the effect of cutting parameters on the surface roughness is ordered as the speed rate (Asiltürk & Akkuş, 2011), the cutting velocities, and the depth of cut. The order of influence of cutting parameters on the surface roughness based on ANOVA is consistent with the Taguchi analysis (Table 5 and Figure 3). Previous studies confirmed that this affected the order of cutting parameters on the surface roughness (Lalwani et al., 2008; Asiltürk and Akkuş, 2011). A regression model based on ANOVA results in Table 7 is proposed to predict R_a. The model is presented in (2) for the range values of cutting parameters used in the present study. The proposed model has a determination coefficient (R^2) of 0.9985, where R is the correlation coefficient. The value of R^2 expresses the closeness of the regression model, which represents the output response. Since R^2 is close to unity, this regression model can be taken as an objective function for predicting R_a.

$$R_a = 0.05811*v + 113.05*f - 26.25*t - 08183*v*f + 0.02778*v*t - 58.15*f*t + 0.9242*v*f*t \quad (2)$$

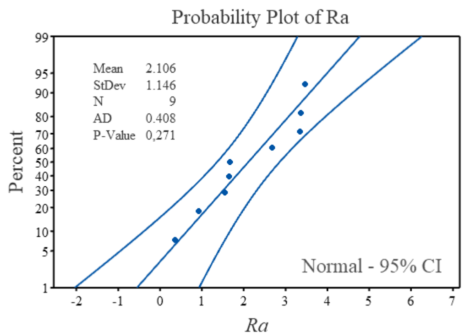

Figure 5. Probability plot of R_a

Table 7. ANOVA for R_a

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	
Regression	7	50.3346	99.85%	50.3346	7.19066	186.56	0.005	Significant
v	1	32.5090	64.49%	4.6237	4.62369	119.96	0.008	Significant
f	1	12.8127	25.42%	5.2740	5.27402	136.83	0.007	Significant
t	1	0.0136	0.03%	3.3607	3.36074	87.19	0.011	Significant
*v**f*	1	0.4313	0.86%	4.5967	4.59670	119.26	0.008	Significant
*v**t*	1	0.0277	0.05%	0.8392	0.83921	21.77	0.043	Significant
*f**t*	1	0.0681	0.14%	2.4310	2.43103	63.07	0.015	Significant
*v**f**t*	1	4.4723	8.87%	4.4723	4.47232	116.03	0.009	Significant
Error	2	0.0771	0.15%	0.0771	0.03854			
Total	9	50.4117	100.00%					
PRESS								4.78058
R^2								0.99850

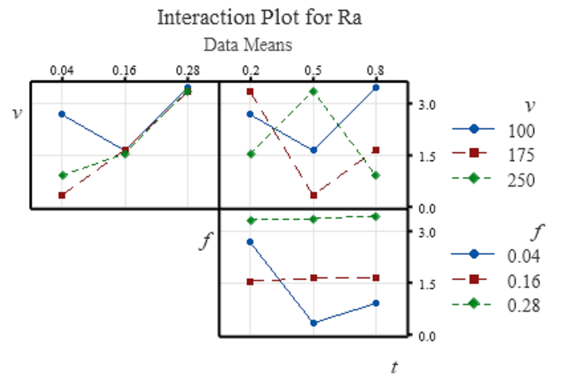

Figure 6. Interaction Plot for R_a

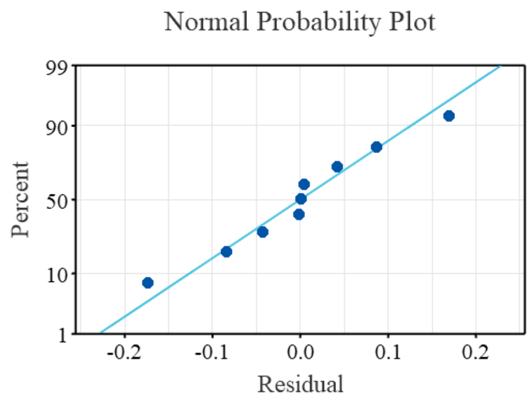

Figure 7. Residual plot for R_a

Table 8. Comparison between prediction and experiments

Trial	Cutting parameters			R_a µm	FITS µm	% Absolute error
	v	f	t			
1	-1	-1	-1	2.682	2.640	4.20
2	-1	0	0	1.639	1.812	17.30
3	-1	1	1	3.453	3.452	0.10
4	0	-1	0	0.345	0.341	0.40
5	0	0	1	1.663	1.494	16.90
6	0	1	-1	3.336	3.249	8.70
7	1	-1	1	0.913	0.956	4.30
8	1	0	-1	1.553	1.555	0.20
9	1	1	0	3.369	3.454	8.50
				% Mean absolute error		6.73
				% Mean square error		0.85

Figure 6 shows the interaction plots of surface roughness. The interaction of cutting speed and feed rate shows that the smoothest surface is obtained when $v = 175$ m/min and $f = 0.04$ mm/r. The interaction plot of the feed rate and depth of cut shows that the minimum surface roughness can be reached when the value of feed rate is 0.04 mm/r and the depth of cut is 0.5 mm. In the interaction plot of cutting speed and depth of cut, the surface roughness is minimized when the cutting speed and depth of cut are 175 m/min and 0.5 mm. This tendency is identical to the result shown in Figures 3 and 4.

The normality assumption was carried out by plotting the histogram of residuals and normal probability, as shown in Figure 7. The error falls along a straight line, which indicates a normal distribution of the residuals and is consistent with the result shown in Figure 5.

A comparison of surface roughness between the experiments and the prediction given by the proposed models (2) is performed and presented in Table 8. The mean absolute errors were calculated to investigate the proposed model's accuracy. The maximum and minimum absolute errors were 17.3% and 0.1%, respectively. Based on the absolute errors, shown in Table 8, the mean absolute and square error values are 6.73% and 0.85%. Based on the above-mentioned analysis, the proposed model (2) can significantly predict surface roughness.

Table 9. Optimal cutting parameters for commonly used surface roughness values obtained by equation (2)

R_a µm	Cutting parameters		
	v (m/min)	f (mm/r)	t (mm)
0,50	250	0,20	0,30
0,75	250	0,17	0,20
1,00	100	0,13	0,48
1,25	250	0,20	0,34
1,50	250	0,05	0,80
1,75	175	0,16	0,75
2,00	250	0,06	0,77
2,25	175	0,16	0,64
2,50	175	0,16	0,60

Table 9 shows the optimal cutting parameters for commonly used surface roughness values based on the proposed model (Eq. (2)).

4. CONCLUSION

The research conducted experiments on turning C45 steel using CNC QUICK TURN 150 SG (Mazak, Japan) with carbide inserts WNMG431PP CA525 (Kyocera Precision Tools TAC08616). The experiment design was based on the Taguchi method. The results show that:

– In three cutting parameters, the feed rate significantly influences surface roughness; the cutting velocity is second in order, and the depth of cut is the weakest influence parameter on the surface roughness.

– The model was proposed to predict the surface roughness, in which it has a determination coefficient (R^2) of 0.9985. The proposed models' predictions are compared to the experiment; the mean absolute errors are then calculated to investigate the proposed model's accuracy. The mean absolute error and the mean square error values are 6.73% and 0.85%, respectively.

CONFLICT OF INTEREST

The authors reported no potential conflict of interest.

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