Optimization of Surface Roughness and Vibration in Turning of Aluminum Alloy AA2024 Using Taguchi Technique

Vladimir Aleksandrovich Rogov, Ghorbani Siamak

Abstract**—**Determination of optimal conditions of machining parameters is important to reduce the production cost and achieve the desired surface quality. This paper investigates the influence of cutting parameters on surface roughness and natural frequency in turning of aluminum alloy AA2024. The experiments were performed at the lathe machine using two different cutting tools made of AISI 5140 and carbide cutting insert coated with TiC. Turning experiments were planned by Taguchi method L_9 orthogonal array.Three levels for spindle speed, feed rate, depth of cut and tool overhang were chosen as cutting variables. The obtained experimental data has been analyzed using signal to noise ratio and analysis of variance. The main effects have been discussed and percentage contributions of various parameters affecting surface roughness and natural frequency, and optimal cutting conditions have been determined. Finally, optimization of the cutting parameters using Taguchi method was verified by confirmation experiments.

Keywords**—**Turning, Cutting conditions, Surface roughness, Natural frequency, Taguchi method, ANOVA, S/N ratio.

I. Introduction

TURNING is one of the widely used machining processes. The productivity of the turning process is mainly limited by machine tool chatter caused by the interaction between cutting tool and workpiece structure and dynamics of the cutting process [1]. Chatter vibrations, occurred in turning operation in the feed and radial directions, lead to irregular distribution of thickness along the cutting edge. In an unstable process, the amplitude of vibrations may grow exponentially until they become as large as chip thickness [2]. This unstable vibration creates large cutting forces, which can damage machine and cause tool wear, tool breakage, unacceptable surface finish and dimensional errors [3]-[7]. Surface roughness is one of the important aspects in mechanical design, since it affects the performance of mechanical parts such as heat generation, wear and corrosion resistances, creep life and fatigue strength [8]. During turning operation several factors such as cutting tool and workpiece materials, feed rate, spindle speed, depth of cut, coolant, tool construction, tool nose radius and tool edge angles affect vibration and surface finish. Therefore, it is necessary to provide an adequate relationship between tool life and cutting conditions, tool geometrical parameters and workpiece and tool material properties, which is difficult because of the complexity of the machining process such as very high temperatures, strains and strain-rates and lack of suitable data [9]. In addition, the optimal cutting condition can minimize costs or cost/production time and enhance surface finish [10].

In recent years, optimization of cutting conditions for the purpose of reducing vibration and minimizing surface roughness during machining process has become one of the main subjects investigated by researchers. Reference [11] proposed a multiple degree of freedom model for chatter prediction in their investigation on the compliance between cutting tool and workpiece in turning process. The significant influence of tool overhang and work cross-section on the stability of the process during orthogonal turning operation has been revealed by [12]. A passive vibration damping in boring process proposed by [13] has improved the surface finish. Reference [14] stated that using impact dampers with different materials, such as cast iron, aluminum, gun metal, phosphor, copper, brass, bronze and structured steel, in boring tools suppresses the chatter by improving stiffness and damping capability of the tool. Reference [15] suggested a new tool design with an increased vibration-damping ability. An investigation on the influence of the geometry, material of the tool and workpiece on process stability in internal finish turning performed by [16] indicated the dominant effect of the ratio of boring bar overhang to bar external diameter on the stability of the process. Reference [17] suggested the mechanical adaptive system for accuracy control by dynamic adjustment of the tool position during turning operation. Reference [18] concluded that feed rate has the most significant effect on surface roughness in machining of a Hybrid Aluminium Metal Matrix Composite (Al6061-SiC-Al2O3). The investigations performed by [19], [20] on turning of the 6063 Al alloy TiC composites and Al-7075, respectively, using Taguchi method showed that the feed rate has the greatest effect on surface roughness followed by cutting speed. Reference [21] has used Taguchi method for surface finish optimization in end milling of Aluminum blocks. Reference [22] investigated the machinability of Al/SiC MMC and observed a better surface finish at high speed with low depth of cut and feed rate. References [23], [24] conducted studies on the effect of cutting parameters on the surface roughness in turning of Al-7050using Taguchi method. Analysis of variance (ANOVA) indicated that the feed rate is the influenced factor affecting surface roughness

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followed by cutting speed and the effect of depth of cut and nose radius are not significant. Reference [25] developed multiple linear regression model and ANN model for predicting the surface roughness in turning of AA 6351 alloy by using the experimental data. It was determined that feed rate is the most dominant cutting parameter on the surface roughness followed by cutting speed and depth of cut.

The purpose of this study is to obtain optimal cutting conditions to reduce vibration and minimize surface roughness when turning of aluminum alloy AA2024 using two cutting tools with the same material (AISI 5140) but different constructions (Fig. 1). Spindle speed (n), feed rate (f), depth of cut (a) and tool overhang (l) were selected as cutting parameters. Table I shows cutting parameters and their levels. The experiments were performed according to the L_9 orthogonal array of the Taguchi experimental design method for each cutting tool. The optimal cutting conditions and significance of the cutting parameters were determined using signal to noise ratio and analysis of variance. Finally, the predicted optimal cutting conditions obtained by Taguchi method were verified by the confirmation tests.

II. Materials And Method

A. Design of Experiment

The main goal of any business is to improve quality and increase productivity by using an appropriate method. In engineering design activities design of experiment, which is centered on factors, responses and runs in the experiment process, is widely used. Sometimes design of experiment is too complex, time-consuming, costly and not easy to use. When the number of factors increases more trial needs to be carried out. To overcome these problems, in engineering applications, the Taguchi experimental design method is widely used among the various classical designs of experiment such as factorial, fractional factorial, Placket-Burmann, central composite design and etc. [26]. The reason that makes Taguchi method a powerful, unique and efficient technique for analysis of experiment and product/process optimization is that this method by using orthogonal arrays highly fractionates the factorial designs and minimizes the number of trials in comparison with the classical design of experiment; consequently time and coast are considerably saved [27].

In Taguchi approach the experimental results are analyzed in order to establish the optimum conditions for a product/process; to estimate the percent contribution of each factor and to predict the response according to the optimum conditions. Taguchi method uses a statistical measure of performance known as signal-to-noise (S/N) ratio, which takes into consideration both the mean and the variability. The standard S/N ratios generally used for the quality characteristic to be optimized are as follows: the-nominal-the-better, the-smaller-the-better and the-larger-the-better. The optimal setting is the parameter combination with the highest S/N ratio. Besides, to determine the statistical significance of the parameters Taguchi method uses the analysis of variance (ANOVA). Then with the help of ANOVA and S/N ratio the optimum combination of the parameters is determined. Finally, confirmation tests are recommended by Taguchi to verify the effectiveness and efficiency of the method in optimizing the parameters for the response [27].

In this study spindle speed (n), feed rate (f), depth of cut (a) and tool overhang (l) and two different cutting tools are chosen as cutting parameters to be optimized for average surface roughness (R_a) and natural frequency in turning of aluminum alloy AA 2024. L_9 orthogonal array of Taguchi method is used in design of experiment.

In order to obtain the optimal cutting parameters the-smaller-the-better performance characteristics for R_a and natural frequency are used. Therefore, in this case S/N ratio (η) is determined according to (1) [27]:

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

where η is the S/N ratio, n is the number of experiment and Y_i is the observed data.

By the help of the (1) the S/N ratio of the variables parameters are calculated for the average surface roughness and natural frequency. To determine the factors effect on the average surface roughness and natural frequency in ANOVA the 95% confidence level is chosen. Minitab 16 software is used to optimize the processes, which is a statistical analysis software and it is used to improve the quality in engineering, mathematics, economics statistics, sports and economics.

B. Experimental Setup

The study was carried out using a lathe machine model 16K20VF1 (Russia) with maximum power of 5.5 kW and maximum spindle speed of 1600 rpm. The cutting tools used for experimentation were hardened steel AISI 5140 tool of different construction (Fig. 1). Carbide rhombic cutting insert coated with TiC, manufactured by SandvikCoromant, was used as a cutting tool insert. Experiments were performed under dry conditions. As a workpiece material the aluminum alloy AA2024 having size of 200 mm in length with 65 mm diameter was used in this study. Table II shows the chemical compositions of the selected material by weight percentage. In addition, before machining, in order to remove the rust layer and to minimize any effect of inhomogeneity of the material on the experimental results, the skin layers were removed using a new cutting insert. Besides, to minimize the effect of tool wear on the experimental results in each trial a new cutting insert coated with TiC was used.

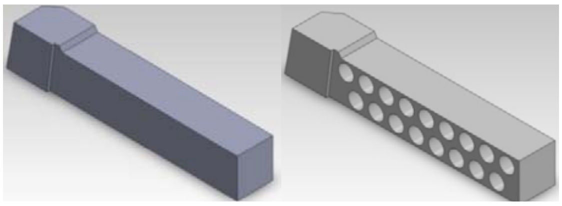
The average surface roughness (R_a) was measured using a profilemeter model 130 (Russia) with a sampling length of 12.50mm and measurement speed of 0.5mm/s. The R_a values were calculated by averaging four roughness values obtained from four different points of machined surface in 90^0 increments around the circumference. Measurement of frequencies occurred during turning was performed by using a piezoelectric accelerometer KD-35 and ZETLAB software (Russia). Vibrations occurred during machining were recorded by KD-35 attached on the lower side of the cutting edge of the tool and passed through the multifunctional spectrum analyzer A17-U8 to a personal computer to visualize the results.

TABLE I
MACHINING PARAMETERS AND THEIR LEVELS

Variables	Level1	Level 2	Level 3
A - Spindlespeed (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

TABLE II
CHEMICAL COMPOSITIONS OF ALUMINUM ALLOY AA2024

Element	Al	Mn	Cu	Si	Fe	Zn	Ti	Mg	Cr
Weight (%)	93.2	3.8	3.8	0.5	0.5	0.25	0.15	1.2	0.1



(a) (b)

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

III. EXPERIMENTAL RESULTS AND DISCUSSION

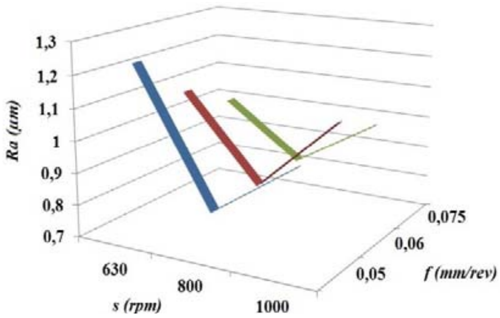
A. Evaluation of R_a for AA2024

In this investigation, the average surface roughness values (R_a) and S/N ratios obtained in turning of AA 2024 according to the L_9 orthogonal array of the Taguchi experimental design method of three spindle speeds, feed rates, depth of cut and tool overhangs using two different cutting tools are shown in Table III. The S/N ratios were calculated according to the Taguchi's "the-smaller-the-better" quality characteristics.

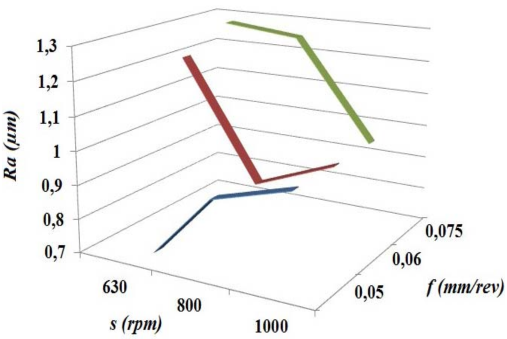
Due to design of experiment the machining parameters were distributed randomly, which can explain the irregular tendency of R_a values as shown in Figs. 2-4.

As seen from Figs. 2 (a), (b) at 0.05 mm/rev feed rate increase in spindle speed decreases the R_a for standard cutting tool, while the R_a value increases for cutting tool with holes in toolholder. However, the smallest R_a value was obtained as 0.64 µm at the same feed rate due to 630 rpm spindle speed for cutting tool with holes in toolholder (Table III). During the experiments, at which feed rate is 0.06 mm/rev, variation of the R_a values for both cutting tools was not regular. Although the R_a values of standard cutting tool showed a different trend compared to the cutting tool with holes in toolholder at 0.075 mm/rev feed rate, the highest R_a value has been observed as1.285 µm at the same feed rate due to 630 rpm spindle speed for cutting tool with holes in toolholder (Table III).

It can be seen from Figs. 3 (a), (b), in spite of that at 0.05 mm depth of cut R_a values of cutting tools showed different trends, the smallest R_a value was obtained due to 630 rpm spindle speed (Table III). At 0.1mm depth of cut, when spindle speed increases from 630 rpm to 1000 rpm, variation of the R_a shows an irregular tendency for both cutting tools. The highest R_a value has obtained in turning of AA2024 for cutting tool with holes in toolholder at 0.15 mm depth of cut due to 630 rpm spindle speed (Table III). Besides, based on experimental data given in Table III and Fig. 3, the R_a values decrease parallel to increase in depth of cut for both cutting tools, except 630 rpm spindle speed for cutting tool with holes in toolholder. This reveals the need to choose the higher depth of cut to obtain small values of surface roughness in turning of aluminum alloy AA2024.



(a)



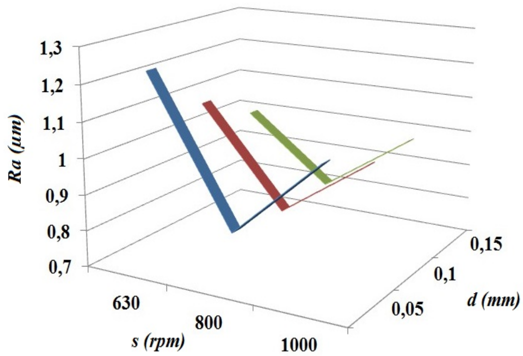
(b)

Fig. 2 Relationship between R_a, spindle speed (s) and feed rate (f) in turning of AA2024 with: (a) standard cutting tool and (b) cutting tool with holes in toolholder

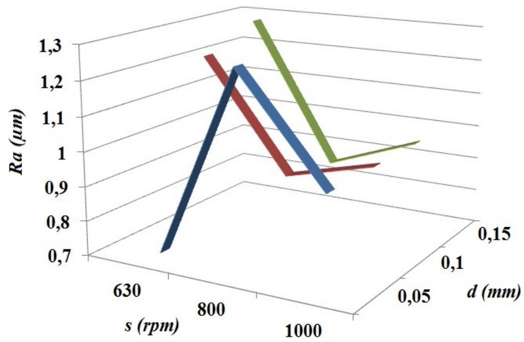
Figs. 4 (a), (b) indicate that, when the R_a values for 41mm tool overhang were evaluated, the R_a values obtained by cutting tool with holes in toolholder increased parallel to increase in spindle speed while the R_a values obtained by standard cutting tool showed an irregular tendency. On the other hand, at 65mm tool overhang, the R_a values for both cutting tools showed similar trends. At 630 rpm spindle the smallest and the highest R_a values were obtained due to 41mm and 65mm tool overhang with cutting tool with holes in toolholder, respectively. Besides, however, the surface roughness values are close to each other, variation of the Ra values was irregular at 50mm overhang when spindle speed increases from 630 rpm to 1000 rpm for both cutting tools (Table III).

TABLE III
EXPERIMENTAL RESULTS AND S/N RATIOS FOR R_a

Experiment No.	A	B	C	D	R_a for standard cutting tool (µm)	S/N ratio(dB)	R_a for cutting tool with holes (µm)	S/N ratio(dB)
1	1	1	1	1	1.231	-1.80516	0.640	3.87640
2	1	2	2	2	1.090	-0.74853	1.218	-1.71295
3	1	3	3	3	1.006	-0.05196	1.285	-2.17806
4	2	1	2	3	0.814	1.78751	0.893	0.98297
5	2	2	3	1	0.820	1.72372	0.864	1.26973
6	2	3	1	2	0.831	1.60798	1.260	-2.00741
7	3	1	3	2	0.986	0.12246	0.961	0.34553
8	3	2	1	3	1.055	-0.46505	0.957	0.37995
9	3	3	2	1	0.983	0.14893	0.960	0.35458

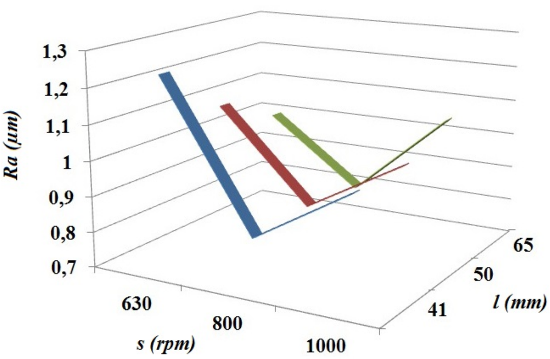


(a)

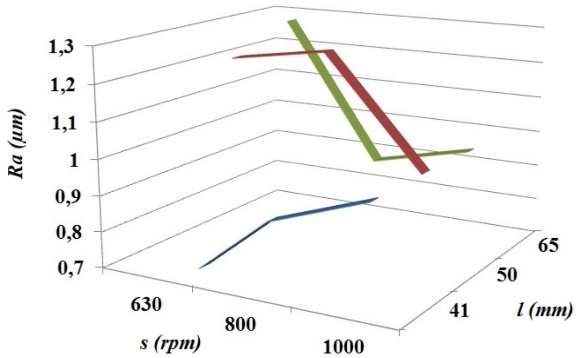


(b)

Fig. 3 Relationship between R_a, spindle speed (s) and depth of cut (d) in turning of AA2024 with: (a) standard cutting tool and (b) cutting tool with holes in toolholder



(a)



(b)

Fig. 4 Relationship between Ra, spindle speed (s) and tool overhang (l) in turning of AA2024 with: (a) standard cutting tooland (b) cutting tool with holes in toolholder

To determine the optimal levels of each parameter the S/N ratios of the R_a obtained from experimental results were calculated using (1) (Table III). These values are graphically analyzed to look for relative effects of the parameters on the R_a (Fig. 5). A steeper slope in the graphed S/N ratio effects indicates a greater effect of cutting parameter on the R_a. Figs. 5 (a), (b) indicate a much stronger effect on the R_a for spindle speed than the other three parameters for standard cutting tool, while the feed rate and tool overhang are the parameters that strongly affect the R_a for cutting tool with holes in toolholder. On the basis of data given in Table III and Fig. 5, the optimum cutting conditions in turning of AA2024 were determined, which are $A_2B_3C_3D_3$ for standard cutting tool and $A_3B_1C_1D_1$ for cutting tool with holes in toolholder. The smallest R_a value and S/N ratio under optimum cutting conditions can be calculated by (2), (3) [27]:

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

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

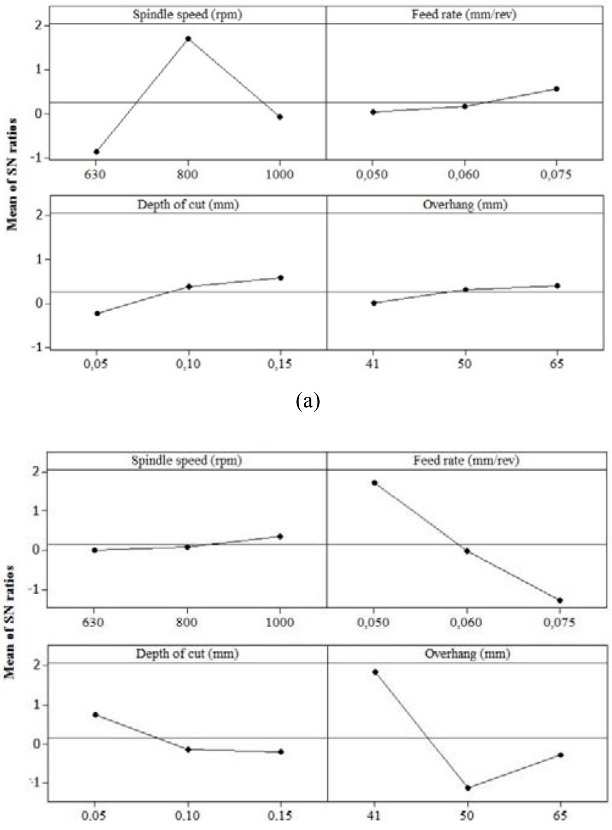
where: η_{opt} is the S/N ratio under optimum conditions (dB), m is the overall mean value of S/N ratio for the experimental region (dB), m_i is the S/N ratio under optimum condition (dB) and R_{aopt} is the surface roughness under optimum condition.

Calculated S/N ratios and surface roughness values were determined as 2.523 dB and 0.748µm, respectively, for standard cutting tool and 4.24129 dB and 0.614μm, correspondently, for cutting tool with holes in toolholder.

However, the statistical analysis ANOVA was done to determine the significance level of each parameter on the surface roughness (Tables IV, V). The significance level of each parameter is determined by Fisher's ratio (*F*), which is the ratio of factor mean square to the error mean square. To determine significance of the parameter on the R_a the *F*-test value is compared with the standard *F*-table value (F_α) at α significance level [27]. The analysis was performed for a confidence level of 95%. Consequently, the *F*-table value for parameters degree of freedom (df_1=2) and error degree of freedom (df_2=4) is $F_{0.05}$=6.9443. If *F*-ratio for each design parameter is greater than $F_{0.05}$, then the cutting parameter influence is significant. The ANOVA results indicate that the most influential parameter on the R_a of AA2024 is spindle speed with 81.301% for standard cutting, while feed rate and tool overhang are the factors that significantly affect the R_a for cutting tool with holes in toolholder with 47.328% and 46.006%, respectively. In addition, the R_a for standard cutting tool is also affected by depth of cut with 10.71%.

B. Evaluation of Natural Frequency Occurred in Turning of AA2024

In this study the influence of cutting parameters on vibration was established in order to improve the design and implementation of new cutting tool. The natural frequency occurred during turning of AA2024 was recorded by using piezoelectric accelerometer K-D35 and ZETLAB software. Cutting variable and their levels are shown in Table I. The S/N ratios for natural frequency were calculated according to Taguchi's "the-smaller-the-better" quality characteristics. Table VI illustrates the experimental results for natural frequency and S/N ratios. Figs. 6-8 show the variation of natural frequency depending on spindle speed (s)-feed rate (f), spindle speed (s)-depth of cut (d) and tool overhang (l)-spindle speed (s). As can be seen, however, the graphs show irregular tendencies, natural frequency values for both cutting tools show similar trends. Presumably, the randomized distribution of cutting variable due to design of experiment causes the irregular tendency of natural frequency values.



(a)

(b)

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

Figs. 6 (a), (b) indicate that natural that frequency values, at 0.05 mm/rev and 0.06 mm/rev feed rate, show an irregular tendency for both cutting tools as spindle speed increases. In contrast, it has been observed that at 0.075 mm/rev feed rate natural frequency values increase linearly as spindle speed is increased from 630 rpm to 1000 rpm for both cutting tools. It was determined that the highest natural frequency value is 3973.4 Hz, which is obtained at 800 rpm spindle speed due to0.06 mm/rev in turning of AA2024 using cutting tool with holes in toolholder. While at 630 rpm spindle speed and 0.075mm/rev feed rate, and at 1000 rpm spindle speed and 0.06 mm/rev feed rate the smallest natural frequency value was observed, which is 2038 Hz for standard cutting tool (Table VI).

TABLE IV
ANOVA FOR R_a OF AA2024FOR STANDARD CUTTING TOOL

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	0.127482	0.0637408	20.4264	0.021	81.301
Feed rate	2	0,007767*	0.0038834	1.2444	0.540	4.952
Depth of Cut	2	0.016839	0.0084194	2.6981	0.791	10.710
Overhang	2	0.004715*	0.0023574	0.7554	0.934	3.007
Error	0	0	0			
Total	8	0.156802				100
(error)	(4)	0.012482	0.0031205			

* Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis.

TABLE V
ANOVA FOR R_a OF AA2024FOR CUTTING TOOL WITH HOLES IN TOOLHOLDER

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	0.011696*	0.0058478	0.9728	0.881	3.243
Feed rate	2	0.170704	0.0853519	14.1987	0.261	47.328
Depth of Cut	2	0.012349*	0.0061744	1.0272	0.887	3.423
Overhang	2	0.165937	0.0829683	13.8022	0.274	46.006
Error	0	0	0			
Total	8	0.360685				100
(error)	(4)	0.024045	0.00601125			

* Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis

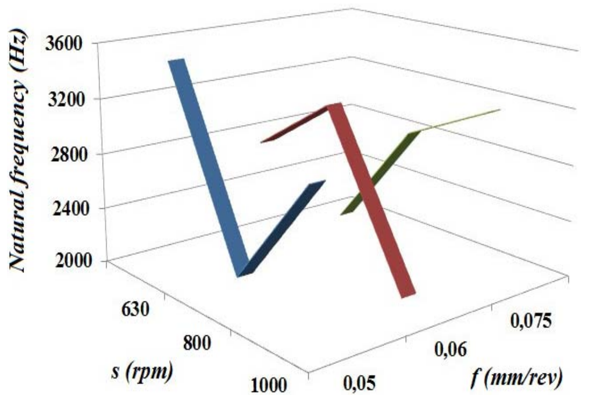
As seen from Fig. 7, when natural frequency results for 0.05mm depth of cut were evaluated, they decreased parallel to increase in spindle speed. On the other hand, at 0.1 mm and 0.15mm depth of cut the natural frequency values of neither cutting tool showed a regular tendency (Fig. 7). However, at 630 rpm spindle speed and 0.15 mm depth of cut, and 1000 rpm and 0.1mm depth of cut the smallest value of natural frequency was obtained with standard cutting tool, while the highest value of natural frequency was obtained at 800 rpm spindle speed and 0.15 mm depth of cut for cutting tool with holes in toolholder (Table VI).

It can be noticed from Fig. 8 that at 41mm tool overhang natural frequency value decreases parallel to increase in spindle speed for standard cutting tool, while the natural frequency value for cutting tool with holes is irregular. However the highest natural frequency value was obtained at the same tool overhang due to 800 rpm spindle speed for cutting tool with holes in toolholder (Table VI). At 50mm tool overhang the natural frequency value increases and decreases linearly as spindle speed is increased for standard cutting tool and cutting tool with holes in toolholder, respectively. During the experiments, at which tool overhang is 65mm the variation of natural frequency values are not regular, while the natural frequency values for cutting tool with holes decreased parallel to increase in spindle speed. At the same tool overhang the smallest natural frequency value was obtained due to 630 rpm and 800 rpm for standard cutting tool.

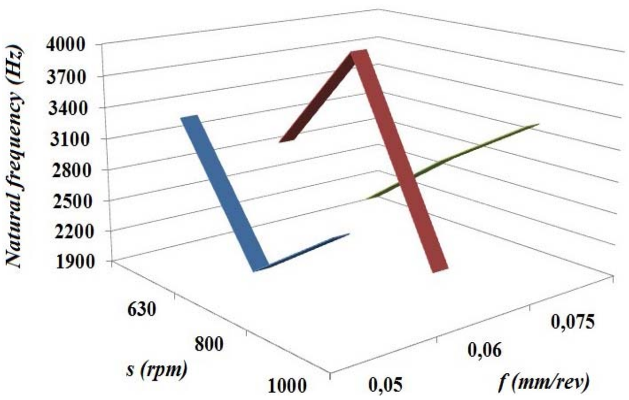
The S/N ratios of natural frequency given in Table VI were calculated according to (1). Fig. 9 illustrates the graphs of S/N ratios for natural frequency in turning of AA2024. The graphs reveal that tool overhang is the influenced factor affecting natural frequency, which can be explained by the fact that increase in tool overhang decreases tool stability during machining process leading to more vibration and poor surface roughness. Based on experimental data in Table VI and Fig. 9 the optimal cutting conditions in turning of AA2024 were determined which are $A_3B_2C_2D_3$ are for standard cutting tool and $A_3B_3C_1D_3$for cutting tool with holes in toolholder.

Refer to (2), (3), the predicted S/N ratios and natural frequency values under optimum conditions are -65.9622 dB and 1986.59 Hz, respectively, for standard cutting tool and -66.0265 dB and 2001.36 Hz, correspondently, for cutting tool with holes in toolholder.

Using ANOVA results the significance level of each cutting parameter on natural frequency was determined (Tables VII, VIII). It was revealed that tool overhang is the significant parameter affecting natural frequency in turning of AA2024 with 96.12% and 90.536% for standard cutting tool and cutting tool with holes in toolholder, respectively. The effect of other cutting parameters on natural frequency is not significant.



(a)

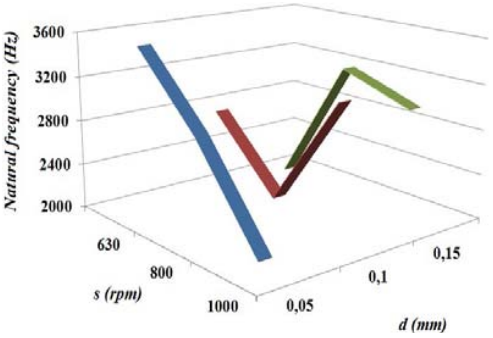


(b)

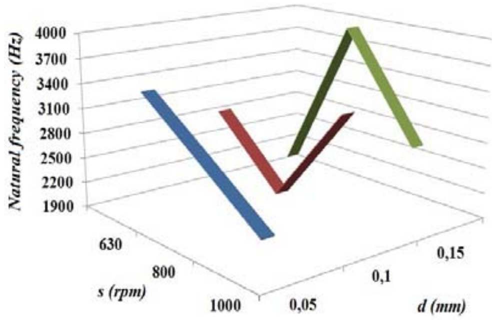
Fig. 6 Relationship between natural frequency, spindle speed (s) and feed rate (f) in turning of AA2024 with: (a) standard cutting tool and (b) cutting tool with holes in toolholder

TABLE VI
EXPERIMENTAL RESULTS AND S/N RATIOS FOR NATURAL FREQUENCY

Experiment No.	A	B	C	D	Natural frequency for standard cutting tool (Hz)	S/N ratio (dB)	Natural frequency for cutting tool with holes (Hz)	S/N ratio (dB)
1	1	1	1	1	3491.2	-70.8595	3332.5	-70.4554
2	1	2	2	2	2771.0	-68.8527	2917.5	-69.3002
3	1	3	3	3	2038.6	-66.1866	2124.0	-66.5431
4	2	1	2	3	2148.4	-66.6423	2148.4	-66.6423
5	2	2	3	1	3198.2	-70.0981	3973.4	-71.9832
6	2	3	1	2	2868.7	-69.1537	2764.9	-68.8336
7	3	1	3	2	2978.5	-69.4800	2740.5	-68.7566
8	3	2	1	3	2038.6	-66.1866	2185.1	-66.7894
9	3	3	2	1	3173.8	-70.0316	3314.2	-70.4076

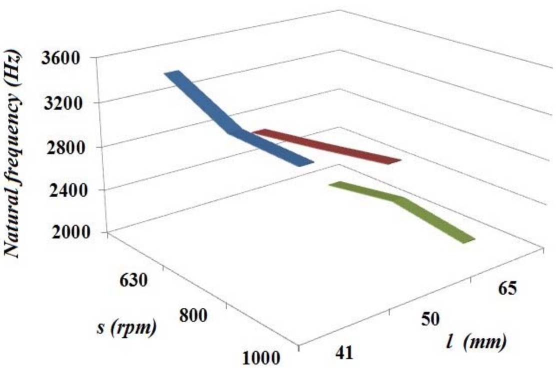


(a)

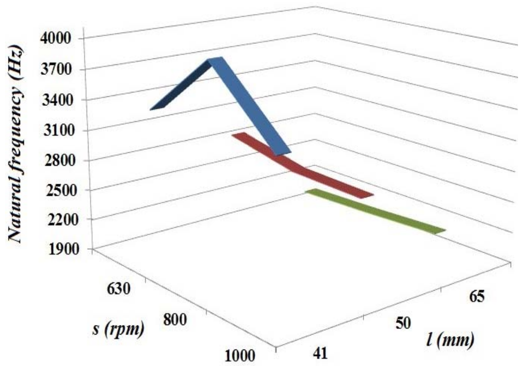


(b)

Fig. 7 Relationship between natural frequency, spindle speed (s) and depth of cut (d) in turning of AA2024 with: (a) standard cutting tool and (b) cutting tool with holes in toolholder



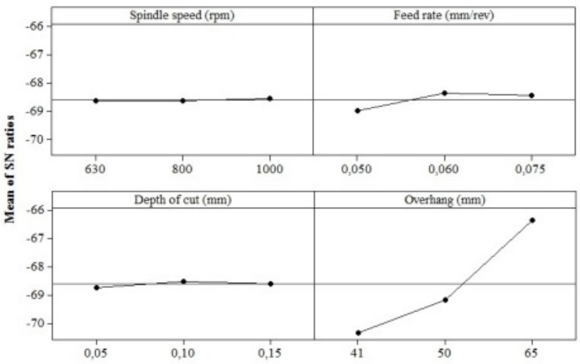
(a)



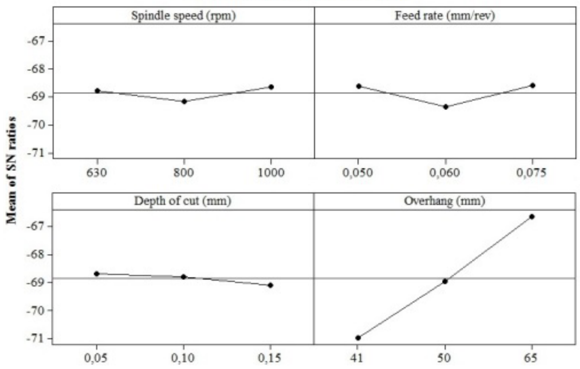
(b)

Fig. 8 Relationship between natural frequency, spindle speed (s) and tool overhang (l) in turning of AA2024 with: (a) standard cutting tool and (b) cutting tool with holes in toolholder

General evaluation in terms of the influence of cutting tool construction on the R_a and natural frequency values in turning of AA2024 reveals that the R_a and natural frequency values obtained by cutting tool with holes in toolholder are greater than those of obtained by standard cutting tool (Tables III, VI). This can be explained by the heterogeneous structure of cutting tool with holes in toolholder. Vibration waves pass through the mediums: metal-air-metal-air. Because of the staggered holes in toolholder vibration occurred during turning of AA2024 is suppressed, partially reflected and its direction is changed. Consequently, vibration damping is occurred. However the staggered holes reduces the stiffness of the cutting tool with holes in comparison with standard cutting tool, which causes more vibration of the tool relative to workpiece and, in consequence, it leads to poor surface finish. Therefore, cutting tool construction is one of the key factor affecting the surface roughness and natural frequency.



(a)



(b)

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

C. Confirmation Test

After identifying the most significant factors, the confirmation tests at optimal settings are recommended by Taguchi in order to verify the calculated S/N ratios, surface roughness and natural frequency under optimal conditions obtained by (2), (3). For this reason, the confidence interval (CIs) values are used to evaluate the closeness of the experimental and calculated results. The CIs values at 95% confidence band are determined according to (4), (5) [27]:

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

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

where $F_{0.05}(1,f_e)$ is the F value from statistic table at a 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.

Table IX, X illustrate the comparison of the results of the confirmation experiments between experimental results performed according to the optimal cutting conditions and calculated values using (2), (3) for R_a and natural frequency (f). The optimal levels of cutting parameters are considered valid if the difference between calculated S/N ratio and S/N ratio obtained in experimental results is within CI value.

TABLE VII
ANOVA FOR NATURAL FREQUENCY OF AA2024FOR STANDARD CUTTING TOOL

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	2220*	1110	0.2472	0.998	0.094
Feed rate	2	74023	37012	8.2423	0.938	3.122
Depth of Cut	2	15742*	7871	1.7523	0.687	0.664
Overhang	2	2278522	1139261	253.7047	0.001	96.120
Error	0	0	0			
Total	8	2370507				100
(error)	(4)	17962	4490.5			

* Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis.

TABLE VIII
ANOVA FOR NATURAL FREQUENCY OF AA2024FOR CUTTING TOOL WITH HOLES IN TOOL HOLDER

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	77706*	38853	1.114	0.949	2.433
Feed rate	2	165848	82924	2.435	0.896	5.195
Depth of Cut	2	58620*	29310	0.860	0.650	1.836
Overhang	2	2890858	1445429	42.439	0.006	90.536
Error	0	0	0			
Total	8	3193031				100
(error)	(4)	136236	34059			

* Indicates sum of squares added together to estimate the pooled error sum of squares shown within parenthesis.

TABLE IX
COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED RESULTS OF R_a

Type of cutting tool	Experimental results		Predicted results		Differences	
	R_{aexp}, μm	η_{exp}, dB	R_{apred}, μm	η_{pred}, dB	R_{aexp}- R_{apred}	η_{exp}-η_{pred}
Standard cutting tool	0.765	2.327	0.748	2.52300	0.017	-0.196
Cutting tool with holes	0.628	4.040	0.614	4.24129	0.014	-0.200

TABLE X
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	2142.3	-66.617	1986.59	-65.9622	155.71	-0.6548
Cutting tool with holes	2081.3	-66.367	2001.36	-66.0265	79.94	-0.3405

At the 95% confidence level, the CIs of R_a calculated according to the (4), (5) are ±0.2193 dB and ±0.3044 dB for standard cutting tool and cutting tool with holes in toolholder, respectively. Similarly, the CIs of natural frequency are ±263.18 dB and ±724.63 dB for standard cutting tool and cutting tool with holes in toolholder, correspondently. Since the calculated errors are within CIs values the optimal levels of variables can be validated (Tables IX, X).

IV. CONCLUSIONS

This paper presents the application of Taguchi method for optimizing surface roughness and natural frequency in turning of AA2024 under dry condition. Spindle speed, feed rate, depth of cut and tool overhang were chosen as cutting parameters. Two cutting tools with the same material made of AISI 5140 but different constructions were used to perform turning operation. Using signal to noise (S/N) ratio and ANOVA results the significance of cutting parameters was determined to get lower natural frequency and better surface roughness. The experimental results revealed that:

- Taguchi method is a powerful technique for designing and analyzing the experimental results in machining researches.
- The smallest R_a values occurred in turning of AA2024 are 0.814µm and 0.64µm for standard cutting tool and cutting tool with holes in toolholder, respectively.
- The smallest natural frequency values occurred in turning of AA2024 are 2038.6 Hz and 2124 Hz for standard cutting tool and cutting tool with holes in toolholder, correspondently.
- The dominant factor affecting the R_a is spindle speed with 81.301% for standard cutting tool; while these variables are feed rate and tool overhang with 47.328% and 46.006%, respectively, for cutting tool with holes in toolholder.
- Natural frequency is strongly affected by tool overhang with 96.12% and 90.536% for standard cutting tool and cutting tool with holes, respectively.

Further study could use composite materials with high damping capacities in the holes of the cutting tool with holes in toolholder to increase stiffness of the cutting tool and to see how the composite materials affect the vibration level and surface roughness.

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