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The Effect of Tool Construction and Cutting Parameters on Surface Roughness and Vibration in Turning of AISI 1045 Steel Using Taguchi Method

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ABSTRACT

This paper presents an experimental investigation focused on identifying the effects of cutting conditions and tool construction on the surface roughness and natural frequency in turning of AISI1045 steel. Machining experiments were carried out at the lathe using carbide cutting insert coated with TiC and two forms of cutting tools made of AISI 5140 steel. Three levels for spindle speed, depth of cut, feed rate and tool overhang were chosen as cutting variables. The Taguchi method L_9 orthogonal array was applied to design of experiment. By the help of signal-to-noise ratio and analysis of variance, it was concluded that spindle speed has the significant effect on the surface roughness, while tool overhang is the dominant factor affecting natural frequency for both cutting tools. In addition, the optimum cutting conditions for surface roughness and natural frequency were found at different levels. Finally, confirmation experiments were conducted to verify the effectiveness and efficiency of the Taguchi method in optimizing the cutting parameters for surface roughness and natural frequency.

KEYWORDS

Surface Roughness; Cutting Condition; Natural Frequency; Vibration; Turning; ANOVA; Taguchi Method; S/N Ratio

1. Introduction

One of the most fundamental metal removal operations used in manufacturing industry is turning, which is done with a long and slender tool so that it can fit into or through complex workpiece geometry. Machining depends on many factors such as machine rigidity, fixing rigidity, tool rigidity, good vibration damping capability and rigidity of component parts [1]. Surface roughness is one of the important aspects in mechanical design, since it dominates the requirements of many mechanical parts such as wear and corrosion resistances, fatigue strength, product life and heat generation. Chatter vibrations occurring in turning operation create large cutting forces, which can damage the machine, cutting tool and workpiece, consequently, causing tool wear, tool breakage, unacceptable surface finish and dimensional errors [2,3]. For this reason, avoidance of chatter vibrations is crucial. Besides, turning operation contains many parameters such as workpiece and cutting tool materials, feed rate, spindle speed, depth of cut, coolant, tool construction, tool overhang, tool nose radius and tool edge angles. Therefore, it is difficult to achieve the required surface quality [4-6]. However, severe chatter vibrations occur in turning operation due to a dynamic motion between the work piece and the cutting tool [7-9].

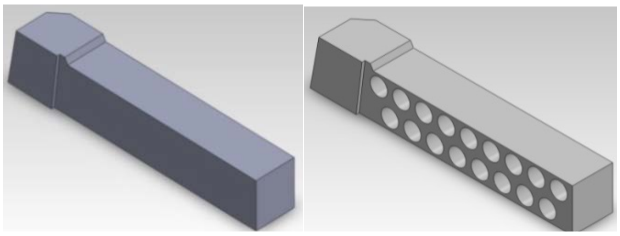
From the literature review of vibration induced by a machining process, clearly the majority of works attempt to reduce vibration during machining process. The aim of vibration reduction is to increase dynamic stiffness of machining system or change its main natural frequency or feedback-controlled actuators, which can be achieved by using a vibration damper, applying a special coating on a cutting insert or using a toolholder made of material with a high damping capability [10]. Kanase and Jadhav [11] and Abuthakeer *et al*. [12] used a passive damping pad of viscoelastic material of neoprene and a passive vibration damping in their investigations to predict and suppress the vibration level of cutting tool. They found that impact damping has improved the surface finish in machining operation. Devin and Osadchii [13] proposed a new tool design with an increased vibration-damping ability, which includes special elements made of damping materials to reduce vibration amplitude and surface roughness. Sortino *et al*. [14] studied the influence of the material and geometry of the tool and workpiece on process stability in internal finish turning. They found that the ratio of boring bar overhang to bar external diameter has a significant effect on the stability of the process. Kopač *et al*. [15] performed an investigation on identification of the dynamic instability in hard turning process based on the determination of natural frequencies of machine tool components on different positions in work area and position of resonance frequency determination. The results showed that if cutting instability and push-off effect do not have dominant influence, it is possible to achieve minimum roughness on machined surface. Mustafa and Emre [16] evaluated the effects of cutting parameters on surface roughness and found the optimal cutting parameter levels in turning of Ni-Hard (62 HRC and 50 HRC) by using statistical methods of signal to noise ration and ANOVA. The results indicate that feed rate and cutting speed are the dominant parameters in turning of Ni-Hard with 62 HRC and 50 HRC, respectively. Suresh *et al*. [17] studied the influence of cutting parameters on the surface roughness during hard turning of AISI 4340 high strength low alloy steel using coated carbide insert. It was found that better surface roughness could be achieved at higher cutting speed with lower feed rate and depth of cut. Philip and Chandramohan [18] investigated the surface roughness during dry turning of AISI 304 Austenitic Stainless Steel. They reported that feed rate has the most significant influence on surface roughness, followed by cutting speed and depth of cut. Ali Riza [19] performed an investigation on surface roughness in turning of AISI 8660 hardened alloy steels using PVD coated ceramic cutting tools under different conditions. The results indicated that the feed rate and depth of cut have the greatest effect on surface roughness. Bhattacharya *et al*. [20] conducted a study on the effect of cutting parameters on the surface roughness by high speed machining of AISI 45 steel. The result showed that the influence of cutting speed on surface roughness is significant, while the other parameters do not have substantial effect on the surface roughness. An investigation performed by Dilbag and Venkateswara [21] on finish hard turning of the bearing steel (AISI 52100) with Mixed ceramic inserts made up of aluminum oxide and titanium carbonitride (SNGA) showed that the feed rate has the greatest effect on surface roughness followed by cutting speed and tool rake.

Thus the purpose of this work is to investigate the influence of tool construction, tool overhang and cutting parameters (spindle speed, depth of cut and feed rate) on the surface roughness (R_a) and vibration in turning of AISI1045 steel. Two forms of cutting tools made of AISI 5140 steel were used: the standard cutting tool and cutting tool with a new design of toolholder, which has horizontal holes arranged in a chess-board pattern (**Figure 1**). The experiments were performed under dry conditions. Three levels for spindle speed (*n*), feed rate (*f*), depth of cut (*a*) and tool overhang (*l*) were selected. The influence of the cutting parameters on the surface roughness and natural frequency was tested by using Taguchi method. L_9 orthogonal array was used in the design of experiment. Therefore, 9 trials were planned for each cutting tool. The cutting parameters and their levels are illustrated in **Table 1**.

2. Materials and Method

2.1. Design of Experiment

In any business finding appropriate method to improve quality and increase productivity plays an important role. The conventional methods based on trial-and-error searches are complex, time-consuming and costly; hence they are changed to the powerful and cost effective statistical methods [16]. Design of experiment is one of the



(a) (b)

Figure 1. 3D-model of the cutting tools inSolidWorks: a) standard cutting tool; b) cutting tool with horizontal holes arranged in a chess-board pattern (Ø 10 mm).

Table 1. Cutting parameters and their levels.

Variables	Level 1	Level 2	Level 3
A-Spindle speed (rpm)	630	800	1000
B-Feed rate (mm/rev)	0.05	0.06	0.075
C-Depth of cut (mm)	0.05	0.1	0.15
D-Overhang (mm)	41	50	65

widely used methods, which is centered on factors, responses, and runs in the experiment process. It is used as an important tool in the engineering design activities and for improving the performance of a manufacturing process. Design of experiments is able to determine unknown factors and the influence of the factors on the response [18].

Taguchi method is one of the important tools used in the industry to shortage product design, develop time and produce lower product cost. Taguchi method also takes into consideration the effect of uncontrollable factors on the response. This method is also highly flexible and can allocate different levels of factors, even when the numbers of the levels of factors are not the same [16]. In Taguchi approach, optimization, data analysis and the prediction of the optimum results are provided by objective function, which is called signal to noise ratio (S/N). Signal factors represent system control inputs. Noise factors represent variables, which are expensive or difficult to control. The S/N ratios generally used are: the-nominal-the better, the-lower-the-better and the-larger-the-better. Different parameters affect the response to a different degree. Using analysis of variance (ANOVA) the relative effect of the different parameters is determined. S/N ratio and ANOVA provide determining of the optimum cutting parameters for the response [22]. Finally, confirmation testsare recommended in Taguchi method to verify the effectiveness and efficiency of the Taguchi method in optimizing the parameters.

In this investigation, cutting parameters are optimized for the average surface roughness (R_a) and natural frequency in turning of AISI 1045 steel. The responses variables are measured in micrometer (μm) and hertz (Hz), correspondently. Three levels of spindle speed (n), feed rate (f), depth of cut (a) and tool overhang (l) and two different cutting tools are utilized as cutting parameters. In the design of experiment the L_9 orthogonal array of Taguchi method was used.

Optimization of the cutting parameters for both cutting tools has been performed separately. For surface roughness and natural frequency analysis the-smaller-the-better performance characteristics were used. Therefore, in this case S/N ratio (η) is defined as:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (1)$$

where η is the S/N ratio, n is the number of experiment and Y_i is the observed data. Using Equation (1) the S/N ratios of the variable parameters are calculated for the average surface roughness and natural frequency.

In ANOVA, the 95% confidence level was chosen to determine the factors effect on the average surface roughness and natural frequency. The optimization processes were performed by using the powerful statistical analysis software Minitab 16, which is used to improve the quality in different fields, such as: statistics, sports, mathematics, economics and engineering.

2.2. Experimental Procedure

Machining experiments were carried out at the lathe machine model 16K20VF1 (Russia), which has a maximum spindle speed of 1600 rpm and maximum power of 5.5 kW. The standard cutting tool and a new model of cutting tool with horizontal holes in toolholder arranged in a chess-board pattern, with general specification of PCLNR 2525M12 made of AISI 5140, were used (**Figure 1**). Carbide rhombic cutting insert with a general specification of CT35M coated with TiC, manufactured by Sandvik Coromant, was used as a cutting tool insert. In this study AISI1045 steel was used as workpiece with 65 mm diameter and 200 mm length. The chemical compositions of the selected material by weight percentage are shown in **Table 2**. During turning the homogeneity of the workpiece material affects the experimental result, so to reduce its effect on the results, in each trial the rust layers were removed by using a new cutting insert. Also, in each trial a new cutting insert CT35M coated with TiC was used in order to minimize the effect of tool wear on the experimental results.

In this study, the average surface roughness (R_a), which is one of the most important criteria in machining process, is selected. Measurement of the average surface roughness (R_a) was performed using a profile meter model 130 (Russia) with a sampling length of 12.50 mm and measurement speed of 0.5 mm/s. The values of the average surface roughness (R_a) were calculated by averaging four roughness values obtained from four different points of machined surface in 90˚ increments around the circumference. Frequencies occurred during machining was measured using piezoelectric accelerometer KD-35 and ZETLAB software (Russia). For this purpose on the lower side of the cutting edge of the tools the piezoelectric accelerometerKD-35 was attached. Vibrations occurred during machining were recorded by KD-35 and passed through the multifunctional spectrum analyzer A17-U8 to a personal computer to visualize the results.

3. Experimental Results and Discussion

3.1. Evaluation of Surface Roughness for AISI 1045 Steel

The experiments were performed according to the L_9

Table 2. Chemical compositions of AISI 1045 steel.

Element	Fe	Mn	C	S	P
Weight (%)	98.51	0.9	0.5	0.05	0.04

orthogonal array. The average surface roughness (R_a) during machining of AISI 1045 steel was measured and then according to the Taguchi's "the-smaller-the-better" quality characteristics the S/N ratios were calculated. The experimental results of R_a and S/N ratios are given in **Table 3**.

Figures 2-4 illustrate the relationships between R_a and cutting parameters in turning of AISI 1045 steel for both cutting tools. As it can be seen from graphs 2 to 4, however the R_a values show irregular tendencies, they show similar trends for both cutting tools. The irregular tendency of surface roughness values can be explained by randomized distribution of cutting parameters due to design of experiment. In **Figures 2(a)** and **2(b)** it can be clearly seen, that surface roughness decreased with increasing spindle speed for both cutting tools at 0.05 mm/rev feed rate. At 0.06 mm/rev feed rate for cutting tool with holes in toolholder, the smallest value of R_a was observed due to 1000 rpm spindle speed. The highest value of the R_a has been obtained as 2.673 µm in turning of AISI 1045 steel with cutting tool with holes in toolholder at 0.075 mm/rev feed rate and 630 rpm spindle speed (**Table 3**).

Figure 3 indicates that R_a value decreases as spindle speed and depth of cut increase from 630 rpm to 1000 rpm and 0.05 mm to 0.15 mm, respectively, except increase in depth of cut at 630 rpm and 1000 rpm spindle speed for cutting tool with holes in toolholder. Besides, it was determined that the R_a values obtained by standard cutting tool at all cutting conditions, except 630 rpm spindle speed are higher. At 0.15 mm depth of cut and 630 rpm spindle speed the highest R_a value was obtained for cutting tool with holes in toolholder (**Table 3**).

As seen from **Figure 4**, when the R_a values for 50 mm tool overhang were evaluated, the R_a values obtained by

Table 3. Experimental results and S/N ratios for R_a.

Exp. No.	A	B	C	D	R_{a1}, (µm)	S/N ratio (dB)	R_{a2}, (µm)	S/N ratio (dB)
1	1	1	1	1	2.0720	−6.32780	2.390	−7.56796
2	1	2	2	2	2.4900	−7.92399	1.920	−5.66602
3	1	3	3	3	1.8310	−5.25377	2.673	−8.53998
4	2	1	2	3	1.3840	−2.82272	0.974	0.22882
5	2	2	3	1	1.0810	−0.67651	0.859	1.32014
6	2	3	1	2	1.2190	−1.72007	1.200	−1.58362
7	3	1	3	2	1.0330	−0.28201	0.588	4.61245
8	3	2	1	3	1.3200	−2.41148	0.569	4.89775
9	3	3	2	1	1.3971	−2.90455	1.640	−4.29668

R_{a1}—surface roughness value for standard cutting tool and R_{a2}—surface roughness value for cutting tool with holes.

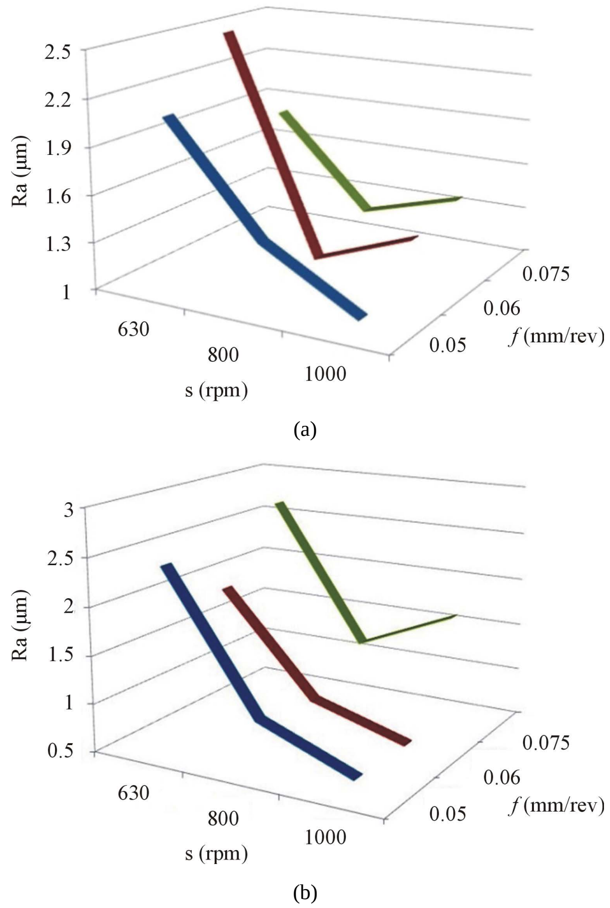


Figure 2. Relationship between R_a, spindle speed (s) and feed rate (f) in turning of AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.

cutting tool with holes in toolholder decreased parallel to increase in the spindle speed while the R_a values obtained by standard cutting tool showed an irregular tendency. On the other hand, the R_a values for both cutting tools showed similar trends at 41 mm and 65 mm tool overhangs. The R_a value decreases as tool overhang increases, except 800 rpm spindle speed for standard cutting tool. While, increase in tool overhang, except 1000 rpm spindle speed, increases the R_a value for cutting tool with holes in toolholder. The highest and smallest R_a values were obtained at 630 rpm and 1000 rpm spindle speed, correspondently, at 65 mm tool overhang with cutting tool with holes in toolholder (**Table 3**). The results show that the need to choose higher spindle speed is revealed to achieve the small R_a value during machining of AISI 1045 steel with both cutting tools.

According to the Equation (1) the S/N ratios of average surface roughness obtained from experimental results were calculated, which are used to identify the optimal levels of each factor (**Table 3**).

The graphs of S/N ratios of R_a for both cutting tools are illustrated in **Figure 5**. The power of the factor effect

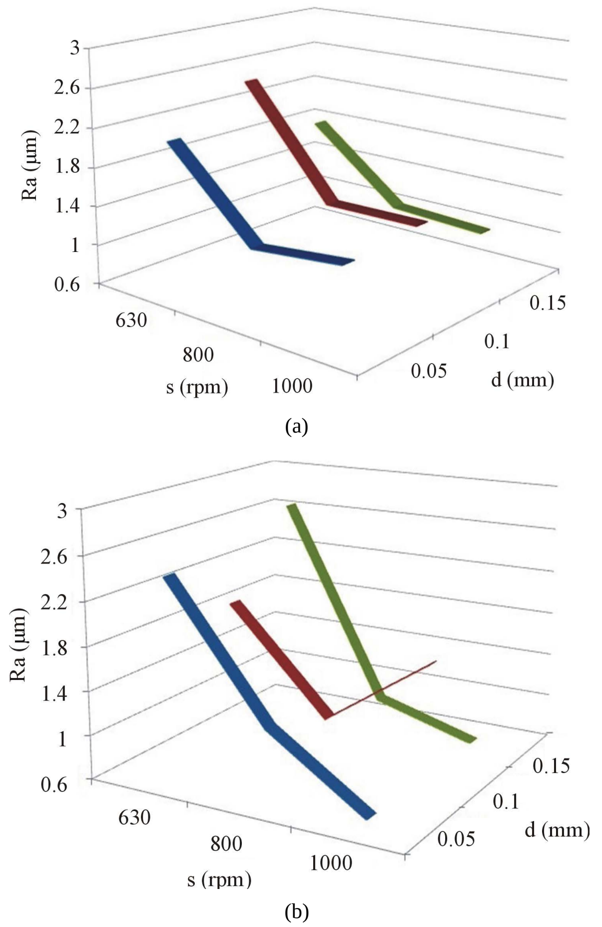


Figure 3. Relationship between R_a, spindle speed (*s*) and depth of cut (*d*) in turning of AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.

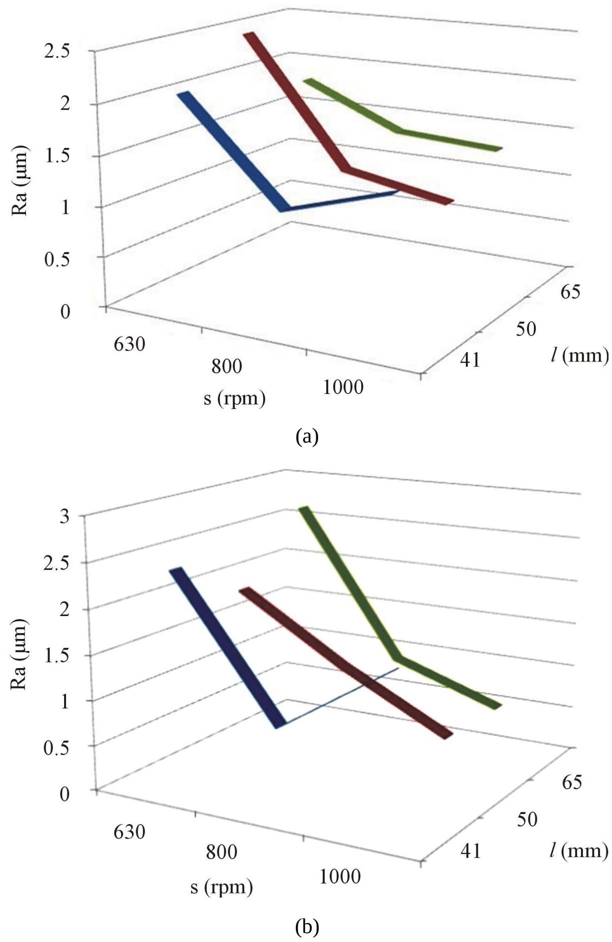


Figure 4. Relationship between R_a, spindle speed (*s*) and tool overhang (*l*) in turning of AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.

on the R_a is determined by the slope of the line. The graphs reveal a dominant effect of spindle speed on the surface roughness. The significant influence of spindle speed can be explained by the fact that as spindle speed increases, the interaction between cutting tool and workpiece decreases, which leads to less vibration and consequently to better surface roughness. From the Figure 5 and Table 3, one can observe that the optimal combination of cutting parameter levels in turning of AISI 1045 steel is $A_2B_1C_3D_1$ for standard cutting tool and $A_3B_2C_3D_2$ for cutting tool with holes in toolholder. The smallest values of S/N ratio and surface roughness under optimum conditions are predicted using Equations (2) and (3) [23].

$$\eta_{opt} = m + \sum (m_i - m) \quad (2)$$

$$Ra_{opt} = 10^{-\frac{\eta_{opt}}{20}} \quad (3)$$

where: η_{opt} is the S/N ratio under optimum conditions (dB), m is the overall mean value of S/N ratio for the experimental region (dB), m_i is the S/N ratio when the variable parameter is at optimum level (dB) and Ra_{opt} is the surface roughness under optimum condition.

Predicted S/N ratios and surface roughness values were determined as −0.150028 dB and 1.017 μm, respectively, for standard cutting tool and 5.7053 dB and 0.518 μm, correspondently, for cutting tool with holes in toolholder.

However, the statistical analysis ANOVA was conducted to find the relative contribution of each cutting parameter on the R_a and confirm initial assumption of the optimal conditions. The ANOVA results for S/N ratio are illustrated in Tables 4 and 5. Here, P value indicates the influence of the factor on the R_a as: significant if $P < 0.05$; mildly significant if $0.05 < P < 0.1$ and insignificant if $P > 0.1$. Taking into consideration the *F*-ratio, the significance of the factor effect is determined. The ratio of factor mean square to the error mean square is called Fisher's ratio (*F*). It is used to determine whether the parameter has a significant effect on the quality characteristic by comparing the *F* test value of the parameter with the standard *F* table value (F_α) at the α significance level.

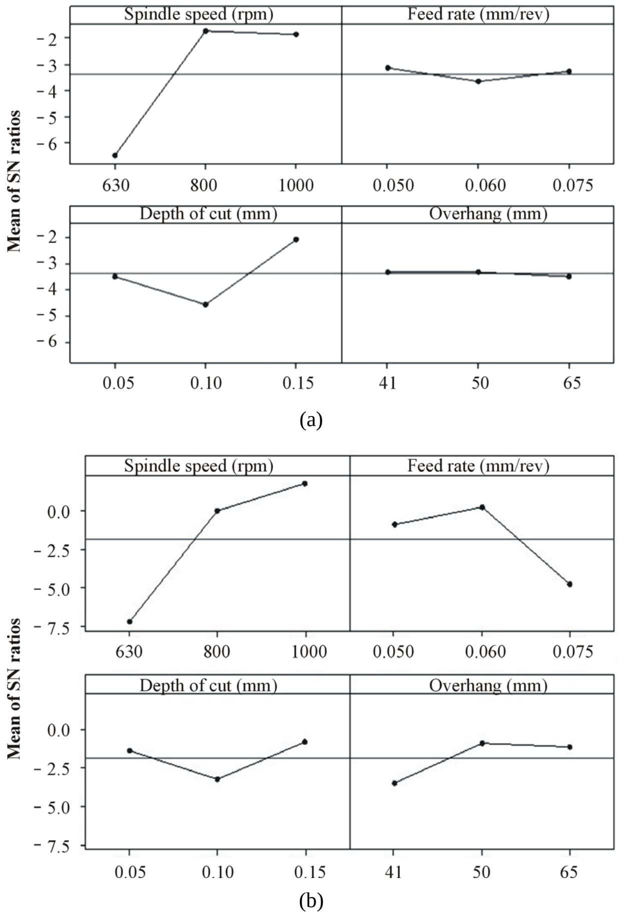


Figure 5. Maine effect plots for S/N ratios of R_a for: (a) standard cutting tool and (b) cutting tool with holes in toolholder.

Table 4. ANOVA for R_a of AISI 1045 with standard cutting tool.

Source	DF	SS	MS	*F* ratio	P value	% of Total
A	2	1.59200	0.796000	64.58410	0.025	82.31
B	2	0.04005*	0.007950	0.64503	0.780	2.07
C	2	0.29309	0.036965	2.99918	0.719	15.15
D	2	0.00888*	0.000190	0.16227	0.989	0.46
Error	0	0	0			
Total (error)	8 (4)	1.93402 0.04893	0.012325			100

The analysis was performed for a confidence level of 95%. $F_{0.05}$ for parameters degree of freedom ($df_1 = 2$) and error degree of freedom ($df_2 = 4$) is 6.9443. To be significant the calculated *F*-ratio for each design parameter must be greater than $F_{0.05}$ as shown in the ANOVA table. The ANOVA results indicate that the R_a of AISI 1045 is significantly influenced by spindle speed with 82.31% and 77% for standard cutting tool and cutting tool with holes, respectively. Other factors that influence the R_a are depth of cut with 15.15% for standard cutting tool, and feed rate with 17.38% for cutting tool with holes.

Table 5. ANOVA for R_a of AISI 1045 with cutting tool with holes in toolholder.

Source	DF	SS	MS	*F* ratio	P value	% of Total
A	2	3.68675	1.8433	24.4302	0.025	77.00
B	2	0.83208	0.4160	6.19084	0.780	17.38
C	2	0.03484*	0.0174	0.25921	0.719	0.73
D	2	0.23397*	0.1169	1.74857	0.989	4.88
Error	0	0	0			
Total (error)	8 (4)	4.78765 0.26881	0.0672			100

*Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis; DF—Degree of Freedom; SS—Sum of Squares; MS—Mean of Squares; A—Spindle speed; B—Feed rate; C—Depth of Cut and D—Tool Overhang.

3.2. Evaluation of Natural Frequency Occurred during Machining of AISI 1045 Steel

In order to improve the design and implementation of new cutting tool, the effect of cutting conditions on vibration have to be established. In each trial, the natural frequency (*f*) was recorded with the help of ZETLAB software and piezoelectric accelerometer KD-35. Cutting parameters and their level are illustrated in Table 1. According to the Taguchi's "the-smaller-the-better" quality characteristics the S/N ratios were calculated. The experimental results for natural frequency and S/N ratios are given in Table 6. Figures 6-8 have been constructed to illustrate the variation of natural frequency depending on spindle speed (*s*)-feed rate (*f*), spindle speed (*s*)-depth of cut (*d*) and spindle speed (*s*)-tool overhang (*l*). These graphs indicate that natural frequency values for both cutting tools show similar trend, although they show irregular tendencies, which is probably caused by randomized distribution of cutting parameters due to design of experiment.

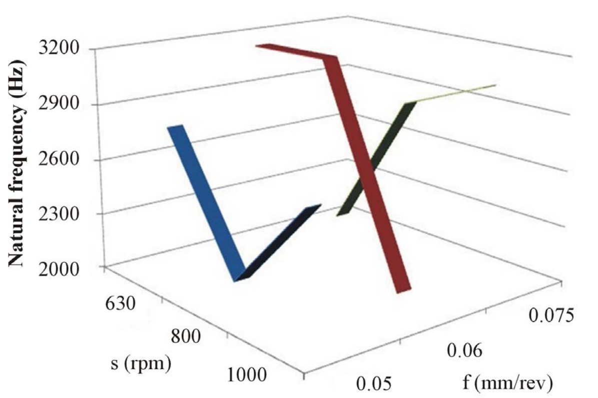
Figure 6 illustrates that at 0.05 mm/rev and 0.06 mm/rev feed rate, increase in spindle speed decreases natural frequency value. On the other hand, increase in spindle speed at 0.075 mm/rev increases natural frequency value. The highest natural frequency value has been observed as 3527.8 Hz in turning of AISI 1045 steel at 800 rpm spindle speed and 0.06 mm/rev feed rate performed by cutting tool with holes in toolholder (Table 6).

It can be noticed from Figure 7 that natural frequency decreased with increasing spindle speed at 0.05 mm depth of cut for both cutting tool. The natural frequency values of neither cutting tool showed a regular tendency

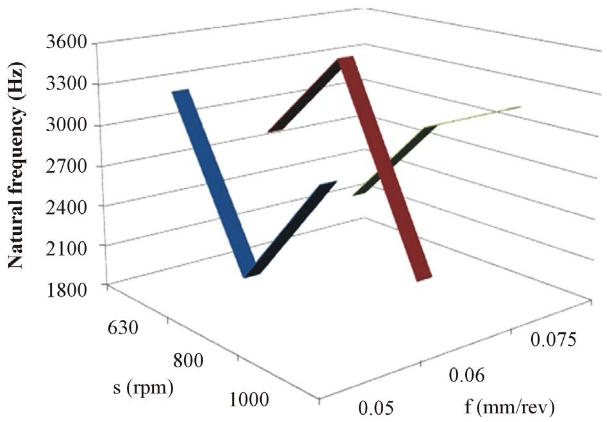
Table 6. **Experimental results and S/N ratios for natural frequency.**

Exp. No.	A	B	C	D	f_1 (Hz)	S/N ratio (dB)	f_2 (Hz)	S/N ratio (dB)
1	1	1	1	1	2795.4	−68.9289	3271.5	−70.2949
2	1	2	2	2	3161.6	−69.9981	2844.2	−69.0792
3	1	3	3	3	2069.1	−66.3156	2185.1	−66.7894
4	2	1	2	3	2111.8	−66.4931	2124.0	−66.5431
5	2	2	3	1	3173.8	−70.0316	3527.8	−71.4291
6	2	3	1	2	2856.4	−69.1164	2905.3	−69.2638
7	3	1	3	2	2636.7	−68.4212	2966.3	−69.4443
8	3	2	1	3	2075.2	−66.3412	2136.2	−66.5928
9	3	3	2	1	3039.6	−69.6563	3192.1	−70.0815

f_1—Natural frequency value for standard cutting tool and f_2—Natural frequency value for cutting tool with holes.



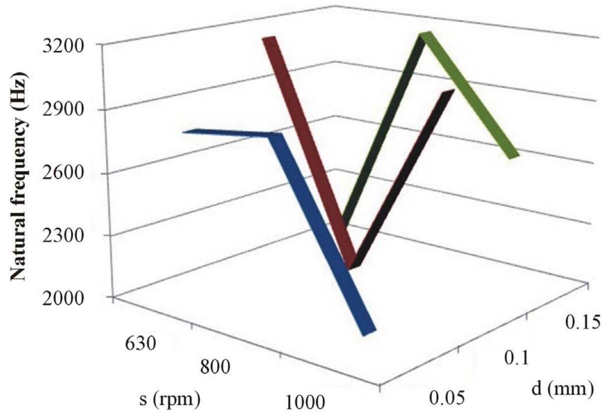
(a)



(b)

Figure 6. **Relationship between natural frequency, spindle speed (*s*) and feed rate (f) AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.**

at 0.1 mm and 0.15 mm depth of cut. However, at 0.15 mm depth of cut the smallest and highest values of natural frequency were obtained due to 630 rpm and 800 rpm for standard cutting tool and cutting tool with holes in toolholder, respectively (**Table 6**).



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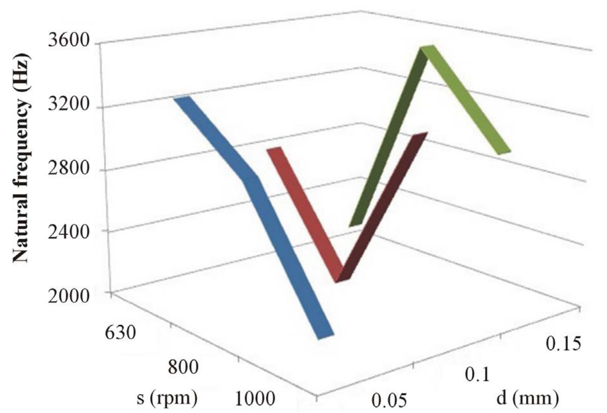

(b)

Figure 7. **Relationship between natural frequency, spindle speed (*s*) and depth of cut (*d*) AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.**

Figure 8 indicates that at 41 mm tool overhang the highest natural frequency value was obtained at 800 rpm spindle speed, although the variation of natural frequency for both cutting tool was not regular. At 50 mm tool overhang the variation of spindle speed from 630 rpm to 1000 rpm has decreased and increased linearly the natural frequency for standard cutting tool and cutting tool with holes in toolholder, correspondently. During the experiment at which tool overhang is 65 mm, natural frequency values increased parallel to spindle speed for standard cutting tool, while they have decreased for cutting tool with holes in toolholder, however, their values are close to each other. Additionally, for the same tool overhang the smallest value of natural frequency was determined as 2069.1 Hz due to 630 rpm spindle speed (**Table 6**).

According to the Equation (1) the S/N ratios of natural frequency obtained from experimental results were calculated, which are used to identify the optimal levels of

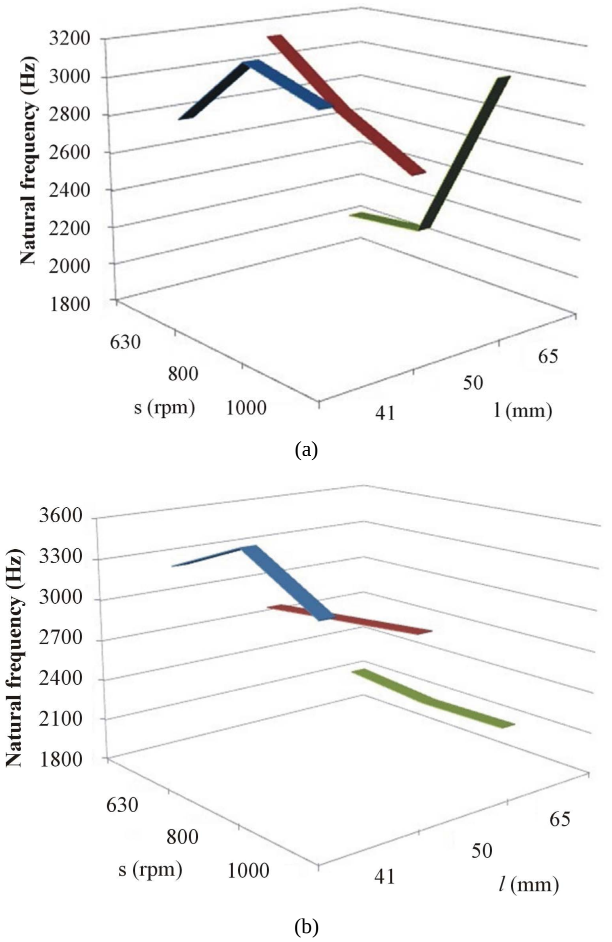

Figure 8. Relationship between natural frequency, spindle speed (*s*) and tool overhang (*l*) AISI 1045 steel: (a) with standard cutting tool and (b) with cutting tool with holes in toolholder.

each factor (Table 6). Figure 9 shows the graphs of S/N ratios that were calculated for natural frequency of standard cutting tool and cutting tool with holes in toolholder in turning of AISI 1045 steel. The graphs reveal a significant effect of tool overhang on natural frequency. The influence of tool overhang can be explained by the fact that as tool overhang increases, stability of the tool decreases, which leads to more vibration of the tool and consequently to poor surface roughness. From the Figure 9 and Table 6, it can be revealed that the optimal combination of cutting parameter levels in turning of AISI 1045 steel is $A_3B_1C_1D_3$ for standard cutting tool and $A_3B_3C_2D_3$ for cutting tool with holes in toolholder. The smallest values of S/N ratio and natural frequency under optimum conditions are predicted using Equations (2) and (3).

Predicted S/N ratios and natural frequency values were determined as −65.4968 dB and 1883.34 Hz, respectively, for standard cutting tool and −66.1215 dB and 2023.37 Hz, correspondently, for cutting tool with holes in toolholder.

The significance of the parameter on natural frequency occurred during turning of AISI 1045 steel with standard cutting tool and cutting tool with holes in toolholder was determined by ANOVA results given in Tables 7 and 8. *F*-ratios and percent contribution of parameters in Tables 7 and 8 were taken into consideration to determine the significance of the factor effect. The ANOVA results show that tool overhang significantly affect natural frequency in turning of AISI 1045 steel with 87.496% and

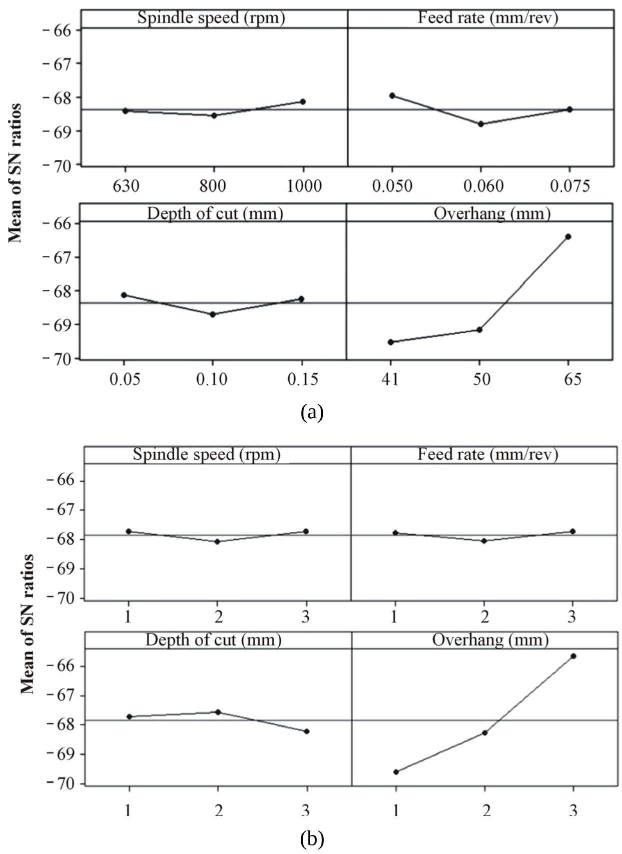

Figure 9. Maine effect plots for S/N ratios of natural frequency for: (a) standard cutting tool and (b) cutting tool with holes in toolholder.

Table 7. ANOVA for natural frequency of AISI 1045 with standard cutting tool.

Source	DF	SS	MS	*F* ratio	P value	% of Total
A	2	26,814*	13,407	0.6064	0.966	1.570
B	2	125,228	62,614	2.8323	0.875	7.330
C	2	61,613*	30,807	1.3935	0.506	3.604
D	2	1,495,114	697499.5	31.5514	0.009	87.496
Error	0	0	0.00			
Total (error)	8 (4)	1,708,769 88,427	22106.75			100

93.072% for standard cutting tool and cutting tool with holes, respectively. Other factors that influence the natural frequency are the feed rate with 7.3% and depth of cut with 3.749% for standard cutting tool and cutting tool with holes, respectively.

General evaluation is made in terms of cutting tool construction, the R_a and natural frequency values in turning of AISI 1045 steel obtained by cutting tool with holes are less and greater than those of standard cutting tool, respectively. This can be explained by the fact that the cutting tool with holes has the heterogeneous structure. Vibration waves pass through the mediums: metal-air-metal-air. Vibration suppression, their partial reflection and the change of direction occur because the holes are staggered in toolholder. As a result, vibrations are damped, which stabilizes the position of the tool leading to improve the surface quality. Therefore, it is possible to say that construction of cutting tool is an important factor for R_a and natural frequency. According to ANOVA results, it was also found that spindle speed has the significant influence on R_a, while this variable is tool overhang for natural frequency for both cutting tool.

Table 8. ANOVA for natural frequency of AISI 1045 with cutting tool with holes.

Source	DF	SS	MS	*F* ratio	P value	% of Total
A	2	46,906*	23,453	1.148	0.963	1.840
B	2	34,167*	17,083	0.836	0.973	1.339
C	2	95,635	47,818	2.341	0.210	3.749
D	2	2,373,981	1,186,991	58.112	0.001	93.072
Error	0	0	0			
Total (error)	8 (4)	2,550,689 81,073	20425.75			100.00

*Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis; DF—Degree of Freedom; SS—Sum of Squares; MS—Mean of Squares; A—Spindle speed; B—Feed rate; C—Depth of Cut and D—Tool Overhang.

3.3. Confirmation Experiments

When the optimal combination of cutting parameters does not correspond to any trial runs already completed in the orthogonal array, the verification of the predicted result is recommended by Taguchi using confirmation tests at the chosen setting. The confirmation tests results performed at the optimum variable levels were evaluated by taking into consideration the confidence interval (CI) at 95% confidence band to statistically judge the closeness of the predicted and experimental results. The CI is calculated from Equations (4) and (5) [23].

$$CI = \sqrt{F_{0.05}(1, f_e) V_e \left(\frac{1}{n_{eff}} + \frac{1}{r} \right)} \quad (4)$$

$$n_{eff} = \frac{N}{1+v} \quad (5)$$

where $F_{0.05}$ (1, f_e) is the F value from statistic table at 95% confidence level, f_e is the error degree of freedom, V_e is the mean square of error, n_{eff} is the repeating number of the experiments, r is the number of confirmation experiments, N is the total number of the experiments and υ is total degree of freedom of all variables.

Tables 9 and 10 show the comparison of the results of the confirmation tests between experimental values conducted according to the optimum levels of the parameters and predicted values using Equations (2) and (3) for surface roughness (R_a) and natural frequency (f) for both cutting tools. The optimal levels of variables are valid if the difference between predicted S/N ratio and S/N ratio obtained experimentally is within CI value.

At the 95% confidence level, the CIs of R_a were calculated according to the Equations (4) and (5), which are ± 0.436 dB and ± 1.018 dB for standard cutting tool and cutting tool with holes in toolholder, respectively. Simi-

Table 9. Comparison between experimental and predicted results of surface roughness.

Type of cutting tool	Experimental results		Predicted results		Differences	
	Ra_{exp}, μm	η_{exp}, dB	Ra_{pred}, μm	η_{pred}, dB	Ra_{exp} - Ra_{pred}	η_{exp} - η_{pred}
Standard cutting tool	1.05	−0.424	1.017	−0.150028	0.033	−0.275
Cutting tool with holes	0.56	5.0362	0.518	5.7053	0.042	0.6691

Table 10. Comparison between experimental and predicted results of natural frequency.

Type of cutting tool	Experimental results		Predicted results		Differences	
	f_{exp}, Hz	η_{exp}, dB	f_{pred}, Hz	η_{pred}, dB	f_{exp} - f_{pred}	η_{exp} - η_{pred}
Standard cutting tool	2130.1	−66.568	1883.34	−65.4986	246.76	−1.0694
Cutting tool with holes	2087.4	−66.392	2023.37	−66.1215	64.03	−0.2705

larly, the CIs of natural frequency are ± 583.80 dB and ± 561.16 dB for standard cutting tool and cutting tool with holes in toolholder, correspondently. It can be seen from **Tables 9** and **10** that the difference between R_a values and difference between natural frequencies values for both cutting tools are within CI values. Hence, the optimal levels of variables can be validated.

4. Conclusions

In this study, with the help of S/N ratio and ANOVA results, the effects of cutting parameters and cutting tool construction on average surface roughness and natural frequency in turning of AISI 1045 steel under dry condition were evaluated to determine the optimum cutting conditions. Turning operations were performed by using standard cutting tool and cutting tool with holes in toolholder made of AISI 5140. The experimental results revealed that:

- The obtained results confirm one more time the successful implementation of Taguchi method in machining researches.
- The smallest R_a values occurring in turning of AISI 1045 steel are 1.033 µm and 0.569 µm for standard cutting tool and cutting tool with holes in toolholder, respectively.
- The smallest natural frequency values occurring in turning of AISI 1045 steel are 2069.1 Hz and 2124 Hz for standard cutting tool and cutting tool with holes in toolholder, correspondently.
- Using ANOVA, the most significant parameter was determined, which was spindle speed for R_a, while this variable was tool overhang for natural frequency for both cutting tools.

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