Experimental Investigation of the Surface Roughness for Aluminum Alloy AA6061 in Milling Operation by Taguchi Method with the ANOVA Technique

Nashwan Q. Mahmood[1],*, Yad F. Tahir[2], Mohammed Hikmat[3], Mohammed S. Abdulsatar[4], Peter Baumli[5]

[1,2,3,4] Department of Mechanical Engineering/Production, College of Engineering, Sulaimani Polytechnic University, Sulaimani, Kurdistan, Iraq.
[5] Institute of Physical Metallurgy, Metal Forming and Nanotechnology, University of Miskolc, Miskolc, Hungary.
nashwan.qadir@spu.edu.iq[1], yad.faruq@spu.edu.iq[2], mohammed.hikmat.h@spu.edu.iq[3], mohammed.s.abdulsatar@spu.edu.iq[4], fembaumli@uni-miskolc.hu[5]

Abstract

The surface roughness of the machined parts is the most important parameter to predict the performance of mechanical components. Moreover, predicting the optimal machining parameters conditions is the preferable method for cost reduction and achieving the desired surface quality of the product. This study investigates three cutting parameters, such as depth of cut, spindle speed, and feed for the milling aluminium alloy AA6061, to predict the surface roughness quality. The experimental work utilized a manual milling machine with a coated carbide cutter. Furthermore, the experiments were arranged using the Taguchi L_9 orthogonal array (OA) method. The average surface roughness (Ra) was measured and converted to signal-to-noise (S/N) ratio and then analyzed in the statistical method of analysis of variance (ANOVA). Finally, the optimal combination set speed, feed, and depth of cut was 2400 rpm, 30 mm/min, and 0.5 mm, respectively. Also, according to the ANOVA test, the most influential parameter was the spindle speed among the selected parameters, with the highest P value of (66.42%). In comparison, the lowest P value is a depth of cut (5.34%). Furthermore, spindle speed was the only significant factor statistically. By selecting a high spindle speed (2400 rpm), surface quality was enhanced, but the preferable level was low for depth of cut and feed.

Keywords: Aluminum alloy, Surface roughness, Taguchi method, Analysis of variance, Milling machine, S/N ratio.

التحقيق التجريبي لخشونة السطح لسبيكة الألومنيوم AA6061 في عملية التفريز بطريقة تاغوتشي و تقنية ANOVA

نشوان قادر محمود[1,*]، ياد فاروق طاهر[2]، محمد حكمت حسن[3]، محمد سعد عبد الستار[4]، بيتر باوملي[5]

[1,2,3,4]قسم الهندسة الميكانيكية/الإنتاج، كلية الهندسة، جامعة السليمانية التقنية، السليمانية، كردستان، العراق

[5]جامعة معهد المعادن الفيزيائية وتشكيل المعادن وتكنولوجيا النانو، جامعة ميشكولس، ميشكولس، هنغاريا

الخلاصة

تعد خشونة سطح الأجزاء المُشگَّلة من أهم العوامل للتنبؤ بأداء الأجزاء الميكانيكية. علاوة على ذلك، فإن التنبؤ بالظروف المثلى لعوامل التشغيل هو الطريقة المفضلة لخفض التكلفة وتحقيق جودة السطح المطلوبة للمنتج. في هذة الدراسة، تم دراسة ثلاث عوامل قطع، وهم عمق القطع، سرعة محور الدوران، والتغذية، باستخدام عملية التفريز على سبيكة ألومنيوم AA6061 للتنبؤ بجودة خشونة السطح. تم تنفيذ التجارب العملية بأستخدام ماكنة تفريز يدوية مع اداة قطع مطلية بالكربيد. بالأضافة الى ذلك، تم ترتيب التجارب باستخدام طريقة تاغوتشي للمصفوفة المتعامدة (OA) مكونة من تسعة مستويات، وتم قياس متوسط خشونة السطح (Ra) وتحويلها إلى نسبة الإشارة إلى الضجيج (S/N) ومن ثم تحليلها بأستخدام الطرق الأحصائية كطريقة تحليل التباين (ANOVA). أخيرًا، تم تحديد التركيبة المثالية لعوامل القطع سرعة محور الدوران، التغذية، وعمق القطع بـ 2400 دورة في الدقيقة و30 مم/دقيقة و0.5 مم على التوالي. وكذلك وفقاً لاختبار ANOVA، فإن العامل الأكثر تأثيرا هو سرعة محور الدوران من بين العوامل المختارة والتي لديها أعلى قيمة P تبلغ (66.42%)، في حين أن أقل قيمة P هي عمق القطع وهي (5.34%). بالأضافة الى ذلك، كانت سرعة محور الدوران العامل الوحيد المهم إحصائيا، من خلال اختيار سرعة محور دوران عالية (2400 دورة في الدقيقة) تم تحسين جودة السطح، ولكن بالنسبة لعمق القطع والتغذية كان المستوى المفضل هي المستويات المنخفضة.

الكلمات المفتاحية: سبيكة المنيوم، خشونة السطح، طريقة تاغوتشي، تحليل التباين، تفريز، تشغيل، نسبة S/N.

1. INTRODUCTION

Metal cutting, which is the basis of the manufacturing industries, is the most widely used method for creating a variety of parts, from vehicles to exact components for the electronics and instrumentation sectors worldwide **(Danesh Narooei and Ramli, 2022; Raju et al., 2011; Shukla et al., 2020)**. Most researchers in the metal cutting field mentioned the characteristics of tools, machine parameters, and work materials that significantly impact the product's processing efficiency and output quality **(Abdelrazek et al., 2020; Ostapenko and Vasilega, 2013)**. Hence optimization of the suitable processing parameter enhances the machining process. Machining operations such as milling, boring, broaching, turning, drilling, grinding, honing, and lapping are the most important value-added operations in metal cutting **(Hussein, 2014; Mukherjee and Ray, 2006).** One of the most widely used material removal methods is milling machines in the industrial field as a traditional machining process. Most suitable machined surfaces are frequently utilized to relate with other components in machinery design, die, and manufacturing industries **(Altintaş, 1994; Lee and Lin, 2000)**. Surface roughness is a fundamental indicator of product technological

quality and an important factor in cost reduction. The mechanism underlying the formation of surface roughness is process-dependent, extremely changing, and intricate, so the theoretical analysis is complex **(Abdulridha et al., 2020; Tsai et al., 1999)**.

Furthermore, surface roughness is a crucial aspect of mechanical design because it affects the performance of mechanical parts such as wear, corrosion resistance, heat generation, fatigue strength, creep life, etc**. (Kadirgama et al., 2012; Khan and Kaiser, 2022; Khudair and Hussein, 2021)**. Also, it significantly impacts the adaptive of two components that connect. Moreover, it improves the tribological properties of the product surface finish, such as corrosion resistance, fatigue strength, and aesthetic appeal. The metal-cutting technique aims not only to shape the part but also to manufacture machined parts in such a way that depends on surface considerations such as dimensional and geometric constraints **(Khorasani et al., 2012; Nouveau et al., 2005)**. Several tools and techniques are utilized for optimization parameters, such as the Taguchi method, Grey Relational Analysis (GRA), Analysis of variance (ANOVA), Response Surface Methodology (RSM), Simulated Annealing Algorithm (SAA), Failure Modes and Effects Analysis (FMEA). Therefore, Obtaining the best surface finish in the shortest amount of time requires parametric optimization to improve and enhance machining processes **(Kadhim, 2019; Patel et al., 2021; Ribeiro et al., 2017; Sabree Bedan et al., 2016)**.

Nevertheless, Genichi Taguchi developed the statistical methods known as "Taguchi methods" for the quality of manufactured parts. Recently, these approaches have been utilized in engineering **(Rosa et al., 2009)**, advertising and marketing **(Selden, 1996**), and biotechnology **(Rao et al., 2008)**. Aluminum 6061 is a well-known alloy that contains magnesium (Mg) and silicon (Si) as the main alloying elements. The main properties are lightweight, low cost, and flexibility for the machining process, with a high strength-to-weight ratio. Therefore, it is widely applied in the bioengineering, structural aerospace, and automobile industries **(Al Attaby et al., 2013; Faris, 2017; Pan et al., 2020; Salman, 2017)**.

Furthermore**, (Öztürk and Kara, 2020)** investigated experimentally and statistically the energy consumption and surface roughness for machining aluminum alloys 6061 by milling machine process utilizing parameters such as cutting speed, feed, and depth of cut. The results revealed that the best surface roughness (Rz) for cutting speed, feed, and depth of cut were (180 m/min) (0.15 mm/rev), and (0.5 mm) respectively. They deduced that according to (ANOVA) results, the speed significantly impacts surface roughness with a range of 39.07% of surface roughness. Also, the surface roughness decreased as the spindle axis motor's energy consumption increased during cutting. **(Najiha et al., 2016)** investigated the influence of wear mechanisms by cutting parameters in the end milling of aluminum alloy AA606. The result revealed that a higher feed rate and depth of cut resulted in more adhesion and edge chipping. MQL based on water is impactful for edge integrity. Tool life can be extended by minimizing damages with the assistance of the TiO2 nanoparticles of a volume fraction of 2.5% (lubricant) **(Chinnasamy et al., 2022**). Therefore, improving the life of cutting tools is required to lower manufacturing costs. Also **(Tsai et al., 1999)** mentioned factors that impact surface smoothness, such as tool wear, depth of cut, cutting speed, feed rate, cutter force, cutter runout, and cutter geometry. According to **(Fuh and Wu, 1995)**, the surface quality enhanced a statistical model for aluminum materials in the end milling process using tool nose radius, cutting speed, depth of cut, feed rate, and flank as control parameters. The result illustrated that the tool nose radius and feed significantly affect surface roughness. **(Ghani et al., 2004),** carried out studies to enhance the cutting parameters for hardened steel in semi-finish and complete conditions. They used

measurable responses such as cutting force and surface roughness. It showed optimal cutting conditions are cutting speed, feed rate, and depth of cut, respectively. The previous review shows that many investigations have been carried out to develop and improve cutting conditions in milling machines. However, a few were performed to enhance Taguchi's Orthogonal Array (OA) method of the surface roughness of AA6061 using milling operation. In the present work, the influence of cutting parameters such as feed, spindle speed, and depth of cut are investigated. Hence, the cutting parameters are converted into the signal to noise (S/N) ratio to assess the Lowest is Better (LB) characteristics of the average surface roughness. Finally, the analysis of variance (ANOVA) has been applied to predict the effectiveness ratio of the proposed cutting parameters and select the optimal combination.

2. MATERIALS AND METHOD

2.1 Materials

The material used for the present study is AA6061 alloy, and its chemical composition is given in **Table 1.** AA6061 aluminum alloy presents high strength, excellent resistance to corrosion, and excellent plane strain fracture toughness. **(Kumar et al., 2019).**

Table 1. Chemical composition of AA6061 **(Kumar et al., 2019)**.

Mn	Cr	Mg	Si	Cu	Fe	Zn	Ti	Al
0.17	0.16	0.88	0.64	0.24	0.16	0.05	0.01	97.67

Furthermore, the tool used is a Carbide cutter type of "Sandvik Coromat (R216.33-08045-AC16P 1630)," is illustrated in **Fig. 1**. Also, the property of this type of carbide cutter is demonstrated in **Table 2.**
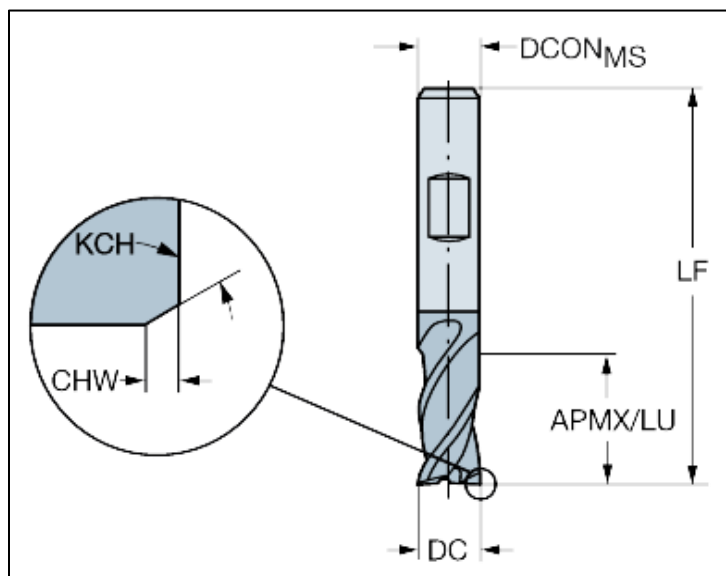
Figure 1. Schematic of Sandvik coromat cutter (R216.33-08045-AC16P 1630**) (Sandvik, 2023).**

Table 2. Properties of the cutter **(Sandvik, 2023)**.

Cutter property	Value	Unit
Cutting diameter (DC)	8	mm
Corner chamfer (KCH)	45	degree
Corner chamfer width (CHW)	0.1	mm
Depth of cut maximum (APMX)	16	mm
Usable length (LU)	16	mm
Connection diameter (DCON)	8	mm

2.2. Control Parameters and Their Levels

The control parameters that affect the surface roughness of the machined surface are spindle speed, depth of cut, and feed. Three adjustable parameters are addressed in this study, and each parameter is adjusted to three levels. The parameters and their levels are shown in **Table 3.**

Table 3. Control parameters and their levels

Parameter	Level			Unit
	Low	Center	High	
Speed (A)	1200	1800	2400	rpm
Depth of cut (B)	0.5	1.0	1.5	mm
Feed (C)	30	110	180	mm/min

Fig. 2 shows the dimensions of the AA6061 workpiece machined by milling machine operation. **Fig. 3** demonstrates the experimental work on the AA6061 workpiece. The nine experiments were carried out on a milling machine with no cutting fluid. Surface roughness was evaluated using a tester for surface roughness. For accurate surface roughness readings, every experimental procedure was repeated three times with the new cutting to be more reliable.
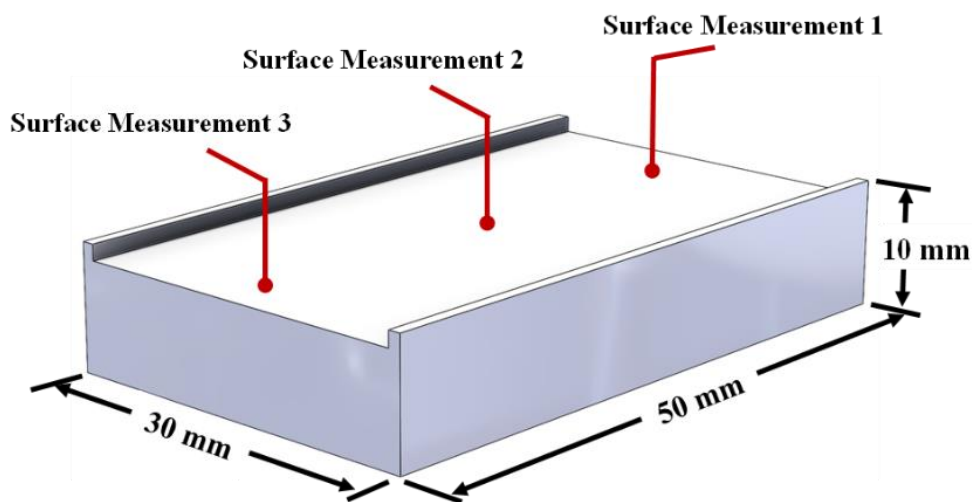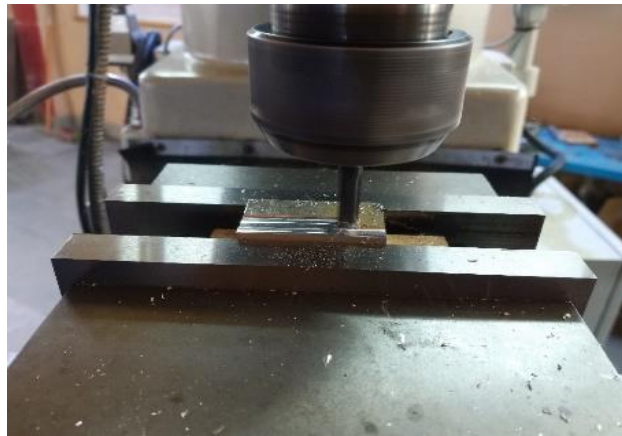

Figure 2. The AA6061 workpiece with locations of surface roughness measurement

Figure 3. Experimental work on the AA6061 workpiece machined
by milling machine operation.

The variety of ways used to express the most typical measurements of surface roughness of workpieces include arithmetic average (Ra), peak roughness (RP), or average peak-to-valley height (Rz), among others. The current study utilized an arithmetic average (Ra) defined by ISO 1302. A portable roughness tester model V2.0 with the serial number K01122033001 was used to measure the surface roughness (Ra). Three surface measurements with different locations were taken to determine the average surface roughness of cuts, as illustrated in **Fig. 2.** Moreover, the experiments are set using the Taguchi fractional factorial design of L_9 design of experiment (DOE) because there are three factors, each with three levels. **Table 4** illustrates the OA.

Table 4. The orthogonal array of L_9.

Run	Spindle Speed (rpm) (A)	DOC (mm) (B)	Feed (mm/min) (C)
1	1200	0.5	30
2	1200	1.0	110
3	1200	1.5	180
4	1800	0.5	110
5	1800	1.0	180
6	1800	1.5	30
7	2400	0.5	180
8	2400	1.0	30
9	2400	1.5	110

3. RESULTS AND DISCUSSION

The cutting parameters, such as feed, depth, and spindle speed of cut on the surface roughness of the aluminum alloy AA6061, were investigated. The tests were performed using a coated carbide cutting tool on a milling machine. Each experiment was repeated

three times, and the data was converted to the S/N ratio for analysis, as shown in **Table 5.** Moreover, **Fig. 4** demonstrates the finished samples, which are machined by the milling machine process, which are the number of experiments selected on samples after 3rd trial for each sample.

Figure 4. Finished sample after the milling machine process.

Table 5. The test results with S/N ratio and standard deviation

Run	Spindle speed (rpm) (A)	Depth of cut (mm) (B)	Feed (mm/min) (C)	1st Trial	2nd Trail	3rd Trail	Average surface roughness (μm)	S/N Ratio	Standard deviation
1	1200	0.5	30	0.79	0.79	0.80	0.79	2.04	0.01
2	1200	1.0	110	2.01	1.75	1.59	1.78	-5.02	0.21
3	1200	1.5	180	3.65	3.63	3.55	3.61	-11.14	0.06
4	1800	0.5	110	2.76	2.50	2.66	2.64	-8.43	0.13
5	1800	1.0	180	2.86	2.90	3.01	2.92	-9.31	0.08
6	1800	1.5	30	2.03	2.08	1.94	2.01	-6.08	0.07
7	2400	0.5	180	0.90	0.79	0.82	0.84	1.54	0.06
8	2400	1.0	30	0.42	0.44	0.43	0.43	7.31	0.01
9	2400	1.5	110	0.66	0.71	0.87	0.75	2.55	0.11

Relating to the surface finish of machine parts, the highest surface roughness number by (μm) was indicated with the run number 3. While run number 8 has the smallest surface roughness number. In addition, **Table 5** displays the surface roughness value, S/N ratio, and standard deviation of the experimental work. It was known that surface roughness must be low for power consumption, cost reduction, and product quality **(Karabulut, 2015)**. The results were changed to the S/N ratio; surface roughness is required to be a small amount to get the best surface quality; therefore, "smaller the better" is chosen as in Eq. (1):

$$\frac{S}{N} = -10 \, log \left[\frac{1}{n} \sum_{i=1}^{n} Y_i^2 \right] \tag{1}$$

Fig. 5 shows the surface roughness variation with the number of experiments and surface roughness. The surface roughness rises due to the lower speed and decreases due to the increasing spindle speed.
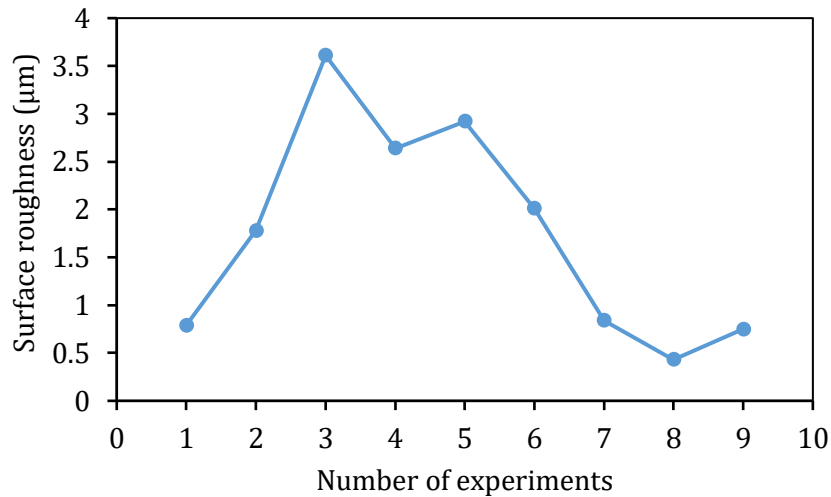
Figure 5. Variation of surface roughness with experiment number.

Table 6 and **Fig. 6** show the most desirable levels of the factors individually. The optimum set of the milling parameters is A3/B1/C1.

Table 6. Response table.

Level	A	B	C
1	-4.704	-1.623	1.105
2	-7.935	-2.328	-3.647
3	3.781	-4.905	-6.314
Delta	11.716	3.282	7.419
Ranking	1	3	2
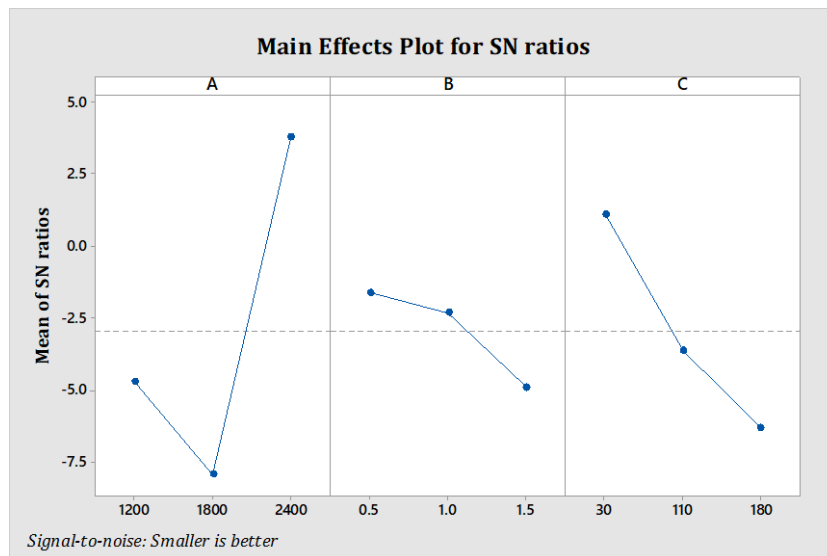
Figure 6. Average performance plot. A: Spindle speed B: Depth of cut C: Feed

Conversely, the optimum cutting parameters are 2400 rpm, 0.5 mm, and 30 mm/min for spindle speed, DOC, and feed, respectively. Additionally, spindle speed is the most influential parameter that impacts the surface roughness of AA 6061 cutting with a coated carbide

cutter in the milling machine. Followed by feed, and the least effective one is the depth of cut. As can be seen, the spindle speed significantly influences surface roughness. Changing the spindle speed, highly decreases the surface roughness compared with the other two parameters. The effect of depth of cut and feed has a proportional relation with surface roughness, as illustrated in **Fig.7**. Increasing the depth of cut or feed results in an increase in the surface roughness. The spindle speed has different effects, which have a reverse relation with surface roughness. For instance, the surface roughness will decrease when the spindle speed increases. Minitab 18 software is used to examine the output characteristic and surface finish, and ANOVA is created to illustrate the percentage contribution of each influencing factor on surface roughness. The ANOVA test was designed from Stat>ANOVA>General linear model>Fit general linear model. In the ANOVA test, the indicator of the significance of the parameter is the P-value. In the current work, a 95.0% confidence level was chosen; therefore, any factor with a P-value under 0.05 is statistically significant and has a great role in the response variable. The data in the analysis of variance table are from Eq.s (2) 2 to 14. Degrees of freedom for each factor and the error of each factor are calculated as follows:
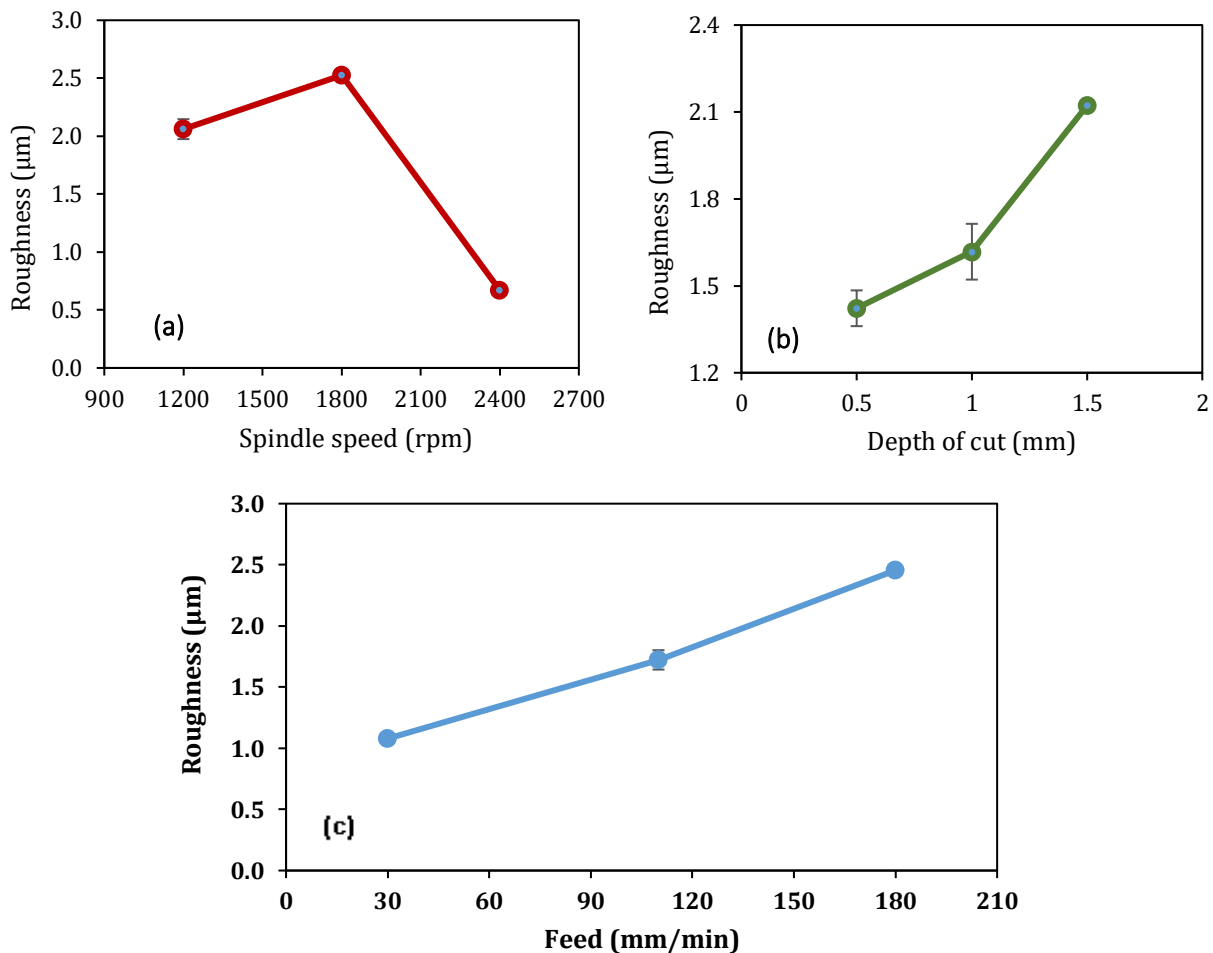
Figure 7. Main Impact Surface roughness plot for (a) Spindle speed, (b) Depth of cut, and (c) Feed

$DOF_T = N-1$ (2)

$DOF_f =$ number of levels-1 (3)

$DOF_e = DOF_T -$ total of DOF_f (4)

The deviation of each factor from the overall average mean gives the relative significance of that factor:

$T = \sum_{i=1}^{n} Y_i$ (5)

$C.F = \frac{T^2}{N}$ (6)

The total sum of squared deviation is:

$SS_T = (\sum_{i=1}^{n} Y_i^2) - C.F$ (7)

The sum of the squared deviation of each factor is:

$SS_f = (\frac{A_1^2}{n_1} + \frac{A_2^2}{n_2} + ...) - C.F$ (8)

Then, the sum of squared deviations of the error term is identified by:

$SS_e = SS_T -$ total of SS_f (9)

The variance or the mean square of each factor is:

$V_f = \frac{SS_f}{DOF_f}$ (10)

The error of variance is defined by:

$V_e = \frac{SS_e}{DOF_e}$ (11)

The variance ratio of each factor is determined by:

$F_f = \frac{V_f}{V_e}$ (12)

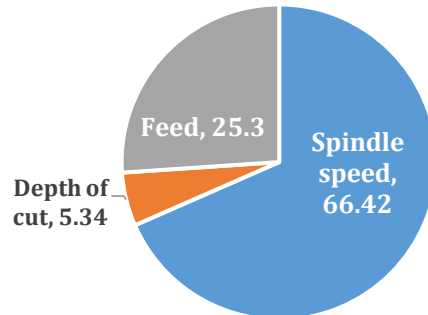The percentage contribution of each factor in the total sum of squared deviations is:

$P_f = \frac{SS_f}{SS_T} \times 100$ (13)

The error of the percentage contribution of the process is:

$P_e = \frac{SS_e}{SS_T} \times 100$ (14)

Furthermore, the ANOVA test was tabulated in **Table 7**. It can be seen the highest value is 66.42% for spindle speed, as shown in **Fig. 8**. Moreover, **Fig. 7a** demonstrates that by raising the spindle speed, the surface quality will be enhanced. This result agrees with the result **(Karabulut, 2015**) that cutting speeds exceeds the limit of the built-up edge constitution. Based on the probability, spindle speed is the only significant factor with a P-value of 0.0422. For the same depth of cut and feed, by increasing spindle speed, the milling cutter could remove more material and reduce built-up edge (BUE) formation. Therefore, the surface becomes smoother, which enhances the surface quality. By increasing the speed from 1200

rpm to 1800 rpm, surface roughness increased by 0.46 μm only. But by increasing it from 1800 to 2400, surface roughness decreased sharply. **Table 5** reported that as the spindle speed rises from run 7 to 9, the surface finish is considerably improved. While in the other runs, as that for runs 4 to 6, the machined part has poor surface quality. It can be seen in **Fig. 7b** that the depth of the cut impacts surface roughness, which is increased by increasing the depth of the cut gradually.

Figure 8. The percentage contribution.

Fig. 7c reported that the surface quality decreased by increasing feed. Besides, working time is one of the most essential measures in the manufacturing process. Setting the parameters properly could reduce cutting time and surface roughness simultaneously to minimize the total cost of the manufacturing process. For instance, the machined surface has a low surface roughness for run number 7 of the feed of 180 mm/min (highest value). Also, run number 9 in a higher depth of cut of 1.5 mm, the lowest surface roughness was obtained due to the effect of spindle speed.

Table 7. Analysis of variance (ANOVA) Data.

Source	DOF	SS	V	F-test	P %	P-value
A	2	220.6	110.33	22.6824	66.42	0.0422
B	2	17.74	8.87	1.8235	5.34	0.3542
C	2	84.07	42.0	8.6421	25.30	0.1037
Residual error	2	9.72	4.86		2.92	
Total	8	332.20				

4. CONCLUSIONS

The average surface roughness performance of the Aluminum alloy AA6061 workpiece was studied experimentally under the effect of three parameters (speed, feed and depth of cut). Nine experiments are tested according to Taguchi's OA. The experimental data were analyzed in the statistical method of ANOVA. The concluded results show that:

1) Each cutting parameter influences the surface roughness of the machine part. In contrast, the most influential parameter was spindle speed, with a percentage contribution of (66.42%), whereas the depth of cut was the least influential (5.34%).
2) Among the selected factors, only spindle speed was significant, with a P-value of 0.0422
3) the optimum levels of the parameters were spindle speed with (2400 rpm), depth of cut (0.5 mm), and feed (30 mm/min).
4) It was demonstrated that the surface quality of machined parts can be improved using proper cutting parameters.

5) Design of the experiment using the Taguchi method enabled to optimize surface roughness of the machine product while minimizing the time and cost of production.

NOMENCLATURE

Symbol	Description	Symbol	Description
ANOVA	Analysis Of Variance	P%	Percentage contribution
C.F	Correction Factor	P-value	Calculated probability
C.I	Confidence interval	Ra	Surface roughness
DOF	Degree of freedom	S/N	Signal-to-noise ratio (dB)
DOF_e	Degrees of freedom of error term	SS	Sum of square
DOF_i	Degrees of freedom of the ith significant parameters	T	Grand total of all results
DOF_m	Degree of freedom means	V	Variance
F-test	Variance ratio	V_e	The error variance
N	The total number of experiments	V_f	The variance or mean square of each factor
n	Number of observations of the result	y_i	The result value of the Surface roughness for ith trial (μm)
OA	Orthogonal Array	Y_{opt}	Expected result of the optimal combination according to the S/N ratio

REFERENCES

Abdelrazek, A.H., Choudhury, I., Nukman, Y., and Kazi, S., 2020. Metal cutting lubricants and cutting tools: a review on the performance improvement and sustainability assessment. *The International Journal of Advanced Manufacturing Technology*, 106, pp. 4221-4245. Doi:10.1007/s00170-019-04890-w

Abdulridha, H.H., Helael, A.J., and Al-duroobi, A.A., 2020. Prediction the influence of machining parameters for CNC turning of Aluminum alloy using RSM and ANN. *Engineering and Technology Journal*, 38(6), pp. 887-895. Doi:10.30684/etj.v38i6A.705

Al Attaby, Q.M.D., Al Saadi, M.H., and Al Naim, I.K.A., 2013. Improvement of AA1050 Sheets. *Journal of Engineering*, 19(2), pp. 217-234. Doi:10.31026/j.eng.2013.02.05

Altintaş, Y., 1994. Direct adaptive control of end milling process. *International Journal of Machine Tools and Manufacture*, 34(4), pp. 461-472. Doi:10.1016/0890-6955(94)90078-7

Chinnasamy, M., Rathanasamy, R., Pal, S.K., and Palaniappan, S.K., 2022. Effectiveness of cryogenic treatment on cutting tool inserts: A review. *International Journal of Refractory Metals and Hard Materials*, 108, 105946. Doi:10.1016/j.ijrmhm.2022.105946

Danesh Narooei, K., and Ramli, R., 2022. Optimal selection of cutting parameters for surface roughness in milling machining of AA6061-T6. *International Journal of Engineering*, 35(6), pp. 1170-1177. Doi:10.5829/IJE.2022.35.06C.08

Faris, M.S., 2017. Study of the Pitting Corrosion for shot peening 6061-T6 Aluminum Alloy in sea water. *Iraqi journal of mechanical and material engineering*, 17(4). https://shorturl.at/gqyzW

Fuh, K.H., and Wu, C.F.,1995. A proposed statistical model for surface quality prediction in end-milling of Al alloy. *International Journal of Machine Tools and Manufacture*, 8(35), pp. 1187-1200. https://shorturl.at/ns149

Ghani, J.A., Choudhury, I., and Hassan, H., 2004. Application of Taguchi method in the optimization of end milling parameters. *Journal of materials processing technology*, 145(1), pp. 84-92. Doi:10.1016/S0924-0136(03)00865-3

Hussein, S.G., 2014. An experimental study of the effects of coolant fluid on surface roughness in turning operation for brass alloy. *Journal of Engineering*, 20(3), pp. 96-104. Doi:10.31026/j.eng.2014.03.09

Kadhim, K.J., 2019. Effect of laser process an inclined surface cutting of mild steel then analysis data statistically by RSM. *Journal of Engineering*, *25*(10), pp. 120-133. Doi:10.31026/j.eng.2019.10.09

Kadirgama, K., Noor, M., and Rahman, M., 2012. Optimization of surface roughness in end milling using potential support vector machine. *Arabian Journal for Science and Engineering*, 37, pp. 2269-2275. Doi:10.1007/s13369-012-0314-2

Karabulut, Ş., 2015. Optimization of surface roughness and cutting force during AA7039/Al2O3 metal matrix composites milling using neural networks and Taguchi method. *Measurement*, 66, pp. 139-149. Doi:10.1016/j.measurement.2015.01.027

Khan, A.A., and Kaiser, M.S., 2022. Wear studies on Al-Si automotive alloy under dry, fresh and used engine oil sliding environments. *Research on Engineering Structures & Materials,* 9(1), pp. 1-18. Doi:10.17515/resm2022.505ma0816

Khorasani, A.M., Yazdi, M.R.S., and Safizadeh, M.S., 2012. Analysis of machining parameters effects on surface roughness: a review. *International Journal of Computational Materials Science and Surface Engineering*, 5(1), pp. 68-84. Doi:10.1504/IJCMSSE.2012.049055

Khudair, A.M., and Hussein, F.I., 2021. Parametric optimization for fatigue life of 6061-t6 Aluminum thin sheets processed with high-speed laser shock peening. *Iraqi Journal of Laser*, 20(2), pp. 8-17. Doi:10.31900/ijl.v20i2.281

Kumar, S., Maity, S.R., and Patnaik, L., 2019. Box-Behnken analysis of surface modification of Aluminium Alloy AA6061 using roller burnishing. *Materials Today: Proceedings*, 18, pp. 4613-4621. Doi:10.1016/j.matpr.2019.07.445

Lee, T., and Lin, Y., 2000. A 3D predictive cutting-force model for end milling of parts having sculptured surfaces. *The International Journal of Advanced Manufacturing Technology*, 16(11), pp. 773-783. Doi:10.1007/s001700070011

Mukherjee, I., and Ray, P.K., 2006. A review of optimization techniques in metal cutting processes. *Computers and Industrial Engineering*, 50(1), pp. 15-34. Doi:10.1016/j.cie.2005.10.001

Najiha, M., Rahman, M., and Kadirgama, K., 2016. Performance of water-based TiO2 nanofluid during the minimum quantity lubrication machining of Aluminium alloy, AA6061-T6. *Journal of cleaner production*, 135, pp. 1623-1636. Doi:10.1016/j.jclepro.2015.12.015

Nouveau, C., Jorand, E., Decès-Petit, C., Labidi, C., and Djouadi, M.A., 2005. Influence of carbide substrates on tribological properties of chromium and chromium nitride coatings: application to wood machining. *Wear*, 258(1-4), pp. 157-165. Doi:10.1016/j.wear.2004.09.034

Ostapenko, M., and Vasilega, D., 2013. Method of evaluation of quality of metal-cutting tool. *Applied Mechanics and Materials*, 379, pp. 49-55. Doi:10.4028/www.scientific.net/AMM.379.49

Öztürk, B., and Kara, F., 2020. Calculation and estimation of surface roughness and energy consumption in milling of 6061 alloy. *Advances in Materials Science and Engineering*, pp. 1-12. Doi:10.1155/2020/5687951

Pan, J., Ni, J., He, L., Cui, Z., and Feng, K., 2020. Influence of micro-structured milling cutter on the milling load and surface roughness of 6061 aluminum alloy. *The International Journal of Advanced Manufacturing Technology*, 110(11), pp. 3201-3208. Doi:10.1007/s00170-020-06080-5

Patel, N., Parihar, P. L., and Makwana, J. S., 2021. Parametric optimization to improve the machining process by using Taguchi method: a review. *Materials Today: Proceedings*, 47, pp. 2709-2714. Doi:10.1016/j.matpr.2021.03.005

Raju, K.V.M.K., Janardhana, G.R., Kumar, P.N., and Rao, V.D.P., 2011. Optimization of cutting conditions for surface roughness in CNC end milling. *International journal of precision engineering and manufacturing*, 12, pp. 383-391. Doi:10.1007/s12541-011-0050-7

Rao, R.S., Kumar, C.G., Prakasham, R.S., and Hobbs, P.J., 2008. The Taguchi methodology as a statistical tool for biotechnological applications: a critical appraisal. *Biotechnology Journal: Healthcare Nutrition Technology*, 3(4), pp. 510-523. Doi:10.1002/biot.200700201

Ribeiro, J., Lopes, H., Queijo, L., and Figueiredo, D., 2017. Optimization of cutting parameters to minimize the surface roughness in the end milling process using the Taguchi method. *Periodica Polytechnica Mechanical Engineering*, 61(1), pp. 30-35. Doi:10.3311/PPme.9114

Rosa, J.L., Robin, A., Silva, M., Baldan, C.A., and Peres, M.P., 2009. Electrodeposition of copper on titanium wires: Taguchi experimental design approach. *Journal of materials processing technology*, 209(3), pp. 1181-1188. Doi:10.1016/j.jmatprotec.2008.03.021

Sabree Bedan, A., Hassan Shabeeb, A., and Nemaha Al-Sobyhawe, H., 2016. Modeling and optimization of machine parameters using Simulated Annealing Algorithm (SAA). *Engineering and Technology Journal*, 34(7), pp. 1473-1482.

Salman, K.D., 2017. Comparison the physical and mechanical properties of composite materials (Al/SiC and Al/B4C) produced by powder technology. *Journal of Engineering*, 23(10), pp. 85-96. Doi:10.31026/j.eng.2017.10.07

Sandvik, 2023. *Sandvik Coromat.* shorturl.at/ptx79

Selden, P.H., 1996. *Sales process engineering: a personal workshop*. ASQ Quality Press.

Shukla, A., Kotwani, A.s, and Unune, D.R., 2020. Performance comparison of dry, flood and vegetable oil based minimum quantity lubrication environments during CNC milling of Aluminium 6061. *Materials Today: Proceedings*, *21*, pp. 1483-1488.

Tsai, Y.H., Chen, J.C., and Lou, S.J.,1999. An in-process surface recognition system based on neural networks in end milling cutting operations. *International Journal of Machine Tools and Manufacture*, 39(4), pp. 583-605. Doi:10.1016/S0890-6955(98)00053-4.