Effect of Composite Material on Damping Capacity Improvement of Cutting Tool in Machining Operation Using Taguchi Approach

S. Ghorbani, N. I. Polushin

Abstract**—**Chatter vibrations, occurring during cutting process, cause vibration between the cutting tool and workpiece, which deteriorates surface roughness and reduces tool life. The purpose of this study is to investigate the influence of cutting parameters and tool construction on surface roughness and vibration in turning of aluminum alloy AA2024. A new design of cutting tool is proposed, which is filled up with epoxy granite in order to improve damping capacity of the tool. Experiments were performed at the lathe using carbide cutting insert coated with TiC and two different cutting tools made of AISI 5140 steel. Taguchi L_9 orthogonal array was applied to design of experiment and to optimize cutting conditions. By the help of signal-to-noise ratio and analysis of variance the optimal cutting condition and the effect of the cutting parameters on surface roughness and vibration were determined. Effectiveness of Taguchi method was verified by confirmation test. It was revealed that new cutting tool with epoxy granite has reduced vibration and surface roughness due to high damping properties of epoxy granite in toolholder.

Keywords**—**ANOVA, damping capacity, surface roughness, Taguchi method, vibration.

I. Introduction

TURNING operation is a commonly used cutting process for manufacturing of the parts. In turning operation, vibrations occur and the cutting tool results in a wave on the surface of the work piece, which magnifies tool vibrations. Because of these vibrations, the tool edge can be released from the work piece. This unstable tool vibration is called chatter. Chatter is a frequent problem in turning operation leading to an unstable cutting process affecting the surface quality, productivity, tool life, tool wear and dimensional accuracy of the machined work piece and it is usually accompanied by considerable noise [1]-[3]. The avoidance of chatter has been a goal for many years. The design and configuration of the tooling structures and the machine, tool and work piece materials and cutting conditions affect vibration. An appropriate choice of tool design and cutting conditions, and stiffness and damping improvement for the modes of vibration resulting in relative motion between tool and work piece can reduce vibration [4]. Cutting tool, in machining process, is the flexible element of the system, with the work piece being rigid [5]. A simple way to reduce the dynamic displacement between cutting tool and work piece is enhancing the stiffness of cutting tool by using a passive damping element, integrated on the tool shaft. The principle of passive control is to convert vibrating energy into other forms by improving the damping capability of the tool [6], [7].

The precision of machine tools depends on the materials used in their structures. These materials reduce vibration during machining process by dissipating the vibrating energy. Hence, these materials must possess good material properties like high damping capability, stiffness, elastic modulus, and thermal expansion coefficient. Nowadays, composite materials such as epoxy granite are typically used in substitution to conventionally used cast irons in structural applications for machine tools which require higher stiffness, strength, and damping than can be achieved with cast irons [8].

Recently the optimization of cutting conditions to improve vibration level and surface roughness in a machining process, as well as the potential of composite materials for the development of precision machine structures were studied by many authors. An investigation performed by [9] indicated that the logarithmic decrement values of the epoxy granite samples are almost three times higher than those of cast iron. Reference [10] studied the mechanical characteristics of an epoxy granite beam against cast iron and steel and observed that for same stiffness, the epoxy granite structure offers a sharp reduction in mass and vibration is dampened out faster by epoxy granite in comparison with steel and cast iron structures. It was also reported that the novel design has increased damping ratio in ten times and improved surface roughness compared to conventional tool. Reference [11] applied a novel carbon based composite coating with multi-layered nanostructure at the clamping area of the tool to suppress tool chatter. A new-type nonlinear tuned mass damper containing an additional element of elastic support dry friction is proposed by [12] to suppress machining chatter. Reference [13] developed an efficient position-dependent multi body dynamic model of a machine tool to evaluate and improve dynamic performance of a machine tool at the design stage. Reference [14] reduced the vibration level of the cutting tool in turning of aluminum alloy 6063 by using passive damping pad of viscoelastic material of neoprene. In addition, analysis of variance (ANOVA) showed that the tool vibration during machining is mainly influenced by depth of cut and cutting speed. A new tool design including special elements made of damping materials presented by [15] has reduced vibration amplitude and surface roughness by improving

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damping capability of the tool. Reference [16] reported that tool overhang and work cross-section are the main factors that affect the stability of machining process. An experimental study carried out by [17] on the effect of the tool and workpiece material, tool geometry and cutting conditions on process stability in internal finish turning revealed the significant influence of the ratio of tool overhang to bar external diameter on the stability of the process. Reference [18] used the diamond as coating material in dry machining of aluminum alloys to improve the tool life. It was also proved that the combination of the optimized cutting conditions and tool geometry leads to achieve high surface quality. References [19]-[21] reported the significant influence of feed rate in turning of Al-7075-T6, aluminum alloy 6063 TiC composites and aluminum alloy 7075 using Taguchi method and ANOVA, respectively. Reference [22] investigated the effect of machining parameters in machining of the aluminum alloy 7050 based on Taguchi L_9 technique. The cutting process was optimized for surface roughness and it was concluded that cutting speed, depth of cut and feed rate are the main parameters that affect surface roughness. Reference [23] by using design of experiment and ANOVA results stated that feed rate has the great impact on surface roughness in turning of aluminum alloy AS17. Reference [24] evaluated the effect of cutting parameters on surface roughness. They determined the optimum cutting condition in turning of aluminum alloy 6063 using Taguchi method. It was found that feed rate is the dominant factor affecting surface roughness compared to cutting speed and depth of cut. Therefore, this discussion about turning operation indicates that it is a vital task to increase the stiffness and damping of machine tool and to select the optimum cutting condition to assure high surface quality of machined work piece.

This paper includes an experimental study that investigates the effect of epoxy granite on damping capability improvement of cutting tool in turning of aluminum alloy AA2024. The new developed tool was compared to the conventional one. This paper also presents the application of L_9 orthogonal array Taguchi method and analysis of variance for determining the optimal cutting condition and the effect of each cutting parameter on surface roughness and natural frequency.

II. Materials and Method

A. Design of Experiment

Design of experiment is a powerful tool that is extensively used in industry to model and analysis the process or product variables that influence product quality. However, in turning operation, a proper implementation and selection of the cutting tool, and cutting condition and parameters require considerable knowledge and experience to design experiments and analysis experimental data. Additionally, conventional experimental design methods are difficult and complicated especially when the number of parameters increases [25]. Therefore, for optimization of cutting parameters for vibration and surface roughness in turning operation a more efficient method is required. Taguchi method is a unique and powerful technique for producing high quality products at subsequently low cost. According to the Taguchi method, the optimum cutting condition of input parameters is determined, while the variation caused by uncontrollable factors is neglected [26]. To study, analysis variation and predict the optimum results the Taguchi method uses a special design of orthogonal arrays and signal-to-noise ratio (S/N). Three forms of S/N ratio used for optimization of the process are the-larger-the-better, the-nominal-the better and the-lower-the-better. Moreover, in order to determine the influence of each parameter on response the analysis of variance (ANOVA) is suggested by Taguchi. In Taguchi method, it is also recommended to perform confirmation run to verify the Taguchi method efficiency in optimizing the parameters [27].

In this study the optimization of cutting parameters were performed for natural frequency and surface roughness in turning of AA2024. The control parameters were spindle speed (s), feed rate (f), depth of cut (d) and tool overhang (l). Three levels were specified for each of the factors as shown in Table I. The orthogonal array chosen was L_9. For surface roughness and natural frequency "The-smaller-the-better" principle is applied among the values expected to be reached at the end of the experiments. In this case, the generic form of S/N ratio is,

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

where η represents the S/N ratio, n is the number of experiments done under experiment conditions and Y_i is the calculated characteristics. Additionally, the 95% confidence level is applied in ANOVA to determine the effect of each factor on natural frequency and surface roughness. To perform the optimization of the process Minitab 16 statistical analysis software is used, which is extensively used in different fields such as mathematics, quality improvement in engineering, economics and sports.

B. Experimental Setup

Machining processes were performed under dry condition at the lathe machine model 16K20VF1 (Russia), which has the maximum spindle speed of 1600 rpm and maximum power of 5.5 kW. The conventional cutting tool and a new proposed cutting tool with new design made of hardened steel AISI 5140 were used as cutting tools (Fig. 1). As it can be seen from Fig. 1 (c) the holes of the cutting tool are filled up with epoxy granite, the physical and mechanical characteristics of which are provided in Table II. The Carbide rhombic cutting insert coated with TiC, manufactured by Sandvik Coromant, was used as tool insert. Aluminum alloy AA2024 having size of 200 mm in length with 65 mm diameter was used as workpiece material, the chemical composition of which is given in Table III. Additionally in each trial, before machining, the skin layers of the workpiece were removed using a new cutting insert coated with TiC to remove the rust layer and to minimize any effect of inhomogeneity of workpiece material on experimental results. Besides, the effect of tool wear on the experimental results in each trial was minimized by using new cutting insert coated with TiC. Fig. 2 shows the experimental setup of machining process using conventional cutting tool.

The surface roughness of the machined workpiece was measured using profilemeter model 130 (Russia) (Fig. 3) with a measurement speed of 0.5 mm/s and sampling length of 12.50 mm. The average surface roughness values (R_a) were calculated by averaging four roughness values obtained from four different points of machined surface in 90 increments around the circumference. Moreover, natural frequencies occurred during turning was measured by piezoelectric accelerometer KD-35 and ZETLAB software (Russia). KD-35, attached on the lower side of the cutting edge of the tool, records vibrations occurred during turning, and then passes it through the multifunctional spectrum analyzer A17-U8 to a personal computer to visualize the results (Figs. 2, 4).

TABLE I
CUTTING VARIABLES 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

TABLE II
PHYSICAL AND MECHANICAL CHARACTERISTICS OF EPOXY GRANITE

Parameter	Epoxy-granite
Density (kg/m^3)	2400–2600
Strength stress (MPa)	
Compression	150-160
Tensile	15-20
Elasticity module (MPa*10^{-4})	3.5–4.0
Poisson's ratio	0.25–0.40
Thermal conductivity (W/(m*K))	1.7–1.75
Linear expansion coefficient (1/°C)	(12–16)*10-6
Damping ratio	0.6

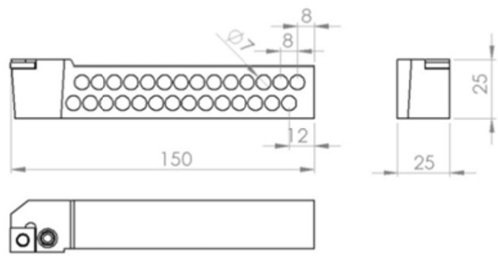
TABLE III
CHEMICAL COMPOSITIONS OF ALUMINUM ALLOY AA2024

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

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Surface Roughness Evaluation

The experiments were carried out based on Taguchi technique L_9 orthogonal array. The average surface roughness values (R_a) were measured and S/N ratios were calculated according to "the-smaller-the-better" principle in Taguchi method. The R_a and S/N ratio values are shown in Table IV. The R_a values during turning of AA2024 using conventional cutting tool and cutting tool filled up with epoxy granite has been evaluated by using graphs given in Figs. 5-7. The randomly distribution of cutting parameters due to design of experiment caused an irregular tendency of surface roughness values as it can be seen from Figs. 5-7.



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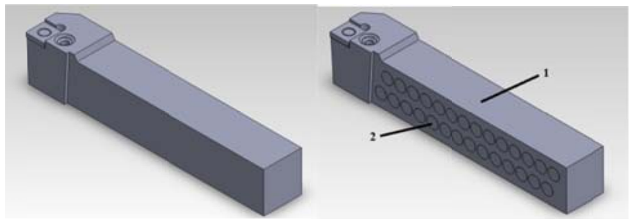


(b) (c)

Fig. 1 3D- model of the cutting tools in SolidWorks: (a) sketch of the modified cutting tool (b) conventional cutting tool; (c) modified cutting tool filled up with epoxy granite: 1 — toolholder and 2 — epoxy granite

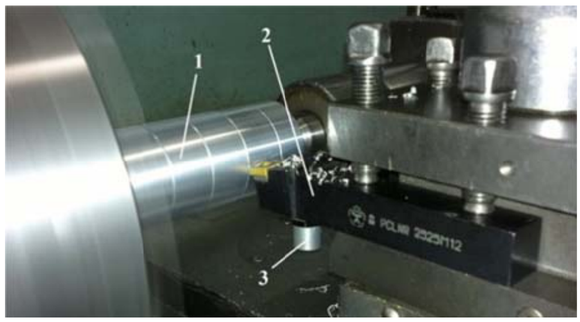


Fig. 2 Experimental setup of machining process: 1- workpiece, 2- cutting tool, 3- piezoelectric accelerometer KD-35

Fig. 3 Measuring surface roughness using profilemeter model 130

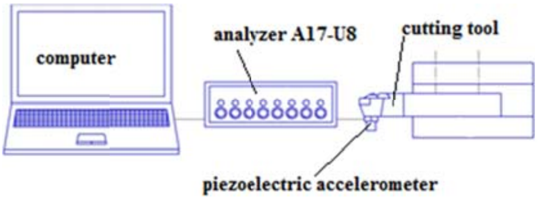
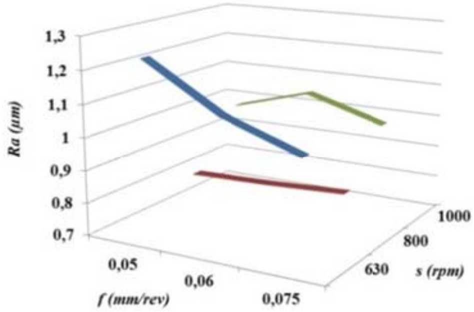


Fig. 4 Scheme of the setup for determining natural frequency during machining process

Fig. 5 clearly shows that the R_a values for conventional cutting tool and cutting tool with epoxy granite have different trends. However, at 630 rpm spindle speed increase in feed rate decreases R_a for conventional cutting tool, while the R_a values increase with increasing feed rate for cutting tool with epoxy granite. In addition, the highest value of the R_a in turning of AA2024 was determined as 1.231 µm at the same spindle speed due to 0.05 mm/rev feed rate using conventional cutting tool (Table IV). At 800 rpm spindle speed, the R_a values decrease parallel to feed rate for cutting tool with epoxy granite, while the R_a values increase for conventional cutting tool. The smallest value of the R_a was obtained at 0.075 mm/rev feed rate due to 800 rpm spindle speed, which is 0.575 µm using cutting tool with epoxy granite (Table IV). At 1000 rpm spindle speed the variation of the R_a values are not regular when machining the AA2024 using conventional cutting tool, while increase in feed rate increases the R_a values using cutting tool with epoxy granite.

As seen from Fig. 6, at 630 rpm, the R_a values decrease linearly as depth of cut increases from 0.05 to 0.15 mm for conventional cutting tool. On the other hand, at the same spindle speed increase in depth of cut increases the R_a values for cutting tool with epoxy granite. At 800 rpm, spindle speed R_a values increase parallel to depth of cut for conventional cutting tool while the R_a values for cutting tool with epoxy granite have an irregular tendency. Moreover, during machining of AA2024 using cutting tool with epoxy granite at 0.05 mm depth of cut the smallest value the R_a was observed due to 800 rpm spindle speed (Table IV). The R_a values for both cutting tools show an irregular tendency at 1000 rpm spindle speed, although the R_a values are close to each other.

Fig. 7 indicates that at 630 rpm spindle speed increase in tool overhang decreases the R_a values for conventional cutting tool, while the variation of tool overhang at the same spindle speed increases the R_a values for cutting tool with epoxy granite. However, at 41 mm tool overhang the highest value of the R_a is determined due to 630 rpm spindle speed for conventional cutting tool (Table IV). Although the smallest R_a value is observed at 50 mm tool overhang due to 800 rpm for cutting tool with epoxy granite, the variation of the R_a values is irregular for both cutting tools. When the R_a results for 1000 rpm spindle speed were evaluated, in spite of the closeness of the R_a values, the R_a values obtained with conventional cutting tool increase with increasing tool overhang form 41 to 65 mm, while the R_a values for cutting tool with epoxy granite show an irregular tendency.



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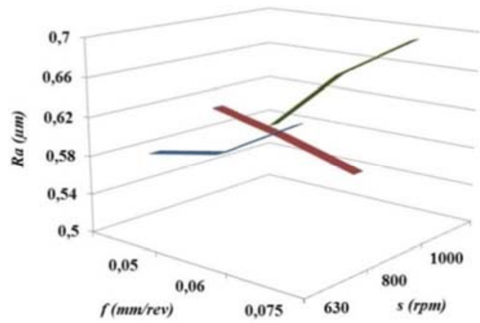
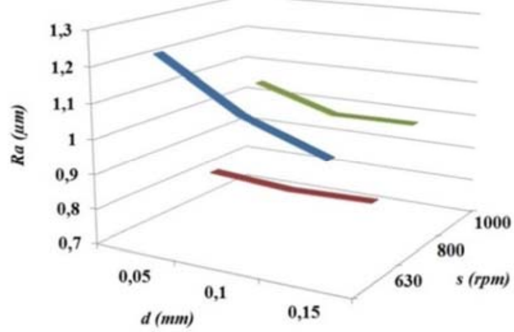


(b)

Fig. 5 Relationship between R_a, feed rate (f) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite



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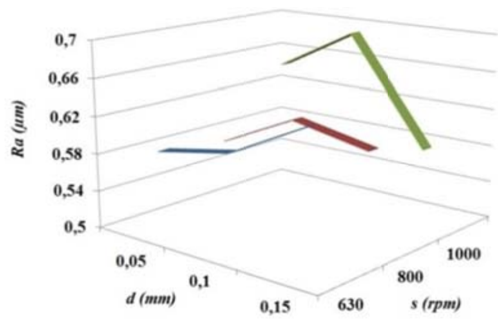


(b)

Fig. 6 Relationship between R_a, depth of cut (d) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite

To determine the optimal levels of each cutting parameter the S/N ratios were calculated using (1) (Table IV). Fig. 8 shows the S/N ratios graphs that were calculated for R_a for both cutting tools. The effect of each cutting parameter on the R_a is determined by the slope of the line in the graph of S/N ratios. The combination of cutting parameters that will give the optimum R_a is determined using S/N ratios values in Table IV and Fig. 8, which are $A_2B_3C_3D_3$ and $A_2B_1C_1D_2$ for conventional cutting tool and cutting tool with epoxy granite, respectively.

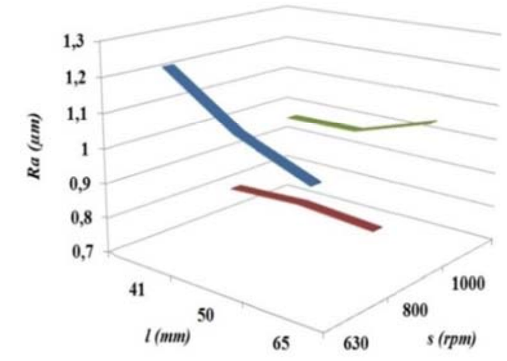
The values of S/N ratios and R_a under optimum cutting conditions can be calculated using (2) and (3) [27].

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

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

where η_{opt} represents 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.

Predicted values of S/N ratios and surface roughness calculated by (2) and (3) are 2.523 dB and 0.748 µm, respectively, for conventional cutting tool and 5.41209 dB and 0.531 µm, correspondently, for cutting tool with epoxy granite. Predicted values of S/N ratios and surface roughness calculated by (2) and (3) are 2.523 dB and 0.748 µm, respectively, for conventional cutting tool and 5.41209 dB and 0.531 µm, correspondently, for cutting tool with epoxy granite. However, the effect of each cutting parameter on surface roughness was statically analyzed using ANOVA (Tables V and VI). In Tables V and VI, the ratio of factor mean square to the error mean square called Fisher's ratio (F) is used to determine the significance level of the parameters. The F-test value was compared to the F-table value (F_α) at α significance level [26]. The analysis was performed for a confidence level of 95%. Therefore, the F-table value for degree of freedom for parameters (df_1=2) and degree of freedom for error (df_2=4) is determined as $F_{0.05}$ =6.9443. The cutting parameter influence is considered significant if F-ratio for the parameter is greater than $F_{0.05}$. The ANOVA results revealed that the surface roughness in turning of aluminum alloy AA2024 is mostly influenced by spindle speed with 81.301% followed by depth of cut with 10.71% for conventional cutting tool. On the other hand, when machining the AA2024 using cutting tool with epoxy granite the effect of factors on surface roughness are contributed in following order: tool overhang (34.5%), spindle speed (25%), feed rate (24%) and depth of cut (16.5%).



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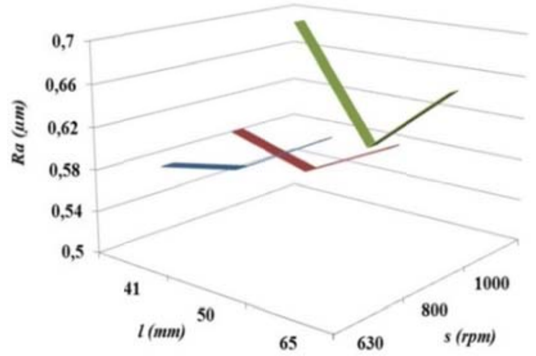


(b)

Fig. 7 Relationship between R_a, tool overhang (l) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite

B. Natural Frequency Evaluation

Chatter tests were conducted in order to obtain the influence of each cutting parameter on natural frequency (*f*) experimentally in turning of aluminum alloy AA2024 for both cutting tools. The piezoelectric accelerometer KD-35 and ZETLAB software were used in order to record natural frequency during machining process (Fig. 4). Cutting variables and their levels are shown in Table I. The S/N ratios were calculated according to the Taguchi's "the-smaller-the-better" quality characteristics by using (1) (Table VII). Relationship between natural frequency and cutting parameters are illustrated in Figs. 9-11.

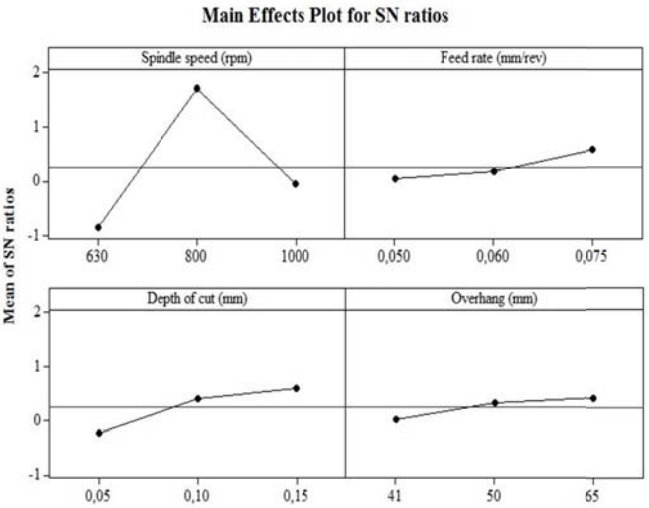
It can be seen from Fig. 9 that at 630 rpm spindle speed the natural frequency values linearly decrease parallel to feed rate for both cutting tools. The highest value of the natural frequency is also observed at the same spindle speed due to 0.05 mm/rev for conventional cutting tool, which is 3491.2 Hz (Table VII). It can be clearly noticed that at 800 and 1000 spindle speeds the graphs have an irregular tendency, although they show similar trends for both cutting tools. However, at 1000 rpm spindle speed the smallest value of natural frequency was obtained due to 0.06 mm/rev feed rate (Table VII).

Fig. 10 indicates that, during turning of AA2024 using both cutting tools, increase in depth of cut from 0.05 to 0.15 mm decreases natural frequency values at 630 rpm spindle speed.

Additionally increasing spindle speed also decreases the natural frequency values at 0.05 mm depth of cut for both cutting tools (Table VII). When the natural frequency values were evaluated for 800 and 1000 rpm spindle speeds the natural frequency values of neither cutting tool show a regular tendency, although they have similar trends. However during machining of AA2024 using cutting tool with epoxy granite at 1000 rpm spindle speed and 0.05 mm depth of cut the smallest value of natural frequency was determined as 1843.1 Hz (Table VII).

TABLE IV
EXPERIMENTAL RESULTS AND S/N RATIOS FOR R_a

Experiment No.	A	B	C	D	R_a for conventional cutting tool (μm)	S/N ratio (dB)	R_a for cutting tool filled up with epoxy granite (μm)	S/N ratio (dB)
1	1	1	1	1	1.231	-1.80516	0.583	4.68663
2	1	2	2	2	1.090	-0.74853	0.598	4.46598
3	1	3	3	3	1.006	-0.05196	0.640	3.87640
4	2	1	2	3	0.814	1.78751	0.614	4.23663
5	2	2	3	1	0.820	1.72372	0.597	4.48051
6	2	3	1	2	0.831	1.60798	0.575	4.80664
7	3	1	3	2	0.986	0.12246	0.578	4.76144
8	3	2	1	3	1.055	-0.46505	0.647	3.78191
9	3	3	2	1	0.983	0.14893	0.693	3.18534



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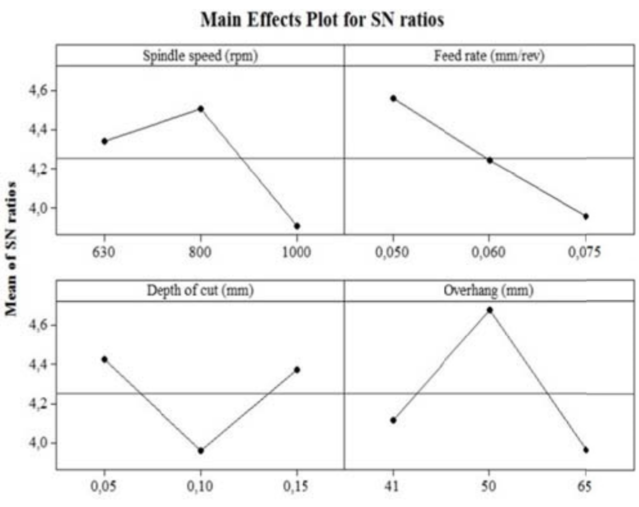
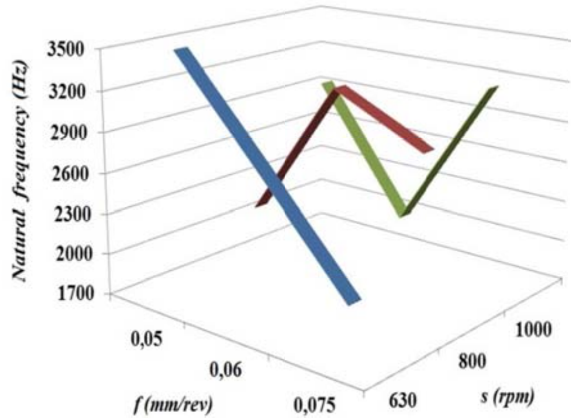


(b)

Fig. 8 Maine effect plots for S/N ratios of R_a for: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite



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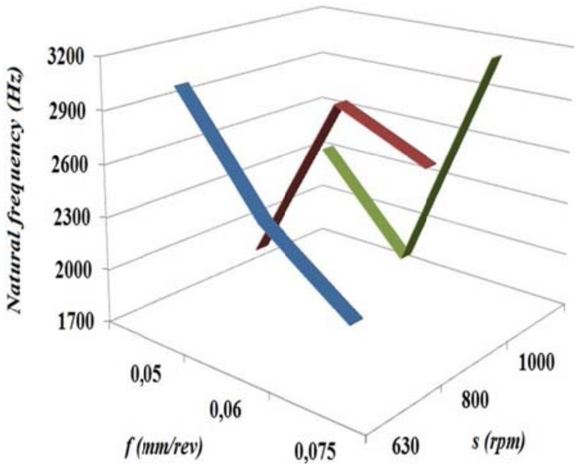


(b)

Fig. 9 Relationship between natural frequency, feed rate (f) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite

TABLE V
ANOVA FOR R_a OF ALUMINUM ALLOY AA2024 FOR CONVENTIONAL 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 VI
ANOVA FOR R_a OF ALUMINUM ALLOY AA2024 FOR CUTTING TOOL FILLED UP WITH EPOXY GRANITE

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	0.0031176	0.0015588	1.2545	0.446	25.00
Feed rate	2	0.0029482*	0.0014741	1.1863	0.462	24.00
Depth of Cut	2	0.0020222*	0.0010111	0.8137	0.562	16.50
Overhang	2	0.0042409	0.0021204	13.8022	0.346	34.50
Error	0	0	0			
Total	8	0.01252306				100
(error)	(4)	0.00497040	0.0012426			

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

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

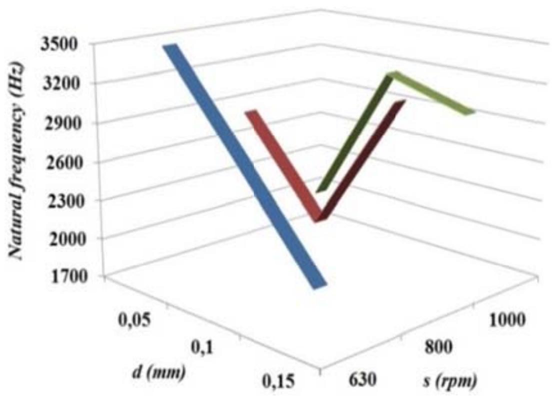
Experiment No.	A	B	C	D	Natural frequency for conventional cutting tool (Hz)	S/N ratio (dB)	Natural frequency for cutting tool filled up with epoxy granite (Hz)	S/N ratio (dB)
1	1	1	1	1	3491.2	-70.8595	3039.6	-69.6563
2	1	2	2	2	2771.0	-68.8527	2417.0	-67.6655
3	1	3	3	3	2038.6	-66.1866	2050.8	-66.2385
4	2	1	2	3	2148.4	-66.6423	1928.7	-65.7053
5	2	2	3	1	3198.2	-70.0981	2917.5	-69.3002
6	2	3	1	2	2868.7	-69.1537	2685.5	-68.5805
7	3	1	3	2	2978.5	-69.4800	2392.6	-67.5774
8	3	2	1	3	2038.6	-66.1866	1843.1	-65.3119
9	3	3	2	1	3173.8	-70.0316	3155.5	-69.9814

As seen from Fig. 11 increase in tool overhang from 41 to 65 mm decreases the natural frequency values linearly at all levels of spindle speed from 800 to 1000 rpm. At 41 mm tool overhang due to 630 rpm spindle speed the highest natural frequency value was observed using conventional cutting tool, while the smallest value of natural frequency was obtained at 1000 rpm spindle speed due to 65 mm tool overhang using cutting tool with epoxy granite in turning of AA2024. During the experiments it was also noticed that the smallest value of natural frequency was obtained at highest spindle speed (1000 rpm) for both cutting tools (Table VII).

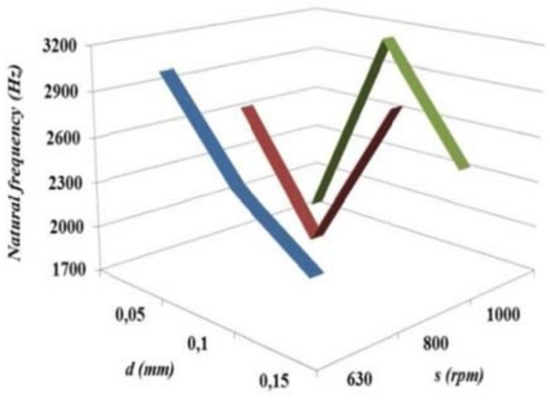
Fig. 12 shows the S/N ratios graphs for natural frequency for both cutting tools calculated by (1). Fig. 12 indicates a much stronger influence of tool overhang on the natural frequency than the other three parameters using both cutting tools in turning of AA2024. Using Fig. 12 and Table VII the optimum combinations of cutting parameters for natural frequency are $A_3B_2C_2D_3$ and $A_3B_2C_3D_3$ for conventional cutting tool and cutting tool with epoxy granite, respectively. Predicted S/N ratios and natural frequency values obtained under optimum conditions are -65.9622 dB and 1986.59Hz, respectively, for conventional cutting tool and -65.1677 dB and 1774.13 Hz, correspondently, for cutting tool with epoxy granite.

In Tables VIII and IX, the results of ANOVA are given to determine statically the effect of each parameter on natural frequency during machining of AA2024. The results of ANOVA analysis indicate that the most effective variable for natural frequency in turning of AA2024 is tool overhang with 96.12% and 96.6% for conventional cutting tool and cutting tool with epoxy granite, respectively. However, the other variables that have effect on natural frequency is feed rate with 3.122% and 4.8% for conventional cutting tool and cutting tool with epoxy granite, respectively.

After determining the optimum cutting condition and evaluating the influence of cutting condition, tool construction and epoxy granite on surface roughness and natural frequency it was observed that the surface roughness and natural frequency values obtained by cutting tool with epoxy granite are less than those of obtained by conventional cutting tool (Tables IV and VII). Therefore, it can be concluded that new cutting tool, which is filled up with epoxy granite has increased the damping capability of the tool compared to the conventional cutting tool. This can be explained by the fact that vibration waves, in the heterogeneous structure of the new cutting tool, pass through the mediums: metal–damping material–metal–damping material. Thus, because of the heterogeneous structure of the tool and damping capability of epoxy granite, vibration occurred during machining process is suppressed, partially reflected and their direction is changed. Consequently, vibrations are damped, which reduces the relative motion between cutting tool and work piece leading to an improved surface quality during machining process. Additionally, ANOVA results revealed that the most significant parameter affecting the surface roughness is spindle speed followed by depth of cut for conventional cutting tool, while this variable is tool overhang followed by spindle speed, feed rate and depth for cutting tool with epoxy granite. Natural frequency is mostly influenced by tool overhang for both cutting tools. Moreover, during machining using both cutting tools, the need to choose higher spindle speed and tool overhang was revealed to obtain the small values of natural frequency.

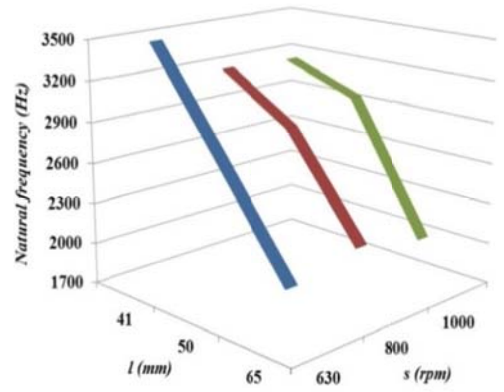


(a)

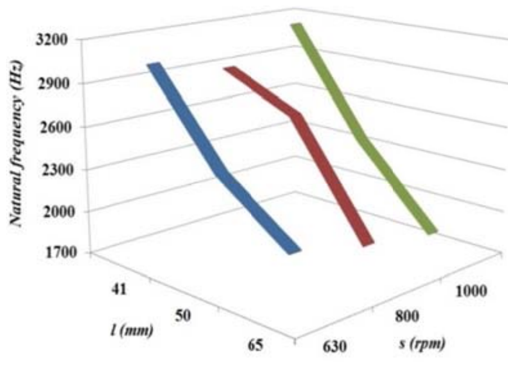


(b)

Fig. 10 Relationship between natural frequency, depth of cut (d) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite

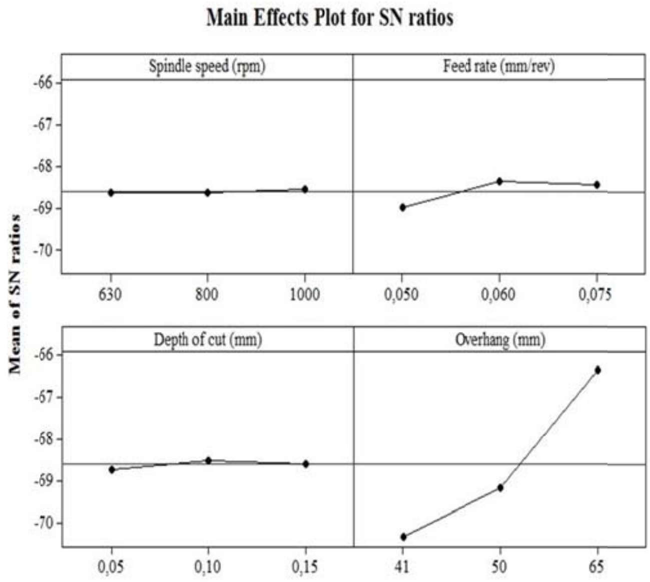


(a)

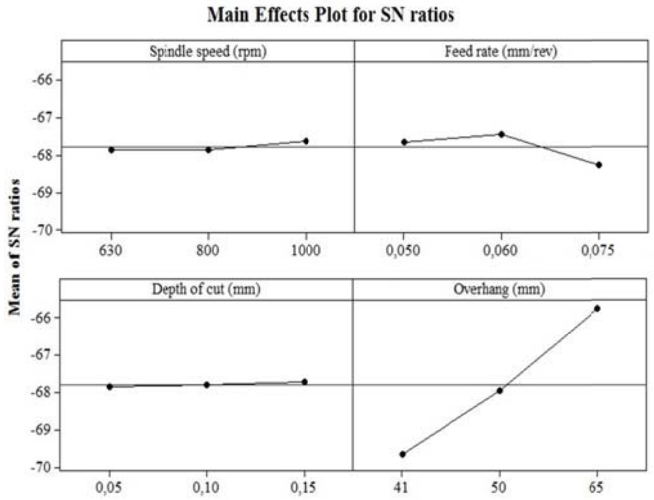


(b)

Fig. 11 Relationship between natural frequency, tool overhang (l) and spindle speed (s) in turning of aluminum alloy AA2024 with: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite



(a)



(b)

Fig. 12 Maine effect plots for S/N ratios of natural frequency for: (a) conventional cutting tool and (b) cutting tool filled up with epoxy granite

TABLE VIII
ANOVA FOR NATURAL FREQUENCY FOR CONVENTIONAL 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 IX
ANOVA FOR NATURAL FREQUENCY FOR CUTTING TOOL FILLED UP WITH EPOXY GRANITE

Source	Degree of Freedom	Sum of squares	Mean of squares	F ratio	P value	% of Total
Spindle Speed	2	3748*	1874	0.6680	0.996	0.2
Feed rate	2	91686	45843	16.342	0.906	4.8
Depth of Cut	2	7473*	3736	1.3317	0.860	0.4
Overhang	2	1803964	901982	321.53	0.003	96.6
Error	0	0	0			
Total	8	1906871				100
(error)	(4)	11221	2805.25			

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

C. Confirmation Test

In Taguchi method, the confirmation run at the predicted optimum condition is suggested in order to verify the optimum cutting condition obtained by using S/N ratios and ANOVA. For this purpose, the 95% confidence band for confidence interval (CI) was chosen to perform the confirmation run. The CI is calculated using (4) and (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, $F_{0.05}(1, f_e)$ represents the F value from statistic table at 95% confidence level. f_e is the degree of freedom of error, 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.

The results for R_a and natural frequency (f) obtained by confirmation runs at optimum levels were compared to the predicted ones using (2) and (3), which are illustrated in Tables X and XI. If the difference between calculated S/N ratio and S/N ratio obtained in experimental results is within CI value, then the optimum combination of cutting parameters are considered valid.

At the 95% confidence level, the CIs of R_a calculated according to the (4) and (5) are ±0.2193 dB and ±0.1384 dB for conventional cutting tool and cutting tool with epoxy granite, respectively. Similarly, the CIs of natural frequency are ±263.18 dB and ±207.96 dB for conventional cutting tool and cutting tool with epoxy granite, correspondently. As seen from Tables X and XI the calculated errors are within CIs values, thus the optimal levels of cutting variables can be validated.

IV. CONCLUSION

The present work is concerned with exploring to determine the effect of composite material with high damping capacity and the optimum cutting condition for surface roughness and natural frequency during turning of aluminum alloy AA2024 using TiC coated carbide insert and two different cutting tools made of AISI 5140. A novel model of cutting tool is proposed, which has staggered holes filled up with epoxy granite in tool holder. Experiments were planned on the basis of Taguchi method L9 orthogonal array. Then, according to the experimental data, the effect of each cutting parameter, optimal cutting parameters and optimal values of the Ra and natural frequency were determined using S/N ratio and ANOVA results. Finally, confirmation experiments were carried out at the predicted optimum condition obtained by Taguchi method in order to verify the effectiveness of the Taguchi technique. The results are summarized as follows:

- Taguchi gives systematic simple approach and efficient method for the optimum machining conditions, which makes it as a powerful method to design and analyze the experimental results in machining researches.
- The smallest R_a values obtained in turning of AA2024 are 0.814 µm and 0.575 µm for conventional cutting tool and cutting tool with epoxy granite, respectively.
- The smallest natural frequency values occurred in turning of AA2024 are 2038.6 Hz and 1843.1 Hz for conventional cutting tool and cutting tool with epoxy granite, correspondently.

- The R_a is mostly influenced by spindle speed with 81.301% for conventional cutting tool, while this variable is tool overhang with 34.5% followed by spindle speed, feed rate, depth of cut with 25%, 24% and 16.5%, respectively, for cutting tool with epoxy granite.
- Tool overhang is the factor that significantly affects natural frequency with 96.12% and 96.6% for conventional cutting tool and cutting tool with epoxy granite, respectively.
- The new proposed design of cutting tool has decreased the R_a and natural frequency values compared to conventional cutting tool due to its heterogeneous structure and high damping capability of epoxy granite.

TABLE X
COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED RESULTS OF R_a

Cutting tool	Experimental results		Predicted results		Differences	
	$R_{a\exp}$, μm	$\eta_{\exp}$, dB	R_{apred}, μm	η_{pred}, dB	$R_{a\exp}$- R_{apred}	$\eta_{\exp}$- η_{pred}
Conventional cutting tool	0.765	2.327	0.748	2.52300	0.017	-0.196
Cutting tool with epoxy granite	0.542	5.320	0.531	5.420	0.011	-0.1

TABLE XI
COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED RESULTS OF NATURAL FREQUENCY

Cutting tool	Experimental results		Predicted results		Differences	
	$f_{\exp}$, Hz	$\eta_{\exp}$, dB	f_{pred}, Hz	η_{pred}, dB	$f_{\exp}$- f_{pred}	$\eta_{\exp}$- η_{pred}
Conventional cutting tool	2142.3	-66.617	1986.59	-65.9622	155.71	-0.6548
Cutting tool with epoxy granite	1934.6	-66.134	1774.13	-65. 731	160. 74	-0.4030

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