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Research article

Experimental and Numerical Investigation of Effective Parameters in Milling Process of 7075 Aluminum Alloy Using Taguchi Method

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Abstract

In the present research, the effective parameters in the milling process of 7075 aluminum alloy were investigated in both experimental and numerical methods. In this regard, cutting depth, feed rate, spindle rotational speed and number of tool teeth were considered as input parameters of the experiment. Then, the effect of these factors on cutting force, surface roughness and machining temperature was investigated using Taguchi design of experiment. Next, the obtained output results were evaluated using the signal-to-noise (S/N) method. Also, the numerical simulation of the milling process was carried out using the finite element method in Deform-3D software. Finally, a comparative study of numerical and experimental results was performed on the cutting force. The results showed that feed rate and depth of cut had the greatest effect on cutting force and surface roughness. Rotational speed also has the greatest effect on machining temperature. The optimal levels of the parameters to reduce the cutting force were the cutting depth of 1 mm, feed rate of 8 mm/min, rotational speed of 200 rpm and number of tool teeth of 2. Moreover, the cutting depth of 1 mm, feed rate of 8 mm/min, rotational speed of 400 rpm and number of tool teeth of 3 were considered as the optimal levels to reduce the surface roughness. The results obtained from the numerical analysis of the milling process regarding the cutting force were in good agreement with the experimental results of the process.

Keywords: Milling, 7075 aluminum alloy, Finite element method, Cutting force, Surface roughness, Taguchi.

1- Introduction

7075 aluminum alloys are widely used in the manufacture of various parts in the aerospace and military industries due to their high strength to weight as compared to steel materials. The high flexibility of aluminum alloys causes many problems in their machining, which can be mentioned such as increased machining force, decreased surface roughness and difficult control of chips during the machining process. Also, the presence of silicon in these alloys causes tool wear. During aluminum machining, in the contact area, a continuous and long chip with a large thickness is formed, which increases the machining forces, machining power, heat generation and low surface quality [1]. For this purpose, to investigate the behavior of aluminum machining, parameters such as forces, stresses, energy consumption, temperature, surface integrity, tool wear, cutting fluid and chip control should be considered. Due to the importance and widespread use of 7075 alloy in many industries, various researches have been conducted on the machining of this alloy. Sequeiera et al. [2] investigated the effect of machining parameters including spindle speed, feed and depth of cut on the surface roughness of AA7075. It was found that the spindle speed and feed were significant as compared to the depth of cut. Escalona and Maropoulos [3] presented a model for high-speed milling of Al 7075-T7351, considering factors such as cutting speed, feed per tooth, depth of cut and tool radius. Pour and Torabizadeh [4] presented a model for the experimental testing of Al 7075-T6 machining using time series analysis to predict dynamic machining forces and surface texture. Pinar et al. [5] investigated the effects of cutting speed, feed rate, depth of cut, and tool tip radius on surface roughness and its optimization through the Taguchi method. Karabulot et al. [6] investigated experimentally and optimized cutting force and tool wear in Al 7075 milling. The results showed that cutting depth and feed rate had the greatest effect on cutting force and tool wear, respectively. Najiha et al. [7] used the minimum lubricant method in the machining of Al 6061-T6. In this research, the effect of parameters such as spindle rotational speed, cutting depth and feed rate on surface roughness was investigated. According to their results, the surface roughness was significantly dependent on the depth of cut, the feed rate, and then the rotational speed. Tsai et al. [8] presented a model for predicting cutting force and cutting coefficient in milling Al 6060-T6. In this research, increasing the feed for each tooth increased the cutting force and decreased the cutting coefficient for cutting forces in the tangential direction. Nurhaniza et al. [9] investigated the effect of machining parameters on the surface roughness of the workpiece in the milling process of aluminum reinforced with carbon fiber. Optimal cutting parameters were determined to achieve high surface roughness, high cutting speed, feed rate and low cutting depth. Kulkarni et al. [10], using full factorial design and analysis of variance, investigated the effect of the cooling method with minimum lubricant instead of the traditional fluid cooling method in milling aluminum Al 7075-T6. Spindle speed, feed rate and depth of cut were selected as machining parameters. The results showed that among the three cooling supply methods, the minimum lubrication method provided better results compared to dry milling and minimum lubrication with nanofluid in terms of surface roughness. Sahoo et al. [11] investigated the dry machining performance of Al 7075-T6 using uncoated and coated TiCN-Al_2O_3 carbide tools. Cutting force, tool tip temperature and tool wear rate were the factors evaluated in this research. They found that the coated tool resulted in higher cutting force, lower tool temperature and lower tool wear compared to the uncoated tool.

According to the review studies, less research has been conducted in the field of simulating the milling process of Al 7075-T6 using finite element analysis and validating the results [12]. Also, in the studies, the effect of the number of tool teeth in the aluminum alloy milling process is less mentioned. Therefore, in the present study, a numerical and experimental investigation of the milling process of Al 7075-T6 was carried out. In this regard, input parameters including cutting depth, feed rate, spindle rotational speed and the number of tool teeth were considered. Next, the effect of these factors on the output parameters such as cutting force, surface roughness and temperature of the machining area were investigated using Taguchi design of experiment. Moreover, the output results of the experiments were evaluated using signal-to-noise (S/N) analysis. Finally, the numerical simulation of the process was carried out using the finite element method in Deform 3D software, and a comparative study of the numerical and experimental results of the process was also carried out on the cutting force.

2- Materials and methods

2-1 Materials

The workpiece used in the research was selected from Al 7075-T6 aluminum alloy. The sample was cut by the sawing process to the dimensions of 95*95*10 mm. The chemical composition of Al 7075-T6 aluminum alloy is given in Table 1.

Table 1: Chemical composition of used Al 7075-T6 aluminum alloy

%Al± 0.1	%Cr±0.007	%Cu±0.013	%Mg±0.681	%Zn±0.020
87.1	0.174	1.586	2.693	5.240

2-2 Experimental method

Fig. 1 (a) shows a view of the equipment prepared for the milling process. A milling machine (FP4M, Tabriz Machining Com.) was used to carry out the tests. To measure the machining forces, a dynamometer (Kistler, model b9265) installed on the milling machine table was used. Also, the surface roughness of the machined samples was measured by a roughness tester (MARSURF, model M300). Fig. 1 (b) shows the end mill tools (Janpo Taiwan (X series)) used for the milling process. The specifications of end mill tools are given in Table 2.

(a)

(b)

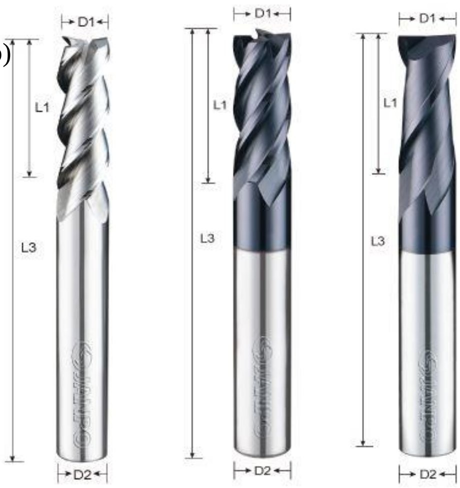

Fig. 1 A view of: (a) equipment prepared for the milling process and (b) end mill tools used in the research.

Table 2: Specifications of the used tools

Tools	Material	Tool diameter (mm)	Tool length (mm)	Tool flute length (mm)	Number of teeth
End mill	Tungsten carbide (WC)	10	75	25	2
					3
					4

In the present research, the machining parameters including the rotational speed of the spindle, the feed rate, the depth of cut and the number of tool teeth were considered as input parameters. Table 3 shows the factors with their levels. The design of experiments was carried out using Mini Tab statistical software based on the Taguchi method with L_9 array to investigate the cutting force and surface roughness. Next, parameter levels were optimized based on signal-to-noise (S/N) analysis (smaller is better).

Table 3: The input parameters with their levels.

Parameters	Level 1	Level 2	Level 3
Spindle rotational speed (rpm)	200	400	630
Feed rate (mm/min)	8	12	20
Depth of cut (mm)	1	1.5	2
Number of tool teeth	2	3	4

2-3 Numerical method

Simulation of the milling process of Al 7075-T6 aluminum alloy was carried out in Deform 3D software based on finite element method. In this way, the machining tool and workpiece were defined as three-dimensional rigid and deformable, respectively. The workpiece material was considered as Al 7075. Fig. 2 (a) shows the schematic model of the tool and workpiece in the machining process. Machining parameters were also adjusted in the software based on the mentioned experimental design during 9 tests. To define the boundary conditions, the bottom surface of the workpiece was fixed in the X, Y and Z directions and the movement of the milling tool was defined in the Y direction. Also, the machining conditions, including temperature and friction conditions were applied according to Table 4. The tetrahedral mesh and the number of elements of 17500 were used for the workpiece. The simulation time of the process was considered to be 9000 s. The chip formation mechanism from the workpiece in the milling process is shown in Fig. 2 (b).

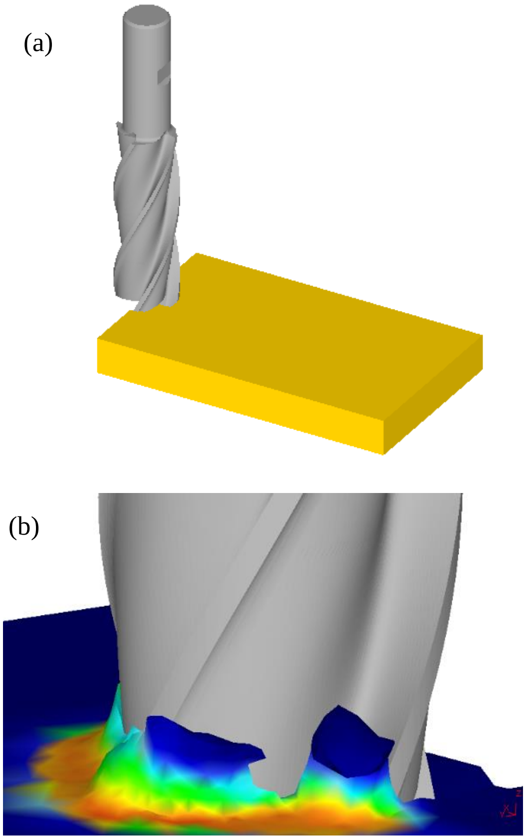

Fig. 2 (a) 3D model of tool and workpiece to simulate the machining process and (b) chip formation mechanism during the milling process.

Table 4: Machining conditions to simulate the milling process.

Parameters	
Ambient temperature (°C)	25
Convection coefficient between the tool and environment (N/sec/mm/°C)	0.02
Coefficient of friction	0.3
Heat transfer coefficient between the tool and workpiece (N/sec/mm/°C)	45

3- Results and discussion

The experimental results for the milling process of Al 7075 workpiece are given in Table 5.

Table 5: Experimental results for the milling process of Al 7075 workpiece based on Taguchi method.

	Machining parameters				Output results	
Test No.	Rotational speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Number of tool teeth	Cutting force (N)	Surface roughness (μm)
1	200	8	1	2	2.4604	0.215
2	400	12	1	3	12.3020	0.207
3	630	20	1	4	26.6044	0.270
4	630	8	1.5	3	9.8416	0.252
5	200	12	1.5	4	31.9852	0.295
6	400	20	1.5	2	44.2872	0.315
7	400	8	2	4	29.5248	0.303
8	630	12	2	2	38.9060	0.340
9	200	20	2	3	78.3516	0.406

3-1 Experimental investigation of cutting force

Fig. 3 shows the signal-to-noise (S/N) plots of the effect of main parameters on the cutting force based on the smaller is better. As can be seen, with the increase in the feed rate, the amount of cutting force was increased. The increase in cutting force with increasing feed rate can be attributed to the increase in the amount of friction between the cutting edge and the workpiece [13]. Moreover, the cutting force was increased by increasing the depth of cut. In fact, by increasing the cutting depth, the contact area between the cutting edge and the workpiece increases, which increases the cutting force [14]. It can also be seen that the factors of the number of tool teeth and the rotational speed of the spindle had less effect on the cutting force. Mehdi and Zghal [15] also found that the number of tool teeth did not affect on the cutting force in the milling process of steel. The contribution of each parameter on the cutting force is also shown in Fig. 4. The feed rate and depth of cut exhibited the greatest effect (39%) on the cutting force.

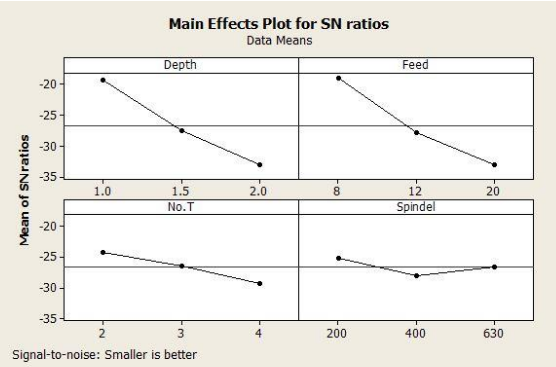

Fig. 3 The signal-to-noise plots of the effect of main parameters on the cutting force.

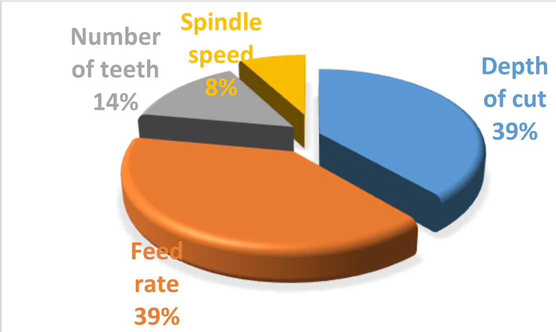

Fig. 4 The contribution of parameters on the cutting force in the milling process of Al 7075.

3-2 Experimental investigation of surface roughness

Fig. 5 shows the signal-to-noise diagram of the effect of the main parameters on the surface roughness based on the smaller-better criterion. As can be seen, with the increase in the depth of cut, the surface roughness was increased. This can be due to the increase of the chatter phenomenon at high cutting depth values. Moreover, the surface roughness was increased with the increase of the feed rate. In fact, with an increase in the feed rate, the friction on the surface of the tool increases, which leads to a decrease in the surface roughness [16]. Some researchers have also considered the increase in the surface roughness by increasing the feed rate can be related to the increase in the chatter, which has a negative effect on the surface roughness [17]. It can also be seen that the spindle rotational speed factor and the number of tool teeth had less effect on the surface roughness. The contribution of each parameter on the surface roughness is also shown in Fig. 6. The depth of cut had the greatest effect (52%) on the surface roughness.

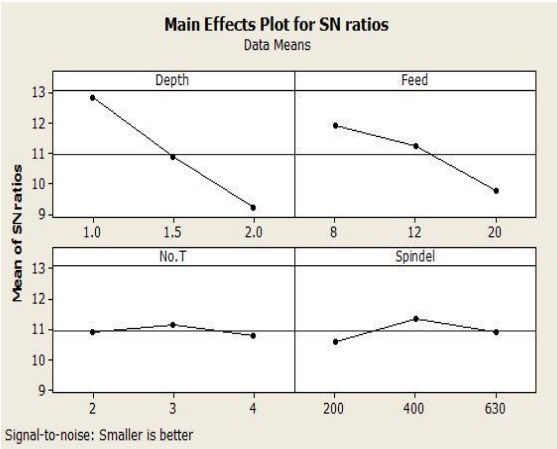

Fig. 5 The signal-to-noise plots of the effect of main parameters on the surface roughness.

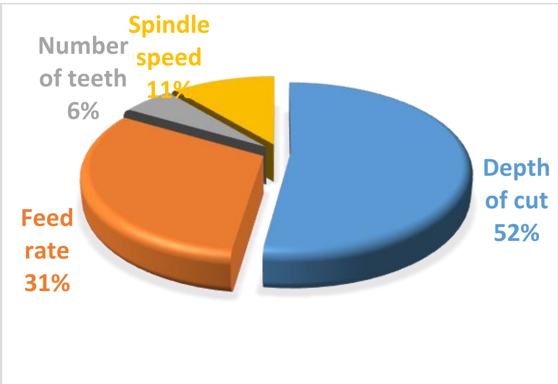

Fig. 6 The contribution of parameters on the surface roughness in the milling process of Al 7075.

3-3 Numerical investigation of cutting force

In the simulation process, the force in the machining direction of Y axis was measured according to the 9 tests based on Taguchi's experimental design. Fig. 7 shows the force-time diagram in the time interval from 0 to 0.003 seconds in two experimental and numerical methods for the third test. According to the figure, the average force value in both experimental and numerical methods is equal to 26.303 N and 24.607 N, respectively, which has a difference of 5.5%. Also, the comparison of cutting force in two experimental and numerical methods is shown in Fig. 8. As can be seen, the simulation results for the cutting force are in good agreement with the experimental results.

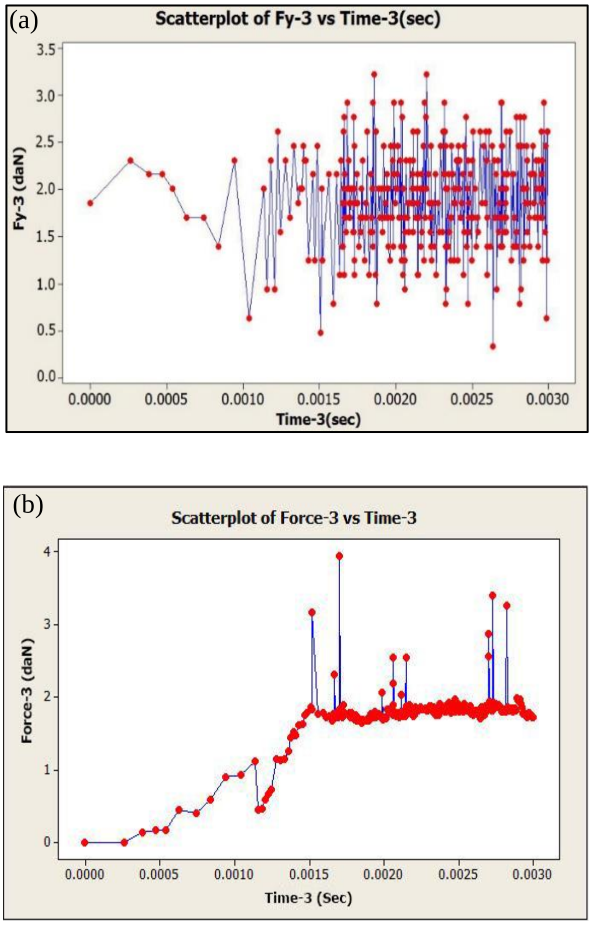

Fig. 7 Force-time diagram in the milling process of Al 7075 workpiece for the third test of Taguchi experimental design: (a) experimental method and (b) numerical method.

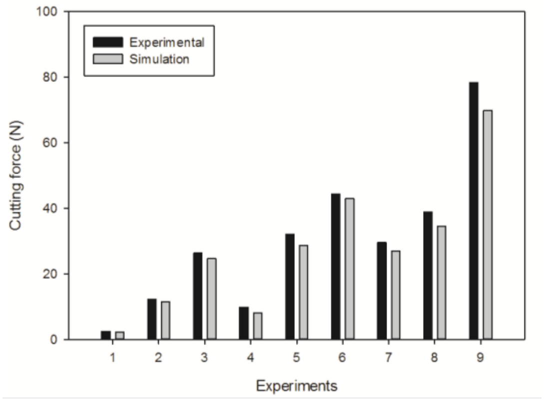

Fig. 8 Comparison of cutting force in two experimental and numerical methods.

3-4 Numerical investigation of machining temperature

Fig. 9 shows the measured temperature of the workpiece in the numerical investigation of Al 7075 machining for 9 tests based on Taguchi method. The signal-to-noise diagram of the effect of the main parameters on the average machining temperature based on the smaller is better criterion is shown in Fig. 10. As can be seen, the temperature value was decreased with the increase of the rotational speed of the spindle. In fact, with the increase in rotational speed, there is not enough time to transfer heat from the chip to the tool and the workpiece, and the chip quickly moves away from the workpiece. Moreover, with the increase in depth of cut and feed rate, the amount of cutting heat was also increased due to the increase in the volume of the undeformed chip [18]. The contribution of each parameter on the machining temperature is shown in Fig. 11. The rotational speed of the spindle had the greatest effect (46%) on the machining temperature. It can also be seen that the factor of the number of tool teeth had no significant effect on the machining temperature.

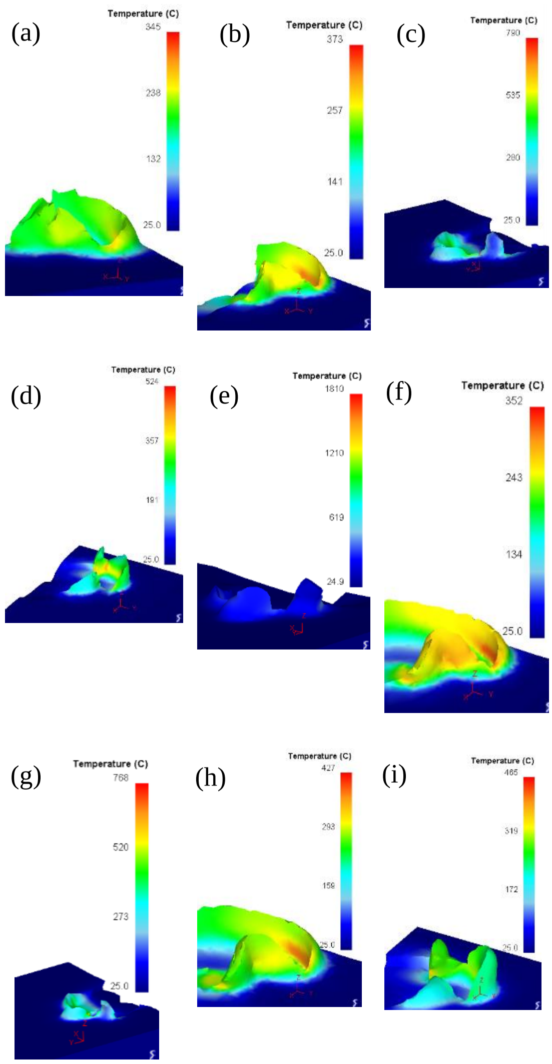

Fig. 9 Temperature measurement of the workpiece in the numerical investigation of Al 7075 machining: (a) Test 1 (b) Test 2 (c) Test 3 (d) Test 4 (e) Test 5 (f) Test 6 (g) Test 7 (h) Test 8 and (i) Test 9.

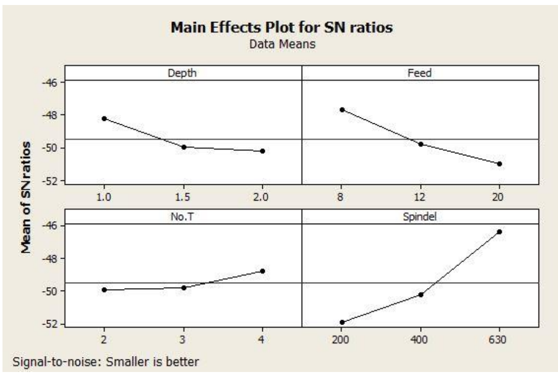

Fig. 10 Signal-to-noise diagram of the effect of main parameters on machining temperature based on the smaller is better criterion.

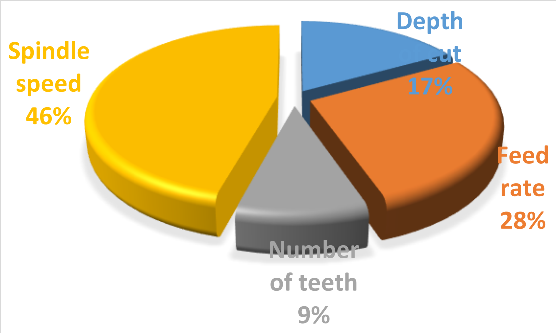

Fig. 11 The contribution of parameters on the machining temperature in the milling process of Al 7075 workpiece.

4- Conclusions

In this research, experimental and numerical analysis of the factors affecting the milling process of Al 7075 was carried out. The input parameters of cutting depth, feed rate, spindle rotational speed and the number of tool teeth were considered. Next, using Taguchi L_9 method, the effect of the above factors on the three parameters of cutting force, surface roughness and machining temperature was investigated. Also, using Taguchi signal-to-noise analysis, the most influential variable and its optimal level for each output were determined. The results of the research are as follows:

- Depth of cut and feed rate exhibited the greatest effect on the cutting force and surface roughness. However, spindle speed had the largest effect on the temperature.
- Number of tool teeth had no significant effect on the cutting force, surface roughness and temperature.
- Based on the signal-to-noise analysis, the optimal levels of depth of cut and feed rate for the cutting force, surface roughness and temperature were 1 mm and 8 mm/min, respectively.
- Based on the signal-to-noise analysis, the optimal level of spindle rotational speed and number of tool teeth for the cutting force, surface roughness and temperature were [200 rpm, 2], [400 rpm, 3] and [630 rpm, 4], respectively.
- The cutting force values for 9 tests in the numerical method are in good agreement with the experimental method. The average error lower than 10 % can be attributed to the vibrations of the milling process.

Declaration of Conflicting Interests

The Author(s) declare(s) that there is no conflict of interest.

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