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Application of experimental data based on Taguchi approach to optimize machining parameters of Al6061-T6 to reduce cutting forces and moments

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Conflicts of interest
The authors declare that there is no conflict of interest.

Abstract. The requirements for the quality and accuracy of manufactured products are constantly increasing. Reliability, durability, and accuracy of machine operation largely depend on the quality of surface treatment. Study on the cutting process, in particular milling, makes it possible to find out the operating conditions of the cutting tool, determine the acting cutting forces, torques, vibrations and temperatures on it. Along with studying the influence of various parameters on the milling process, it is necessary to pay special attention to establishing the nature and degree of influence of the cutting condition (cutting speed, depth of cut and feed rate). In this paper milling operation of Al6061-T6 was performed in a dry condition. The effects of cutting parameters on cutting forces and moments in different directions and around various axes were studied. By applying Taguchi technique and performing experiments, it was shown that cutting force was significantly affected by feed rate followed by rotational speed and cutting depth. Cutting moment is mainly influenced by feed rate, cutting depth, and rotational speed. Moreover, feed rate is the most effective factor on minimizing cutting forces and moments. Finally, the optimum cutting parameters was revealed to get a minimum cutting forces and moments.

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Использование метода Тагучи при обработке Al6061-T6 с целью уменьшения сил и моментов резания

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алюминиевый сплав, фрезерование, режим обработки, метод Тагучи, сила резания, вибрация

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Требования к качеству и точности выпускаемой продукции постоянно повышаются. От качества обработки поверхностей во многом зависят надежность, долговечность и точность работы машин. Изучение процесса резания, в частности фрезерования, позволяет выяснить режимы работы режущего инструмента, определить действующие на него силы резания, моменты, вибрации и температуры. Наряду с изучением влияния различных параметров на процесс фрезерования необходимо особое внимание уделить установлению характера и степени влияния режима резания (скорости резания, глубины резания и скорости подачи). Выполнена фрезеровка заготовки из Al6061-T6 в сухом состоянии. Исследовано влияние параметров резания на силы и моменты резания в различных направлениях и вокруг различных осей. Применяя метод Тагучи и проводя эксперименты, было показано, что на силу резания существенно влияет подача, скорость резания и глубина резания. На момент резания в основном влияют подача, глубина резания и скорость резания. Кроме того, подача является наиболее эффективным фактором для минимизации сил и моментов резания. Наконец, были выявлены оптимальные параметры резания для получения минимальных сил и моментов резания.

Для цитирования

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Introduction

One of the most important criteria in the machining of aluminum and its alloys is the cutting force, which determines the energy costs and consumed power. This may lead to deflection-based surface errors and regenerative chatter, negatively affecting the quality and productivity [1]. Moreover, different parameters such as vibrations, cutting tool geometry and properties, workpiece materials and properties, cutting parameters and cutting conditions influence the cutting force and surface roughness [2]. Hence, achieving high-quality performance and improved production costs in milling operation is possible by controlling and optimising cutting parameters and defining the rate of their impact on the cutting force. Pham et al. have used Taguchi technique and ANOVA analysis to investigate the effects of cutting parameters on the cutting force in high-speed milling of Al6061 aluminum alloy [3]. Elssawi et al. have optimised cutting parameters to reach the minimum cutting forces and the best level of the surface toughness in milling of Al6061 using Taguchi method [4]. Some scholars have stated that increasing the cutting speed decreases the shear stress in the primary shear zone and in the flow zone at the secondary shear region which is related to the cutting temperature [5; 6]. Furthermore, the machining forces are reduced regardless of the strength of the aluminum alloy [7; 8]. As it is related to the high-speed cutting, the machining forces increase with an excessive increase in the deformation rates [9–11]. Moreover, an increase in the depth of cut and/or feed rate leads to an increase in the primary and secondary areas of shear planes, which prevents material shearing and increases the machining forces [7; 8;

12]. Campatelli and Scippa proposed a new model to predict the milling cutting force by studying the effects of cutting speed and feed per tooth on the cutting coefficients of the aluminum alloy 6082-T4 [13]. Zatarain et al. employed Continuous Spindle Speed Variation (CSSV) technique to model milling processes, optimize parameters of the speed variation, reduce the vibration level in milling, and improve the surface quality [14]. Tsai et al. investigated the influence of the tool diameter and the feed per tooth on the milling cutting force and cutting coefficients of aluminum 6060-T6 [15]. Stepan et al. predicted cutting force coefficients in milling as a nonlinear function of cutting speeds, chip loads, and material imperfections [16]. Irene et al. have experimentally studied the effects of the cutting speed, feed rate, and cutting depth on the cutting forces and on the surface quality of the aluminum alloys as a machined part [17].

As can be seen from the literature review, an accurate and effective cutting force and its model are needed to monitor, plan, and control the milling operations of aluminum alloys. Therefore, it is necessary to conduct an in-depth study on the influence of cutting parameters on the cutting forces and moments during the milling of Al6061-T6, which is one of the most widely used 6xxx series aluminum alloys. To this end, experiments were planned utilising Design of Experiment technique, using the signal-to-noise ratio as the result of Taguchi sensitivity analysis, and the influence of each parameter on the cutting forces and moments was statically determined.

1. Experimental works

1.1. Material and specimen

The studied material was 6xxx series aluminum alloy sheets with dimensions of 150 mm ×90 mm ×10 mm, prepared by a casting process. A quantometric test was performed to extract the percentage of constituent elements of the raw material Al 6061 (Table 1). Next, the conventional T6 heat treatment of Al 6061 alloy [18] was used for the preparation of the specimens, as shown in Figure 1.

Table 1

Chemical composition of 6xxx series aluminum alloy, wt%

Al	97.7
Si	0.57
Fe	0.36
Cu	0.21
Mn	0.02
Mg	0.98
Ni	0
Ti	0
Cr	0.16

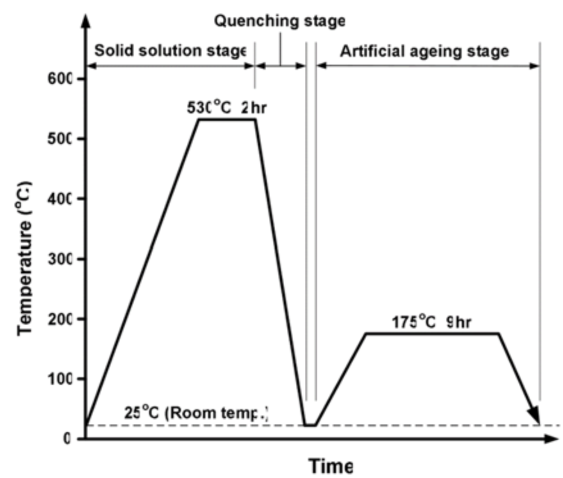


Figure 1. The conventional T6 heat treatment of Al 6061 alloy [18]

1.2. Milling operation

In this study, the specimen (150 mm ×90 mm ×10 mm) was connected to a dynamometer using two M8 screws to measure the cutting forces and moments during machining. To start the milling process, rotational speed, feed rate, cutting depth are set at 1000 rpm, 200 m/min and 1 mm, respectively. Moreover, the start point of milling is $x = 0$, $y = 22$, $z = -1$ and the end point is related to $x = 35$. Therefore, the path of the tool movement was in the x direction. The size and location of the cutting area are shown in Figure 2. In addition, lubrication was not used in the milling process. In this study, a KISTLER dynamometer made in Switzerland (type 9257B) was used to measure the time history of the cutting forces in different directions (F_x, F_y, and F_z). The sensors and measurements were calibrated so

Table 2

Machining parameters and their levels

Cutting Parameter	Level 1	Level 2	Level 3
Cutting depth, mm	1	1.5	2
Rotational speed, rpm	1000	1500	2000
Feed rate, m/min	200	300	400

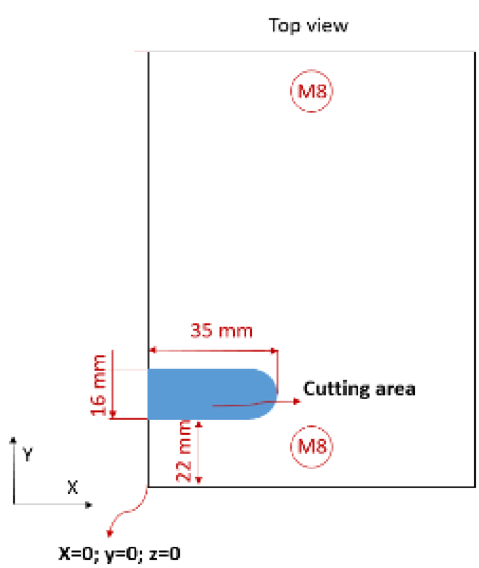
that the uncertainty in loading was 0.053, 0.05, and 0.056 for the *x*-, *y*-, and *z*-directions, respectively. All steps of advice calibration were performed at an ambient temperature of 24°C and a relative humidity of 36 %. In addition, a new specific cutting tool (KORLOY Inc., Korea) was used for each milling process (Figure 3, *a*) to avoid tool wear effects on the experimental results. Moreover, the tool holder was the cylinder with non-uniform cross-section. The cross-sectional diameter of the end of the tool holder tied to the machine is 16 mm, and the other side of the tool holder to which the tool tied is about 13.3, and the height of the cylinder is 120 mm (Figure 3, *b*). Finally, it should be noted that 2/3 of the height of the tool holder is closed inside the machine and 1/3 is free.

1.3. Design of Experiments by Taguchi method

To study the effect of the process parameters on the cutting forces, the milling process and force measurement for different proposed modes were performed using Taguchi Approach (TA) [19–23]. To this end, the cutting depth (a_p), the feed rate per tooth (f_z), and the rotational speed (V_c) were considered as variables (Table 2). In this regard, the settings of the milling process parameters were considered in accordance with Table 3. The distance between the two cutting areas was 6 mm and the cuttings were performed in two rows. In other words, to cut the second row, it is necessary for the tool to move in the *X*-direction by a negative value of 35 mm (Figure 4).

a *b*

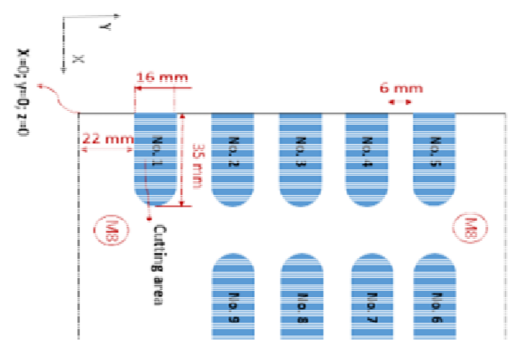
Figure 3. *a* — Special cutting tools,
b — tool holder as equipment used in this experiment



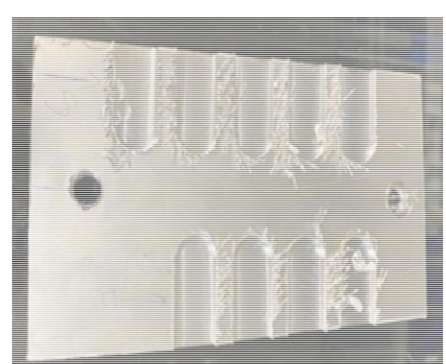
a

b

Figure 2. Size and location of the cutting area:
a — in the schematic form; *b* — in real terms



a



b

Figure 4. *a* — a general schematic of all tests;
b — in real terms

Table 3

Variables and their levels used as input data in the TA

Experiment No.	1	2	3	4	5	6	7	8	9
Cutting depth, mm	1	1	1	1.5	1.5	1.5	2	2	2
Rotational speed, rpm	1000	1500	2000	1000	1500	2000	1000	1500	2000
Feed rate, m/min	200	300	400	300	400	200	400	200	300

2. Results and discussion

To record the output data, including the forces and moments in different directions, the sampling rate and recording time in the dynamometer software were set at 200 Hz and 10 seconds, respectively. The results of the first test mode of F_z are shown in Figure 5. Statistical information, including values of maximum, minimum, mean, and standard deviation, were calculated from the recorded data and are reported as force and moment factors in Tables 4 and 5, respectively. It is clear from Table 4 that the maximum and minimum values of the force history in the X- and Y-directions are approximately the same for all tests, and only F_z changed dramatically in the various tests. Therefore, in the next steps, the focus will be on the Z-force component. Similarly, based on the data in Table 5, the moment around the X- and Y-axes will be considered in future studies. Moreover, increasing the cutting speed resulted in a decrease in the cutting force and moment this phenomenon can be explained by the fact that as the cutting speed increases, the workpiece material (in our case, Al6061-T6) is affected by thermal softening owing to the increased temperature and reduced flow stress in the primary shear zone. Based on the results obtained from the experiments, in Taguchi sensitivity analysis, three variables, force in the z-direction and moments around the x- and y-axes, are considered as the output. It is also assumed that the best-case scenario reduces the number of output variables. Because of the reduction in cutting forces, less energy consumption is required. The main effect plots for the signal-to-noise ratios were used to study the cutting force (F_z) and moments (M_x, M_y) with respect to the process parameters (Figure 6). The minimum value of the cutting force in the z-direction (F_z) corresponded to the cutting parameters at levels $A_2B_1C_3$. This is $A_1B_2C_3$ for M_x and $A_1B_3C_3$ for M_y. Where A represents the cutting depth, B is the rotational speed, and C is the feed speed.

Table 4

Statistical information of force recorded data in different test modes

Test No.	Force in the different directions, N											
	***X*-direction**				***Y*-direction**				***Z*-direction**			
	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev
1	−100	100	16.37	50.43	−100	100	22.74	56.27	−90.54	119.09	25.46	35.62
2	−100	100	14.09	42.94	−100	100	16.10	48.79	−72.41	94.30	11.42	23.37
3	−100	100	11.06	39.35	−100	100	11.18	42.74	−49.80	128.70	12.78	29.99
4	−100	100	15.09	46.39	−100	100	16.79	45.86	−162.3	154.76	3.48	40.60
5	−100	100	11.95	39.57	−94.41	100	12.51	37.38	−128.6	97.97	5.44	26.37
6	−100	95.52	−21.31	48.03	−100	100	−18.41	52.86	−59.86	66.64	21.49	18.27
7	−100	100	−9.6	40.73	−100	100	−11.30	44.40	−170.5	150.64	2.99	30.97
8	−100	100	−24.78	53.53	−100	100	−24.75	60.40	−66.86	74.93	13.59	20.80
9	−100	97.86	−17.74	45.37	−100	100	−16.69	51.33	−59.23	92.38	17.57	19.78

Table 5

Statistical information of moment recorded data in different test modes

Test No.	Moment around different axes, N.m											
	***X*-axis**				***Y*-axis**				***Z*-axis**			
	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev
1	−3.87	24.00	3.88	7.12	−11.30	6.57	−1.54	4.20	−7.74	2.28	−1.5	2.39
2	−5.27	19.43	1.84	5.36	−12.04	5.72	−1.19	3.60	−7.73	2.89	−0.54	1.74
3	−6.68	17.67	1.39	4.21	−12.21	6.59	−0.72	3.05	−7.73	4.09	−0.26	1.45
4	−12.78	24.71	2.57	6.64	−16.10	9.85	−1.62	5.42	−7.75	5.42	−0.19	2.16
5	−10.39	21.20	1.51	4.99	−15.81	8.71	−1.37	4.46	−7.74	6.30	0.01	2.01
6	−17.80	5.13	−2.89	5.58	−4.80	12.33	2.01	4.00	−7.73	3.11	−1.23	2.02
7	−30.00	10.13	−2.13	7.08	−9.83	16.28	1.55	5.15	−7.74	4.29	−0.44	1.80
8	−22.15	7.57	−3.90	7.17	−6.84	15.18	2.77	5.72	−7.77	4.54	−0.77	2.26
9	-20.92	9.16	-2.72	5.83	-6.76	14.64	1.97	4.90	-7.74	6.26	-0.24	2.18

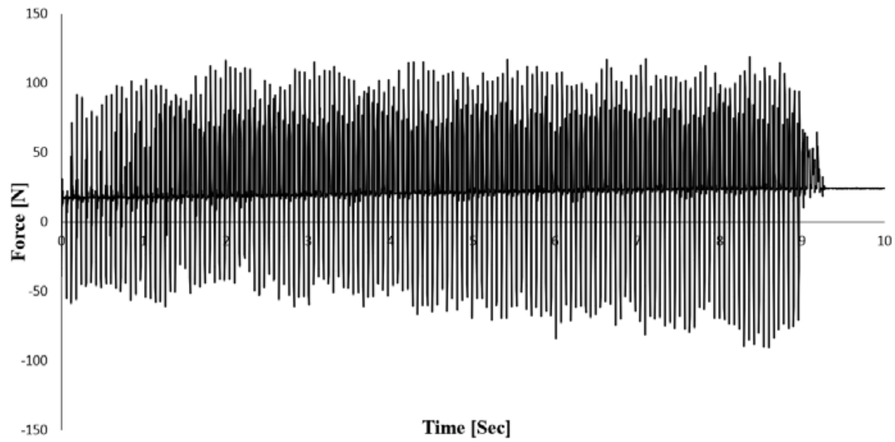
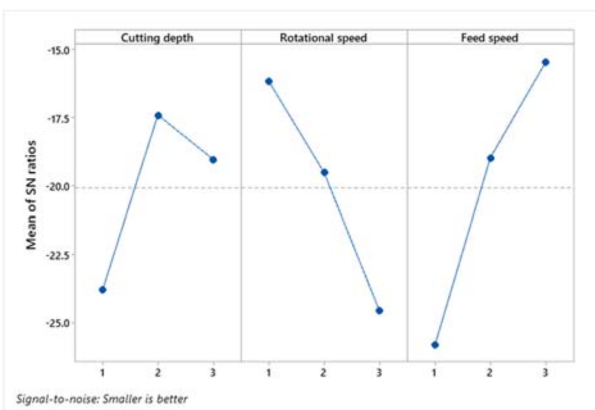


Figure 5. The measurements for the first test mode of cutting force in the *Z*-direction



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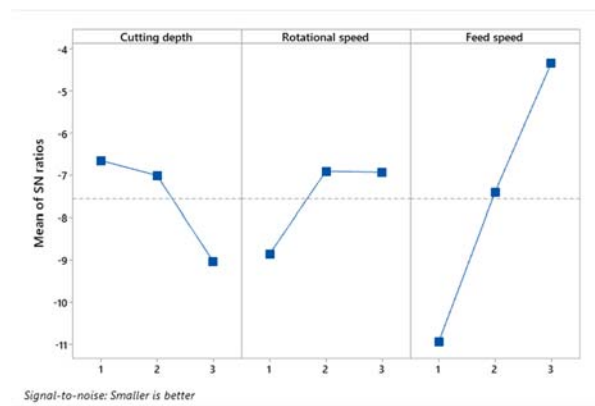

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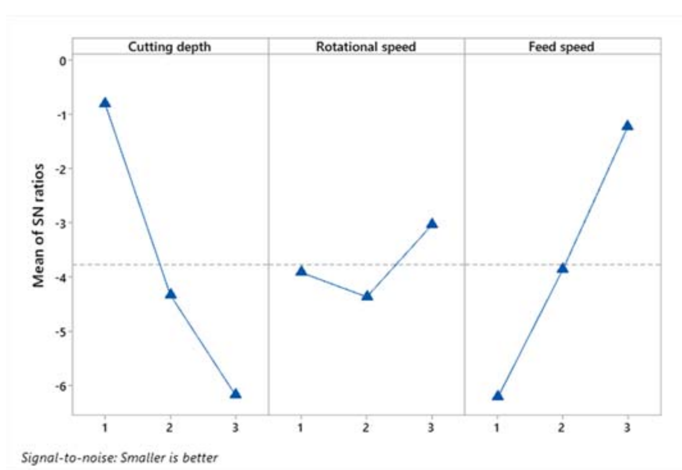

c

Figure 6. Means of SN ratios of different outputs under the impact of milling process parameters, including:
a — mean of cutting force in the *z*-direction, *b* — mean of cutting moment around the *x*-axis;
c — mean of cutting moment around the *y*-axis

A higher feed rate reduces the standard deviation of the thickness errors, leading to a more homogeneous thickness distribution owing to the dynamic behaviour (creating lower vibration amplitudes) of the milling process [17]. Furthermore, the results of Taguchi approach show that the effective parameters for the cutting force (F_z) are the feed rate (41.17 %), rotational speed (33.29 %), and cutting depth (25.44 %). In addition, for the M_x analysis, they are the feed rate (60.39 %), cutting depth (21.78 %), and rotational speed (17.83 %). It can be concluded that the feed rate is the most effective factor for the cutting force in the *z*-direction and cutting moment around the *x*-axis. However, the cutting depth had the greatest effect on the cutting moment around the *y*-axis (45.96 %). Nonetheless, in this analysis, the impact value of the feed rate is equal to 42.66 %, which is not significantly different from the impact value of the cutting depth (owing to the possibility of error in the calculations for the reasons described above, this difference is negligible). Hence, the feed rate is the most effective factor for minimising the cutting forces and moments compared to other milling process parameters. The results of Taguchi approach are presented in Figure 7.

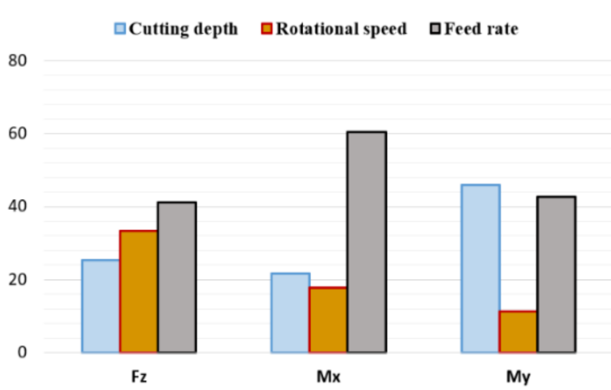

Figure 7. The Results of Taguchi approach for studying the effect of milling process parameters on the cutting forces and moments

Conclusion

In this study, the influence of machining parameters on the cutting forces and moments in the milling of aluminum alloy Al6061T6 was investigated. Taguchi method was used to design the experiment and establish the relationship between cutting parameters and cutting forces and moments. The results of the experiments showed that the maximum and minimum values of F_x, F_y, and M_z did not change, and only the F_z, M_x, and M_y have changed dramatically in the various tests. It is concluded that the effective parameters of the cutting force (F_z) are the feed rate (41.17 %), rotational speed (33.29 %), and cutting depth (25.44 %). In addition, for the M_x analysis, they are feed rate (60.39 %), cutting depth (21.78 %), and rotational speed (17.83 %). The cutting moment along the *y*-axis was mainly affected by the cutting depth (45.96 %). The most dominant factor affecting the cutting force and moment is the feed rate. It is also found that the minimum value of the cutting force in *z*-direction (F_z) corresponded to the cutting parameters at levels $A_2B_1C_3$. This is $A_1B_2C_3$ for M_x and $A_1B_3C_3$ for M_y. As revealed in this study, the machining parameters can be controlled to minimise the cutting force in milling Al6061-T6. This can help to choose the appropriate cutting parameters, and more importantly, by optimising them, it would be possible to design desired cutting tools and estimate the required power.

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