DEU FMD 27(79) (2025) 86-98

Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi
Dokuz Eylul University Faculty of Engineering Journal of Science and Engineering
Elektronik/Online ISSN: 2547-958X

RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

The Effect of Internal and External MQL Methods Used for Environmentally Friendly Manufacturing on Machining Performance in Drilling AA2024 Alloys: A Comparison for ANN And Taguchi Analyzes

AA2024 Alaşımlarının Delinmesinde Çevre Dostu İmalat için Kullanılan İçten ve Dıştan MMY Yöntemlerinin İşleme Performansına Etkisi: YSA ve Taguchi Analizleri için bir Karşılaştırma

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Abstract

In recent years, the interest in sustainable manufacturing has created an increasing demand for the economical and environmentally friendly Minimum Quantity Lubrication (MQL) method. However, there are not enough studies comparing internal and external MQL applications in drilling operations. The aim of this study is to investigate the effects of internal and external MQL application on drilling performance. Using Taguchi L9 experimental design, AA2024 aluminum alloy was drilled under three different cooling conditions (internal MQL, external MQL, dry), three different cutting speeds (100, 125, 150 m/min) and three different feeds (0.10, 0.15, 0.20 mm/rev). Surface roughness (Ra) was determined as the performance criterion, 30 repetitions were made in each experiment and the average Ra values were calculated for each condition. At the end of the experiments, the lowest Ra value (0.5 µm) was obtained in the internal MQL condition where the lowest cutting speed (100 m/min) and feed (0.1 mm/rev) parameters were used. In the external MQL condition, Ra results close to dry cutting were observed. The ANOVA analysis revealed that the control factor with the greatest effect on Ra values was the cooling condition. In addition, tool wear after the 30th hole was examined with SEM images and minimum deformation was observed in the internal MQL. ANN and Taguchi analyses were applied to the Ra data measured in the experiments. It was observed that the measured Ra data were in agreement with the data estimated using the Taguchi approach by 97% and with the data estimated using the ANN approach by 99%.

Keywords: *Drilling, Internal MQL, External MQL, Taguchi, ANN*

Öz

Son yıllarda sürdürülebilir imalata olan ilgi, ekonomik ve çevre dostu Minimum Miktarda Yağlama (MMY) yöntemine artan bir talep oluşturmuştur. Ancak, delme operasyonlarında içten ve dıştan MMY uygulamalarını karşılaştıran yeterli çalışma bulunmamaktadır. Bu çalışmanın amacı, MMY yönteminin içten ve dıştan uygulanmasının delme performansı üzerindeki etkilerini incelemektir. Taguchi L9 deney tasarımı kullanılarak AA2024 alüminyum alaşımı, üç farklı soğutma koşulunda (içten MMY, dıştan MMY, kuru), üç farklı kesme hızı (100, 125, 150 m/dk) ve üç farklı ilerleme (0.10, 0.15, 0.20 mm/dev) ile delinmiştir. Yüzey pürüzlülüğü (Ra) performans kriteri olarak belirlenmiş, her deneyde 30 tekrar yapılmış ve her şart için ortalama Ra değerleri hesaplanmıştır. Deneyler sonunda, en düşük Ra değeri (0.5 µm), en düşük kesme hızı (100 m/dk) ve ilerleme (0.1 mm/dev) parametrelerinin kullanıldığı içten MMY koşulunda elde edilmiştir. Dıştan MMY koşulunda kuru kesmeye yakın Ra sonuçları gözlenmiştir. Yapılan ANOVA analizi, Ra değerleri üzerinde en büyük etkiye sahip kontrol faktörünün soğutma koşulu olduğunu ortaya koymuştur. Ayrıca, 30. delikten sonra takımların aşınması SEM görüntüleriyle incelenmiş ve içten MMY'de minimum deformasyon gözlenmiştir. Deneylerde ölçülen Ra verilerine YSA ve Taguchi analizleri uygulanmıştır. Ölçülen Ra verilerinin, Taguchi yaklaşımı kullanılarak tahmin edilen verilerle %97, YSA yaklaşımı kullanılarak tahmin edilen verilerle %99 uyum sağladığı görülmüştür.

Anahtar Kelimeler: *Delik delme, İçten MMY, Dıştan MMY, Taguchi, ANN*

1. Introduction

In addition to the fact that aluminum alloys are light, the fact that their various alloys have very good strength, electrical and thermal conductivity has made this type of material a fairly common building and engineering material in recent years. The lightness of this material group makes it preferred especially in the aviation and automobile industries. In addition, its resistance to corrosion increases the importance of this material in the health sector. Many studies have been carried out on the machining of aluminum alloys with a versatile combination of properties, and these studies are still continuing [1-4].

DOI: https://doi.org/10.21205/deufmd.2025277912

Geliş Tarihi / Received: 26.01.2024
Kabul Tarihi / Accepted: 08.05.2024

Machining conditions affect the machinability of aluminum alloys as well as the metallurgical structure of the material [3]. The most important problem encountered when machining these alloys is the control of the resulting chips. During the machining of some aluminum alloys, a fairly thick, strong, not easily broken continuous chip structure usually appears. This situation causes serious problems in the removal of chip, especially in the drilling process. In addition, the adhesion of the material to the tool due to its ductility also creates another machining problem [3, 4].

Drilling is the type of operation that has the most problems in machining, especially in removing the chip from the cutting area. In the drilling process, chip formation occurs in the closed area and cannot be seen. It is much more difficult to discharge of resulting chips and transmit the cutting fluid. Friction between chip and helical channel and friction between drill and machined surfaces is much greater. The chip angle varies throughout the mouth and therefore different cutting conditions occur throughout the mouth. For this reason, chip removal with a drill occurs in much more complex and severe conditions than with a single-mouth tool [4]. In the researches, when the hole drilling process is compared with other machining processes, it has been observed that the drilling process has a 33% application frequency [5].

The fact that hole drilling processes have such an important share among machining processes increases the importance of the studies to be carried out on the solution of the problems encountered in the hole drilling process. In this field, various studies have been conducted examining tool life and hole quality, especially in the drilling of ductile materials such as aluminum [6, 7].

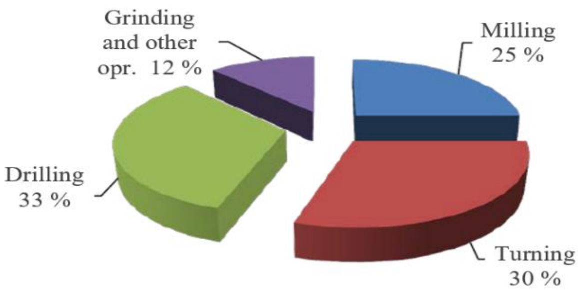


Figure 1. Comparison of drilling with other chip removal operations [5].

The metallurgical structure of the machined material, tool material and geometry, cutting parameters, cooling conditions, machine properties are the factors affecting the machining performance in machining. These factors are also effective in drilling performance as in other machining types [8, 9]. If a performance assessment is to be made in the drilling process, the evaluation criteria can be characterized by cutting tool life, hole quality (surface quality, measurement-shape accuracy in holes) and chip removal efficiency. The factors affecting these criteria are shown schematically in Figure 2.

The application of cutting/cooling fluid is very important to improve machining performance in the machining process. Because in this process, cutting fluids decelerate the heat generated in the cutting zone, while reducing friction on the tool-chip interface with a lubricating effect. It also helps the chip to move away from the cutting area. Thus, the application of cutting fluid increases the machining speed, as well as supply the tool life and improves product quality [10, 11].

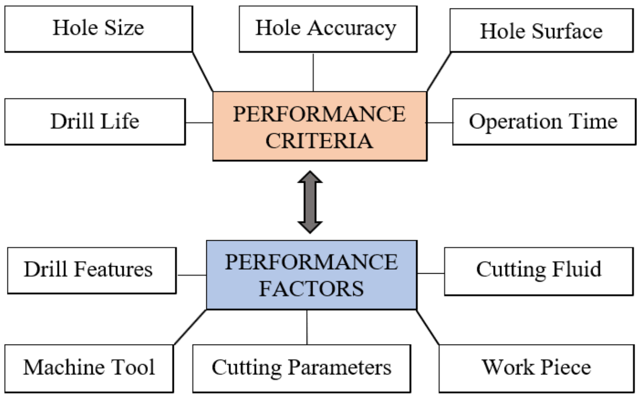


Figure 2. Factors affecting hole drilling performance criteria.

The economics of production, including product quality, production quantity and time, is not enough to describe a successful manufacturing process. In addition, nature and human health should not be adversely affected in this process [10-12]. In addition to its related advantages, the application of cutting fluid with traditional cooling conditions also causes negatives in the manufacturing process. When the waste management of cutting fluids with chemical content is not done well, it mixes with the soil and damages the nature. It has been observed that these chemical liquids that come into contact with the skin of employees on the production line also harm human health [12]. However, the fact that processes such as the supply, storage and disposal of cutting fluids cause additional costs also increases the total cost of production [13, 14].

It is clear that the control of the amount of coolant used in the machining process is important both in terms of its impact on nature and human health, and in terms of the total cost of production. Therefore, reducing the amount of coolant used is seen as a requirement related to the mentioned situations. However, while reducing the amount of coolant used, it is also necessary not to adversely affect the product quality and cutting tool life [15, 16]. The Minimum Quantity Lubrication (MQL) method, the use of which has become widespread in recent years, is a method applied to meet these requirements. In the literature research on the subject, it has been seen that this method provides much better results than dry cutting and close to traditional cooling in terms of tool life and surface quality. Dhar and Islam compared MQL with dry conditions when turning AISI 1040 steel and obtained much better results with MQL in terms of temperature in the cutting zone, tool wear and surface roughness. [16]. Srejit examined the machining performance of AA6061 alloy under three different conditions: dry cutting, MQL and conventional cooling, and found that MQL could be a good alternative to conventional cooling [17]. In addition, various studies have been conducted to determine the most accurate application of the MQL method. In these studies, the type of cutting fluid used, the flow rate and pressures to be applied were investigated. The effects of conditions such as nozzle position, cutting tool properties and cutting parameters on machining performance were also investigated in external MQL applications [18, 19]. Rahim and Sasahara used four different cooling conditions in high-speed drilling of TI6Al4V alloy. These are air cooling, conventional cooling, and application of palm oil and synthetic oil separately to the cutting area with MQL. According to their results, better processing performance was achieved when palm oil was applied to the cutting zone with MQL [19]. Bhowmick and Alpas compared MQL, dry and conventional cooling conditions in drilling 319 Al alloy. In experiments where they used HSS tools with different coating properties, they did not examine the relationship between the force and torque acting on the tools and the wear on the tools. At the end of the experiments, they were able to obtain better results with MQL than dry cutting [20]. In their study, Krishnan and Raj developed an MQL system and applied waste vegetable oils to the cutting zone in the AISI 304 alloy drilling process. They carried out various tests and CFD analyzes for the optimum nozzle design. At the end of the study, they compared the forces acting on the tool, wear on the tools and chip morphology with conventional cooling conditions. They observed that the high viscosity vegetable oil used in the MQL system could provide a reduction in forces [21]. Buss et al., examined the flow behavior of oil mist in the channels inside the tool through numerical analysis during the drilling process using the internal MQL method. As a result of multiphase dynamic analyses, they simulated that most of the oil mist could form an oil film in the regions at the channel entrance, and a small portion could form an oil film in the regions at the channel exits [22].

In machining operations where the cutting event takes place indoors, such as drilling holes, it is very important to choose the correct coolant application parameters. It is estimated that internal or external application of the MQL method in the hole drilling process can significantly affect the results. However, in the literature research, no studies were found that compared these different applications satisfactorily. In drilling, since it is difficult for the cutting fluid to reach the cutting zone, the application of cutting fluid with a small amount of oil mist, such as the MQL technique, may be insufficient. For this reason, in some studies where the MQL method was applied externally in the application of hole drilling, results close to dry cutting conditions were observed [23]. In other studies, conducted on the subject, better results were obtained than dry cutting when applying external MQL, especially in holes that are not deep [19, 20, 21]. On the other hand, it is understood that it is important to correctly adjust the flow rate and pressure parameters of internal MQL application in the drilling process [22].

In order to examine in more detail, the reasons for the different results obtained in the current studies on the effect of the MQL method on the drilling performance, this study was carried out. For this purpose, drilling experiments were carried out under three different conditions: external MQL method, internal MQL method and dry cutting. These conditions have been tested with different cutting parameters. As a workpiece material, AA2024 alloy, which is one of the aluminum alloy groups with a high tendency to plastering, was selected. Thus, a satisfactory comparison of the effect of internal application and external application of the MQL method on processing performance was made in the study.

2. Results and Dicussion

In this study, the effect of the application of the MQL method on the drilling of aluminum alloys was invest gated. In this context, AA2024 alloy was selected as the workpiece. The MQL application was applied from within the tool and from outside the tool (with a nozzle). By comparing these two conditions with dry cutting, experiments were conducted under 3 different cooling conditions in total. In order to examine the effect of different cooling conditions on the machining performance during the experiments, and to what extent different cutting parameters affect the experiments, the experiments were carried out at three different cutting speeds and three different feeds. While determining the cutting parameters, the recommendation of the cutting tool company and the applications in the literature were taken into consideration. The surface roughness values (Ra) of the holes obtained at the end of the experiments and the wear (w) data on the tools were determined as performance criteria. The control factors and levels determined for the experiments are given in Table 1.

Table 1. Control factors and levels for the experiments

Factors	Cooling condition (A)	Cutting speed *{m/min}* (B)	Feed *{mm/rev}* (C)
1.Level	Internal MQL	100	0.10
2.Level	External MQL	125	0.15
3.Level	Dry Cut	150	0.20

The experiments were designed according to the Taguchi L9 vertical array. In this way, the number of 27 experiments were reduced to 9. Table 2 shows the experimental design used when performing drilling experiments on alloy AA2024.

Table 2. Taguchi L9 vertical array experiment design for AA2024.

		A	B	C
Number of experiments	Variables	Cooling condition	Cutting speed *m/min*	Feed *mm/rev*
D1	A1B1C1	Internal MQL	100	0.10
D2	A1B2C2	Internal MQL	125	0.15
D3	A1B3C3	Internal MQL	150	0.20
D4	A2B1C3	External MQL	100	0.20
D5	A2B2C1	External MQL	125	0.10
D6	A2B3C2	External MQL	150	0.15
D7	A3B1C2	Dry Cutting	100	0.15
D8	A3B2C3	Dry Cutting	125	0.20
D9	A3B3C1	Dry Cutting	150	0.10

A total of 9 cutting tools were used by drilling with a new cutting tool under all conditions. Each experiment was repeated 30 times and it was aimed to observe the wear /plastering of the cutting tool used in each condition. The mean values of the relevant conditions were determined by taking the arithmetic average of the data obtained at the end of these 30 repetitions. AA2024 aluminum sheets with a thickness of 25 mm were used as the workpiece. The position of the test holes on the plates is as shown in Figure 4. The holes are positioned with the optimal distance to the workpiece.

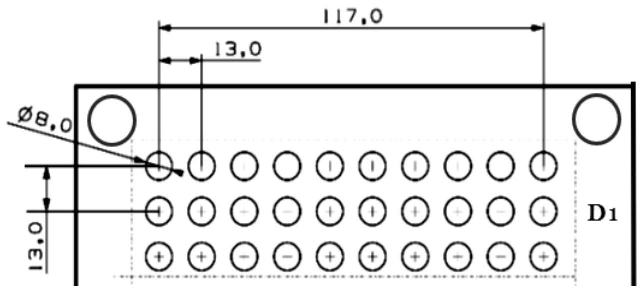


Figure 4. The position of the holes on the workpiece sample.

The chemical and physical properties of the used AA 2024 aluminum alloys are given in Table 3.

Helical, two-mouth, 8 mm diameter, cooling channel, uncoated carbide drills were used in the experiments. Cutting tools were selected as internal cooling channels because the internal MQL system was applied in the experiments. The measurements related to the cutting tools used are given in Figure 5.

The experiments were carried out at the ECOSPEED 2600 (HSM) high-speed machining center. Technical information about the machine tool is given in Table 4.

Table 3. Chemical and mechanical properties of AA2024 aluminum alloys.

Si	Cu	Mn	Mg	Cr	Zn
0.5	4.5	0.6	1.5	0.1	0.2
Heat treatment	Yield Stress *(MPa)*	Tensile Stress *(MPa)*	Elongation (%)	Stiffness Brinell	Modulus of Elasticity *(GPa)*
T4	315 - 330	440 – 465	20.0	120	73.1

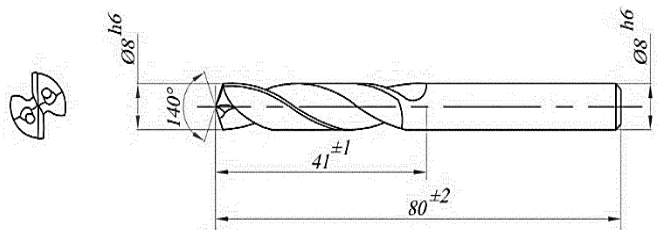


Figure 5. Uncoated carbide drills used in experiments

Table 4. The Technical characteristics of the ECOSPEED 2600 CNC machine tool

Name of the Machine	ECOSPEED 2600 HSM	
Control Unit	SIEMENS 840D	
Maximum speed	30 000	*rev/min*
Machining Table	2500 x 7000	*mm*
Feed on the Axes	X:65 000, Y ve Z:50.000	*mm/min.*
Axial Motion	X: 6800, Y: 2600, Z: 670 A: ±40º, B: ±40º	*mm*

The cooling system on the ECOSPEED 2600 (HSM) machine is the VOGEL Digital-Super MQL cooling system. This system is capable of cooling both from the inside and from the outside. Constant flow rates and pressures were used in the experiments. Haughton CDT MAX-ML 200 cutting oil was used in the experiments. The technical characteristics of the VOGEL brand MQL system used are given in Table 5.

Table 5. Technical characteristics of the VOGEL Digital Super MQL system

Application of cutting fluid	Internal/ External MQL	
	External MQL	
Number of nozzles	8	*piece*
Filter capacity	0.025	*mm*
Maximum flow rate	50	*L/min.*
Maximum pressure	5	*Bar*
	Internal MQL	
Maximum flow rate	20	*L/min.*
Maximum pressure	7	*Bar*

"Mahr" brand Perthometer M1 type, desktop and printable surface roughness measuring device was used for surface roughness measurements of the hole surfaces drilled into the samples. For the reliability of the measurements, four measurements were made from separate points for each measured hole. The average surface roughness (Ra) values were determined for each hole measured by taking the arithmetic mean of the values obtained as a result of the measurements.

The technical characteristics of the surface roughness measuring device used are given in Table 6.

Table 6. Technical characteristics of the surface roughness measuring device.

MODEL	Mahr Perthometer M1	
The principle of measurement	The spectator tip method	
Scanning speed	0.5	*(mm/s)*
Measuring range	100 – 150	
Profile resolution	12	
Filter	Gaussian	
Cut off	0.08 – 0.25 – 0.8 – 2.5	*(mm)*
Scan lengths	1.75 – 5.6 – 17.5	*(mm)*
Number of sampling lengths	1 – 5 can be selected	
Dimensions	190 x 170 x 75	*(mm)*
Approximate weight	900	*(gr)*

In order to measure the effect of process parameters on quality characteristics, the data obtained were subjected to variance analysis. In this study, surface roughness was chosen as the quality characteristic, and cooling condition, cutting speed and feed parameters were selected as process parameters. In addition, in order to determine the optimum conditions, the Signal/Noise (S/N) test was also applied to the data by using the "the smallest is the best" approach. In addition, the results of the experiment were evaluated with the artificial neural networks (ANN) approach and prediction models were obtained. The ANN model used is a feed-forward multilayer ANN model. Pythia software was used while creating the ANN model. Thanks to this software, a 3-6-5-1 network structure has been obtained that can give the closest result to reality. After a part of the data obtained from the experiments was reserved for testing and verifying the ANN model, the remaining part was used in the learning process. The activation function used in the ANN model is a sigmoid-logistic function called "Fermi". In this function, data ranges from 0 to 1 and normalized data is used. The predictions made by the ANN model created for this study were tested with the separated data. Then, the "Absolute Percentage of Change (R2)" verification method was used to measure the prediction performance of the model. Finally, the estimates made by the Taguchi method and the estimates made by the ANN method were compared. The schematic view of the experimental setup, measurements and analyzes is as shown in Figure 6.

3. Results and Discussions

3.1 Analysis of surface roughness (Ra) data

In experiments where 30 drilling repetitions were performed for each cutting condition, 1., 15. and 30. The surface roughness of the three holes was measured for each condition. By taking measurements from 4 different places for each hole, the arithmetic mean of these 4 measurements was accepted as the surface roughness of that hole. Measurements were carried out in accordance with TS EN 10049 standard. In Table 7, the average Ra value obtained from the 1., 15. and 30. holes for each different condition and the arithmetic mean of these three Ra values are given.

In the graphics in Figure 7 in drilling AA2024 aluminum alloy using the internal MQL (a) external MQL (b) and dry cutting (c) methods, the resulting Ra values for 9 different cutting parameters with different cutting parameters (cutting speed - feed) combination in each cooling condition are given. The D1-D9 series used in the graphs express different cutting conditions. The values on the "Repeat Test" axis represent the 1st, 15th and 30th holes drilled using the same cutting condition and the same tool in the repeat tests.

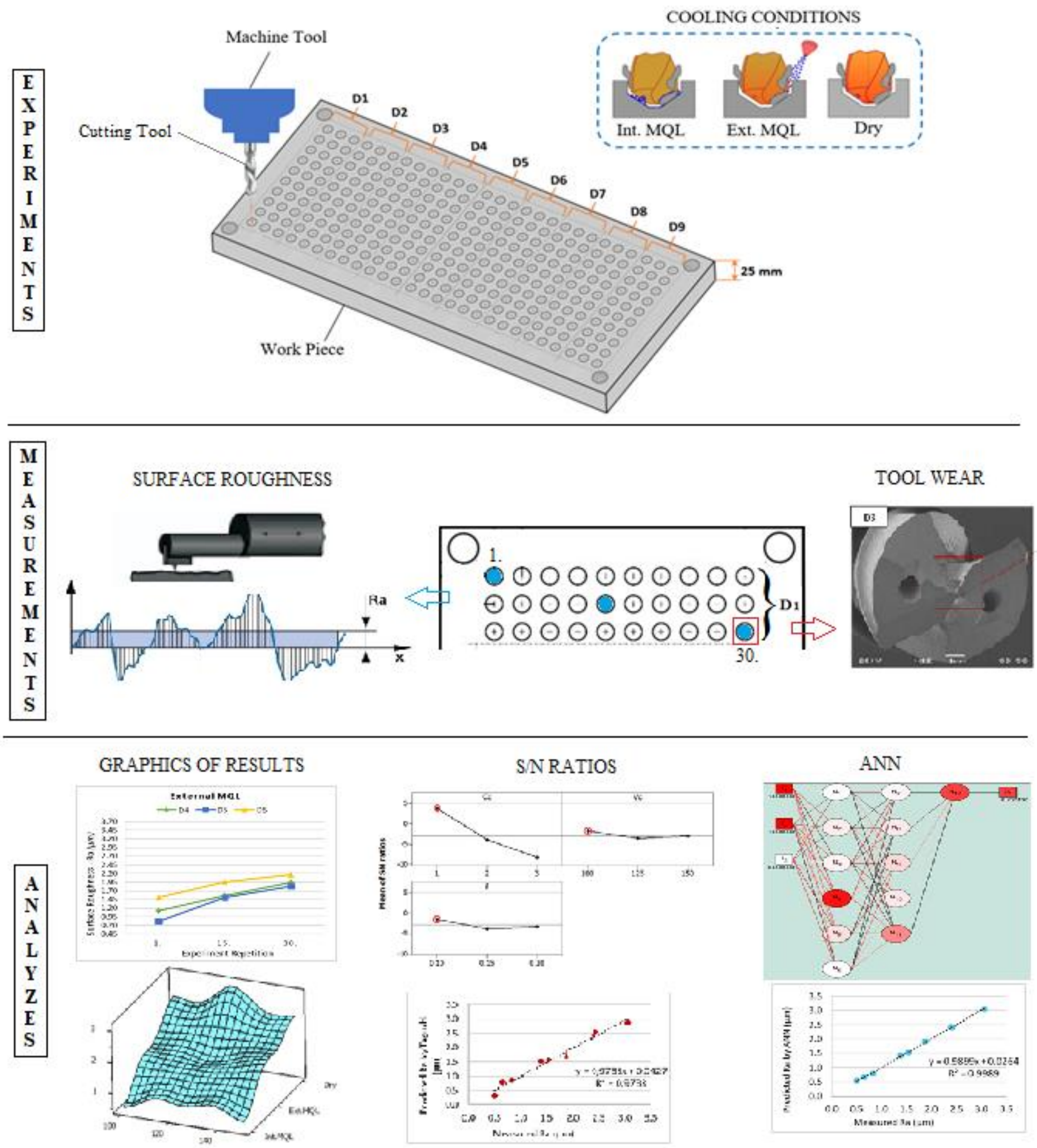
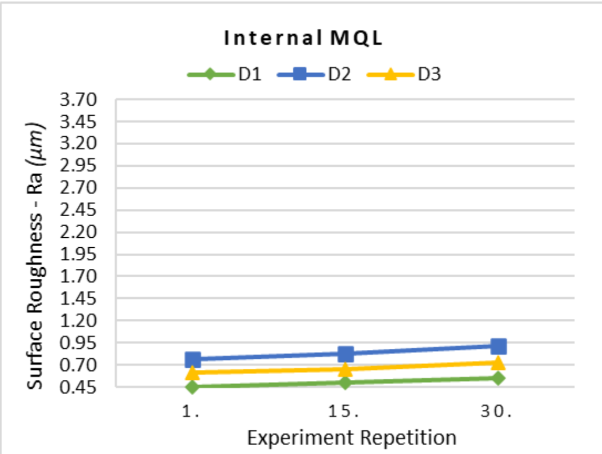


Figure 6. Schematic view of the experimental setup, measurement and analyzes.

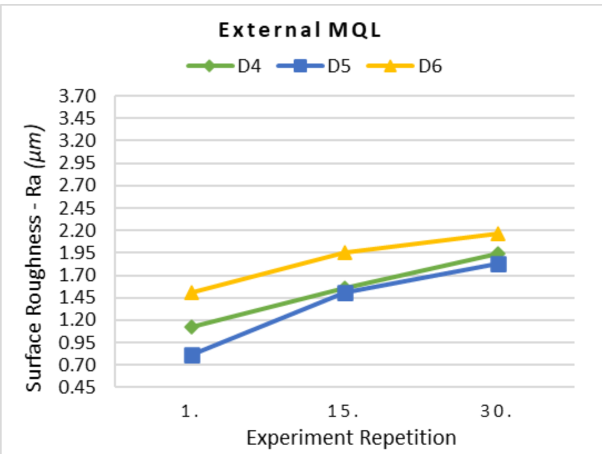
In the graphs in Figure 7 it is seen that there is a slight increase in Ra surface roughness values from the first hole to the last hole for all cutting conditions. This means that a tool used in the repeat test could not perform on the 30. hole as it did on the 1st hole, that is, it was worn/smeared. It is an expected situation that the tool will begin to wear under repeated machining conditions [24]. The point that needs to be considered here is to what extent the applied cooling methods can prevent deformation in the tool. When the graphs in Figure 7 are examined, it is seen that the increase in Ra from the first hole to the last hole is below 20% in the internal MQL application in a graph, around 60% in the external MQL application in the b graph and around 50% in the dry cutting application in the c graph. It is thought that this increase, which is much higher in external MQL and dry cutting applications compared to internal MQL application, may be due to the higher level of smearing and/or wear on the cutting edges of the tools at the end of 30 holes. When external MQL and dry cutting conditions are compared, the values observed between 1-1.5µm in external MQL application at the beginning are seen to increase to 2-2.5µm values at the end of 30 holes. In dry cutting, the data that were initially observed as 2-2.5µm were observed to increase to 2.7-3.7µm after 30 holes. These results show that the external MQL and dry cutting conditions may be insufficient in the drilling process, the tool cannot maintain its property for a long time under these conditions and deforms quickly. For obtain average Ra value of a cutting condition, the surface roughness of the first, fifteenth and thirtieth repeated holes belonging to that cutting condition was measured and determined by taking the arithmetic average of the measured Ra values. Thus, by taking the arithmetic average of the surface roughness (Ra) values of these holes measured in 30 drilling operations repeated for 9 different cutting conditions, the average Ra values were calculated for each different condition.

Table 7. Estimated Ra values with measured Ra values

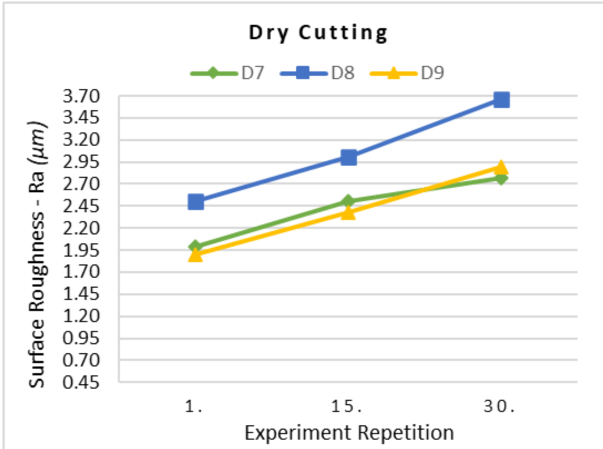
Number of experiments	Variables	A	B	C	Surface roughness results (µm)			
		Cooling condition	Cutting speed *(m/min)*	Feed *(mm/rev)*	1.	15.	30.	Avg.
D1	A1B1C1	Internal MQL	100	0.10	0.452	0.502	0.545	0.500
D2	A1B2C2	Internal MQL	125	0.15	0.764	0.825	0.912	0.834
D3	A1B3C3	Internal MQL	150	0.20	0.613	0.646	0.721	0.660
D4	A2B1C3	External MQL	100	0.20	1.129	1.556	1.943	1.543
D5	A2B2C1	External MQL	125	0.10	0.815	1.514	1.832	1.387
D6	A2B3C2	External MQL	150	0.15	1.503	1.953	2.165	1.874
D7	A3B1C2	Dry Cut	100	0.15	1.993	2.503	2.763	2.420
D8	A3B2C3	Dry Cut	125	0.20	2.505	3.005	3.666	3.059
D9	A3B3C1	Dry Cut	150	0.10	1.899	2.375	2.893	2.389



(a)



(b)



(c)

Figure 7. The change in surface roughness (Ra) values obtained from the 1st. 15th and 30th holes in 30 drilling repetitions for each cutting condition on AA2024 alloy.

3.2. Analysis of variance of average surface roughness (Ra) data

In order to see the effect of the process parameters (cooling condition, cutting speed and feed) on the surface roughness (Ra) determined as a quality characteristic; the relevant data were subjected to variance analysis. The ANOVA results obtained are given collectively in Table 8.

At the end of the analysis of variance. the P value obtained for the cooling condition was less than the value of α (0.05). Since P < α. the type of cooling condition, which is the process parameter, has a significant effect on the surface roughness. which is the quality characteristic. If we look at the degrees of influence of the process parameters from the PD column, it seems that the cooling condition affects the surface roughness the most with 92.5%. Therefore, it is seen that cooling conditions greatly affect the surface quality in drilling operations carried out in closed areas. Because, correctly applied MQL method reduces friction by lubricating the tool-chip and tool-workpiece interfaces. In addition, in the MQL method, compressed air applied to the cutting area helps remove the resulting chip without getting stuck in the hole [25]. For these reasons, it is thought that using the internal MQL method in hole drilling operations without reducing cutting and feed speeds will help to obtain a more error-free product in a shorter time.

Among the process parameters. the P values of the cutting speed and feed factors are 0.593 and 0.461, respectively, and are greater than the acceptable error rate of 0.05. Since the P value of the feed parameter is closer to 0.05, it seems that the effect on surface roughness is greater than the cutting speed. On the other hand, the cutting speed has a more unstable effect compared to other process parameters. While explaining the effect of cutting speed on Ra. increasing the cutting speed makes it easier to cut, thereby improving the surface quality. But the chip formed at the same time and the chip jammed in the unit area increase with the increase in the cutting speed. Jammed chips increase the loads and vibration that affect the tool. Therefore, while increasing the cutting speed facilitates cutting, on the other hand, it deforms the surface with more chip compression [2].

This situation is also considered to be the cause of the unstable effect observed in the ANOVA results.

3.3. Signal/Noise (S/N) analysis of average surface roughness (Ra) data

The Taguchi technique was used in the design of the experiment and in the analysis of the results obtained. Since the lowest surface roughness values will give the best results, in this study which uses the “Smallest is the best” approach. The smallest-best function used in the Taguchi method is given in Eq (1).

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

The surface roughness data obtained by drilling the AA2024 alloy were subjected to Signal-to-Noise (S/N) analysis. In Table 9, the S/N ratios of the control factors according to the Ra results for AA2024 are given.

In Table 10, the analysis of each control factor for the average surface roughness values was performed with the S/N and mean response table. The maximum-minimum value in Table 10 is the difference between the maximum average of the respective levels of each parameter and the average of the minimum values. The higher this value. the greater the degree of influence of that factor [26]. In this context, when Table 10 is evaluated, it can be said that the most important factors affecting the average surface roughness data obtained by drilling the AA2024 alloy are the cooling condition, feed and cutting speed.

One of the important steps in the Taguchi technique is to determine the optimum levels. These levels are used to draw the effect graphs of the levels [26]. In the graph in Figure 8 where the highest S/N ratios express the optimal conditions, these optimal levels are clearly visible.

Table 8. ANOVA results (ANOVA results for surface roughness data obtained by drilling AA2024 alloy).

Source	DF	SS'	SS	MS	F	P	PD (%)
Cooling condition (C_c)	2	5.7562	5.7562	2.8781	35.32	0.028	92.5
Cutting speed (V_c)	2	0.1119	0.1119	0.0559	0.69	0.593	1.8
Feed (f)	2	0.1903	0.1903	0.0951	1.17	0.461	3.1
Error	2	0.1630	0.1630	0.0815			2.6
Total	8	6.2213					100.0

DF: Degree of freedom. SS: Pure sum of squares. SS: Sum of squares. MS: Mean square.
PD: Percentage distribution. F: F-Test statistics. P: Significance values
(S = 0.285454 R-Sq = 97.38% R-Sq(adj) = 89.52%)

Table 9. S/N ratios of control factors according to Ra results for AA2024

Number of experiments	C_c: Cooling Condition	V_c: Cutting Speed (m/min)	f: Feed (mm/rev)	Ra: Average Surface Roughness (µm)	Ra_p: Predicted Ra Values (µm)	S/N ratio
D1	1 (Internal MQL)	100	0.10	0.500	0.319	6.02060
D2	1 (Internal MQL))	125	0.15	0.834	0.875	1.57668
D3	1 (Internal MQL)	150	0.20	0.660	0.801	3.60912
D4	2 (External MQL)	100	0.20	1.543	1.584	-3.76732
D5	2 (External MQL)	125	0.10	1.387	1.528	-2.84153
D6	2 (External MQL)	150	0.15	1.874	1.693	-5.45539
D7	3 (Dry)	100	0.15	2.420	2.561	-7.67631
D8	3 (Dry)	125	0.20	3.059	2.878	-9.71159
D9	3 (Dry)	150	0.10	2.390	2.431	-7.56796

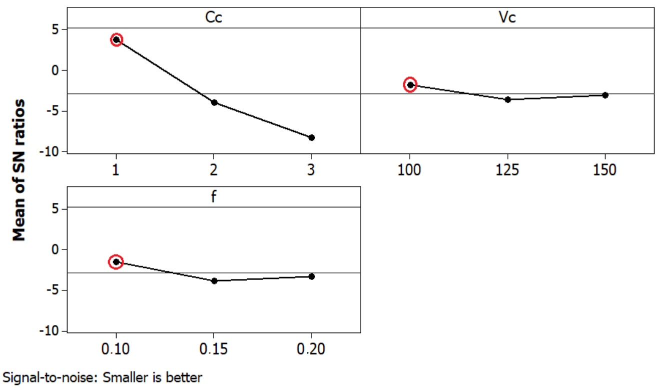


Figure 8. The main effect graph for S/N ratios according to Ra results obtained at AA2024 drilling

Table 10. Average S/N and mean responses for each of the levels of parameters.

Cutting parameters	Level 1	Level 2	Level 3	Max-Min
	S/N Levels			
A (Cooling Conditions C_c)	3.739	-4.021	-8.319	12.054
B (Cutting speed. Vc)	-1.808	-3.659	-3.138	1.851
C (Feed. f)	-1.463	-3.852	-3.290	2.389
	Mean Levels			
A (Cooling Conditions C_c)	0.6647	1.6013	2.6230	1.9583
B (Cutting speed. Vc)	1.4877	1.7600	1.6413	0.2723
C (Feed. f)	1.4257	1.7093	1.7540	0.3283

Table 11. Optimum levels of control factors for surface roughness (Ra).

Control factors	Symbol	Unit	Opt. level	Opt. value
Cooling condition (A)	Cc		1	Internal MQL
Cutting speed (B)	V_c	m/min	1	100
Feed (C)	f	mm/rev	1	0.1

The optimum results of the surface roughness values obtained using the Taguchi optimization method can be either any of the conditions used in the current experiments or a condition other than the current experiments. The optimum results obtained in this study are seen to be the experimental condition used in the experiments (First experiment: D1). In the Taguchi method, Eq (2) is used to estimate the surface roughness (Ra_p) of the optimum condition.

▯▯p= (▯1 − ▯▯▯) + (▯1 − ▯▯▯) + (▯1 − ▯▯▯) + ▯▯a (2)

Here, A1, B1 and C1 are the optimum responses for Ra, and ▯▯a is the arithmetic mean of the Ra values measured in the experiments. When the values are put in place in the equation, Rap = 0.319 mm comes out. The calculation made using the related prediction module of the Minitab package program has also been confirmed. The optimum conditions calculated by the Taguchi method should be within the optimization result range. A confidence interval is needed to compare the Ra value calculated for the optimum condition with the Ra value measured in the experiment. The confidence interval in question can be expressed as in Eq. (3).

$$[Ra_p - CI] < Ra < [Ra_p + CI] \quad (3)$$

Here, in order to be able to calculate the CI value that determines the confidence interval, Eq (4) and Eq (5) is taken advantage of.

$$CI = \sqrt{F_{\alpha;1;f_e} v_e \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \quad (4)$$

$$CI = \sqrt{F_{\alpha;1;f_e} v_e \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \quad (5)$$

Where N is the number of experiments, T_{dof} is the degree of freedom of the main factors, n_{eff} is the number of effective repetitions, F_α is the ratio of F at the level of 1 and 95% confidence, α is the significance level, f_e is the degree of freedom of the error, and the variance of the error, and r is the number of repetitions for the verification test. For r = 3, N = 9, T_{dof} = 6, n_{eff} = 1.286 was calculated.

In Equation 4, the parameter determining the confidence interval was calculated as (CI) ±0.391 when the values $F_{0.05,1,2}$ = 18.51 (using the F test table), v_e =0.0815, n_{eff} = 1.286 were replaced.

For the confidence interval of the estimated mean optimal surface roughness at 95% reliability, when the values of CI, Ra and Rap are substituted in Equation 3 as follows:

[0,319 – 0,391] < 0,500 < [0,319 + 0,391] →-0,072 < 0,500 < 0,710

3.4. Comparison of Taguchi and Artificial Neural Network (ANN) methods in estimating Ra results

Artificial neural networks have become one of the prediction models used in recent years in the field of manufacturing. While creating the ANN model, it is necessary to determine the appropriate network structure, derive the most accurate equations, check the learning, test and prediction values, etc. operations need to be made. In this study, the ANN model was created using the Pythia package program. For the Ra output value, cooling conditions, cutting speed and feed were used as input values. The 3-6-5-1 network structure was used as the most suitable network structure. This network structure, which has 3 levels, has 2 hidden layers and a total of 12 neurons. This network structure used is as shown in Figure 9.

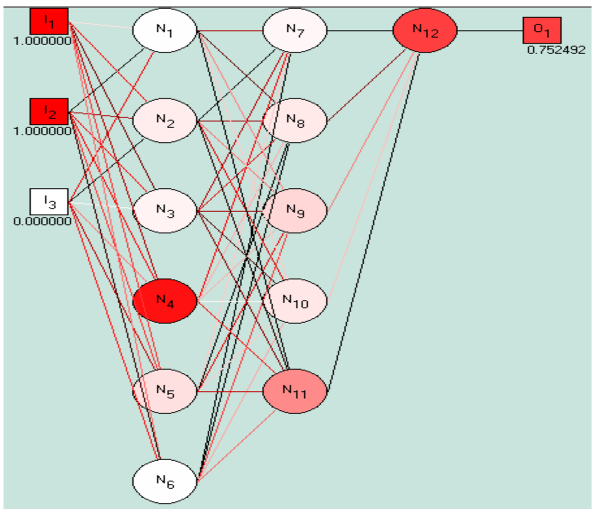


Figure 9. The 3-6-5-1 network structure used in the ANN model

The applied ANN model is feed-forward and a sigmoid function called “Fermi” is used as the transfer function. The Fermi transfer function used is as in Eq. (6):

$$N_{(i)} = \frac{1}{1 + e^{-4(E_i - 0.5)}} \tag{6}$$

Since normalization is required for the selected inputs to be in a comparable range, the input and output values are normalized between 0 and 1 by following Eq. (7).

$$N'_v = \left[\frac{N_i - N_{min}}{N_{max} - N_{\min}}\right] \tag{7}$$

After the input data is normalized with Eq. (7), to calculate the E_i (1) values of level 1 neurons in Eq. (6), Eq. (8) can be written as follows:

$$E_{i(1)} = w_{1i}C'_c + w_{i2}V'_c{}' + w_{i3}f' \tag{8}$$

E_i values for level 2 neurons were calculated with Eq. (9).

$$E_{i(2)} = w_{1i}N_1 + w_{2i}N_2 + w_{3i}N_3 + \cdots + w_{ii}N_i \tag{9}$$

For the level 3 neuron, the Ei value was calculated with Eq. (10).

$$E_{i(3)} = w_{7i}N_7 + w_{8i}N_8 + w_{9i}N_9 + \cdots + w_{ii}N_i \tag{10}$$

In the equations mentioned above, i expresses the number of neurons at that level. The adapted equation for the estimation of Ra values with ANN using the above equations is as follows:

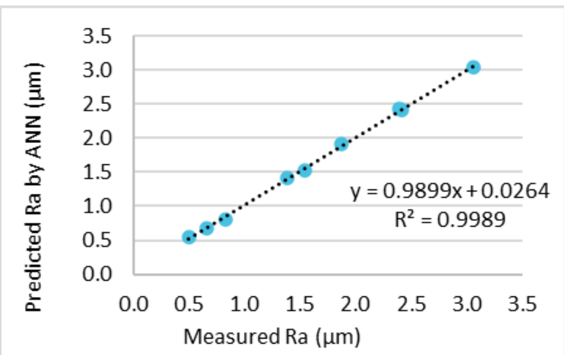
$$N_{Ra} = \left(1 + e^{-4(-1.549869N_7 + 0.750294\,N_8 - 0.260733\,N_9 - 0.122533\,N_{10} + 1.786629\,N_{11} - 0.5)}\right)^{-1} \tag{11}$$

In order to calculate the reliability of the applied model, the absolute percentage of change expressed as R2 was used in the theoretical analysis of the model. For a reliable model, R2 is expected to be between 80% and 100% [27]. In the current study, the R2 value obtained from the YSA model for Ra is calculated as follows.

$$R^2 = 1 - \left[\frac{\sum i\left(Ra_i - N_{Ra_i}\right)^2}{\left(\llbracket (N) \rrbracket_{Ra_i}\right)^2}\right] \tag{12}$$

The R2 value obtained from the ANN model for Ra in Eq. (12) was calculated as 99.86%.

A comparison between the estimated outputs and the measured Ra values by YSA and Taguchi analysis is given in Table 12 and Figure 10.



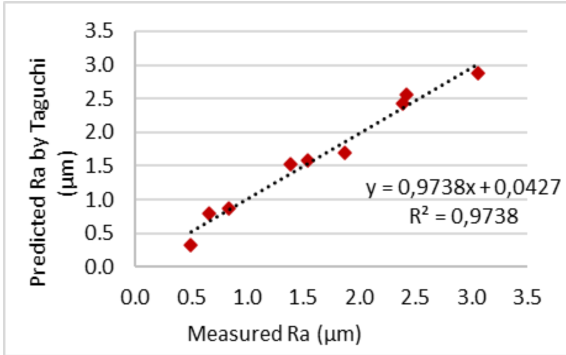


Figure 10. The compatibility of the estimated Ra values with the measured Ra value

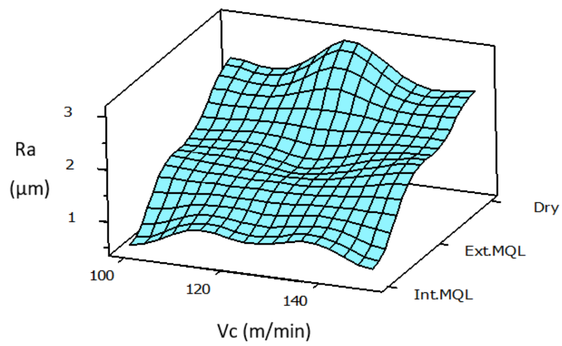
Table 12. Estimated Ra values with measured Ra values

Test No	Variable	Measured Ra (µm)	Predicted Ra by ANN (µm)	Predicted Ra by Taguchi (µm)
D1	A1B1C1	0.500	0.552	0.319
D2	A1B2C2	0.834	0.801	0.875
D3	A1B3C3	0.660	0.684	0.801
D4	A2B1C3	1.543	1.530	1.584
D5	A2B2C1	1.387	1.409	1.528
D6	A2B3C2	1.874	1.910	1.693
D7	A3B1C2	2.420	2.406	2.561
D8	A3B2C3	3.059	3.039	2.878
D9	A3B3C1	2.390	2.426	2.431

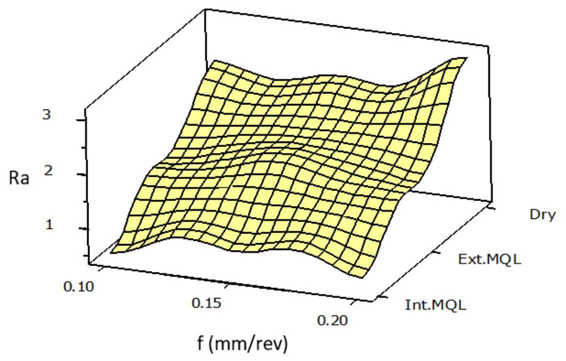
According to these results, it can be said that the outputs obtained from the equations are normally distributed. Due to the high R^2 value in the reliability and validation test results of the models, mathematical models obtained with both YSA and Taguchi estimations can be used to predict the Ra results obtained in drilling AA2024 aluminum alloy. When the prediction performances for Taguchi analysis and artificial neural networks (ANN) are compared, it can be said that the ANN model gives closer to the correct outputs both in terms of theoretical analysis and graphical analysis.

3.5. Effect of cutting tool wear on surface roughness

The variation of these values according to different cutting parameters (Vc and f) and cooling conditions is shown in Figure 11



(a)



(b)

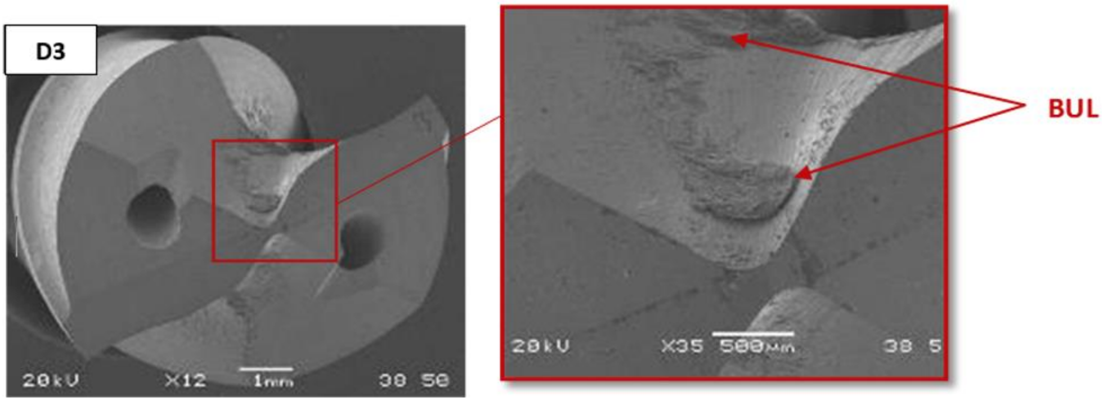
Figure 11. Change of surface roughness according to machining conditions: a) Change according to the cutting speed (Vc) and cooling condition. b) Change according to the feed (f) and cooling condition

Graph a in Figure 11 shows a clear increase in surface roughness as the feed value increases under all cooling conditions. When the effect of cooling conditions on surface roughness is examined in the same graph, it is seen that different cooling conditions used when machining with the same feed parameters have a significant effect on surface roughness. The highest surface roughness was observed under dry cutting conditions, while the lowest surface roughness, as expected, was observed during internal MQL application. The high smearing tendency caused by the high ductility characteristic of AA2024 alloy has been reduced by the application of internal MQL. It is thought that this decrease in the tendency to form built-up edge (BUE) combined with the low strength of the material has positive results on the surface quality [28, 29].

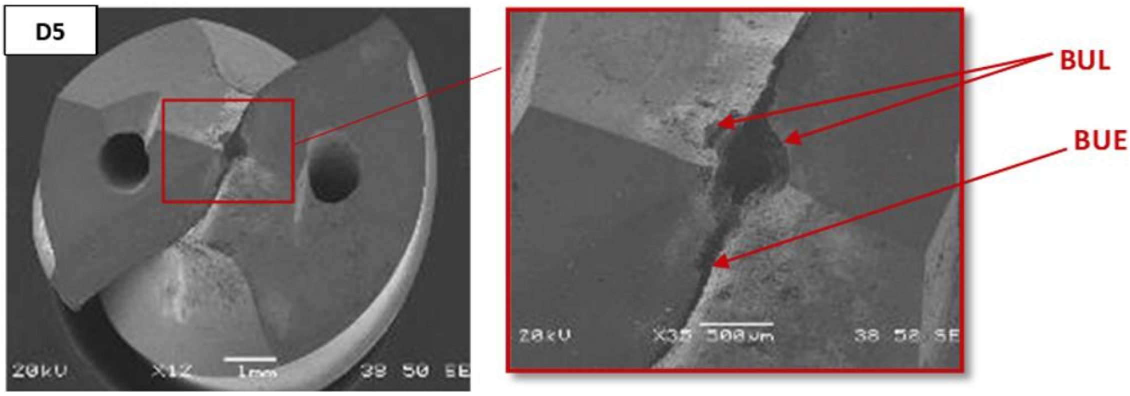
Figure 11 shows the effect of cutting speed and cooling conditions on surface roughness in graph B. When the graph is examined, it is seen that the change in cooling conditions seriously affects the surface roughness when machining at the same cutting speed. While the highest surface roughness is observed in dry cutting conditions, it is seen that the lowest surface roughness is obtained under internal cooling conditions. In the same graph, it is seen that the effect of the change in cutting speed on surface roughness is more unstable, especially under dry cutting and external cooling conditions. It is generally expected that the surface roughness will decrease with the increase of cutting speed in machining [30]. In the drilling process, the situation may be slightly different. Since the drilling process takes place in a closed area, an increase in the volume of chips released per unit time along with an increase in cutting speed can increase chip compression and plastering. In this case, the surface roughness may be more than expected [24, 31]. It is estimated that the uncertainty in the effect on the surface roughness of the cutting speed seen in the graph may be caused by the mentioned conditions of the drilling operation.

A separate cutting tool was used for each condition in the drilling tests performed under 9 different cutting conditions. In order to see the wear on the cutting tools used for each different condition, the experiment was repeated 30 times under the same condition with the same tool. At the end of the experiments, images were taken with Scanning Electron Microscope (SEM) in order to detect the wear of the tools. Detailed images taken from the cutting edges of the tools with SEM are given in Figure 12.

AA2024 aluminum alloy is a ductile and highly adhesive material. For this reason, it is very likely that it will be plastered to the team in drilling operations where chip evacuation is difficult because it takes place in a closed area. When the application of cutting fluid in the drilling process is not applied correctly, it will be inevitable that the ductile aluminum will be plastered onto the tool [2-4]. In dry cutting conditions, it is expected that aluminum will be plastered onto the tool during drilling. The main purpose of this study is to compare the effect of MQL application from within the tool and MQL application with nozzle from outside the tool on machining performance in drilling operations on ductile materials. When the surface roughness of the holes obtained from the experiments was examined in the previous sections, it was revealed that much smaller Ra data were obtained in the internal MQL application than in the external MQL application. The reason for the observation of much larger surface roughness data in the external MQL application compared to the internal MQL application is understood when looking at the SEM images of the cutting tools given in Figure 12. When looking at the SEM image (a) of the tool used in the D3 experiments in Figure 10 and where internal MQL application is applied, it is seen that the chisel edges retain their shape. Only a certain amount of chip accumulation (Built Up Layer -BUL) in the form of a layer on the chip surface of the tool is visible. Again, this time in Figure 12, when the SEM images (b) of the tool used in the D5 experiments and where external MQL application is applied are examined, it is seen that both the main cutting edges and the auxiliary cutting edge (chisel edge) have lost their form. It is seen that the workpiece material starts from the auxiliary cutting edge in the center of the tool and sticks to the tool markedly towards the main cutting edges, disrupting the cutting form of the tool. In addition to the Built-Up Edge (BUE) chips observed along cutting edges, there is also in the forms of layers built-up layer (BUL) on the chip surfaces. Due to the nature of the drilling process, the cutting speed decreases from the tool circumference to the center. Built-up edge formation is more common under low cutting speed conditions rather than high cutting speeds. In the machining of ductile materials, especially conditions where there is no or insufficient application of cutting fluid, such as dry cutting or external MQL, are suitable conditions for the formation of BUE [2-4, 20]. Especially in these cooling conditions, more BUE is seen towards the tool center where the cutting speed approaches zero. In internal MQL conditions, it is thought that the cutting fluid prevents the chip from sticking to the chisel edges because it successfully forms a film layer between the tool and the chip. Thus, it is evaluated that the roughness value is lower on the surfaces processed by the cutting tool that maintains its sharpness.



(a)



(b)

Figure 12. SEM photos of the drills used in the drilling of AA2024 alloy: (a) Internal MQL application. (b) External MQL application.

4. Conclusions

In this study, drilling tests were carried out on AA2024 aluminum alloys using uncoated carbide drills with internal cooling channels. In this study, in particular, the effect of the application of the MQL method through channels in the tool and its application with nozzles from outside the tool on the machining performance was compared. In order to evaluate the machining performance in drilling tests using different cutting parameters and cooling conditions, the surface roughness (Ra) of the holes and wear/plastering on the tools were examined. In order to clearly see the abrasions /plastering on the tools in the experiments carried out under 9 different cutting conditions, each condition was repeated 30 times. The results obtained at the end of the experiments can be summarized as follows:

- ✓ In the repeat experiments conducted for each different condition of the system, it was observed that the Ra values measured at the 30th hole under all cooling conditions were higher than those measured at the 1. hole.
- ✓ However, in these repeat experiments conducted for each different condition, it was determined that the amount of increase in surface roughness from the 1st hole to the 30th hole was very low in internal MQL application. It has been observed that the amount of increase in Ra values under external MQL conditions is close to dry machining conditions. In the re-experiments conducted, the surface roughness from the first hole to the last hole was significantly increased under these two conditions.
- ✓ The arithmetic average of the Ra results measured in 30 drilling repetitions for each different condition was taken. These averages are compared to evaluate the machining performance under each different condition. In the comparison carried out, it was determined that the most important factor affecting the surface roughness is the cooling condition. This situation is clearly demonstrated in the relevant graphs. In addition, the effect rate of the cooling condition in the analysis of variance on Ra data was 92%.
- ✓ The lowest average Ra values in the study were observed in conditions of internal MQL. On the other hand, slightly lower results were observed in external MQL application than in dry conditions. It has been revealed that the effect of cooling conditions on Ra is much more pronounced, especially in conditions where high cutting parameters are applied.
- ✓ The increase in these feed parameters, as expected, increased the surface roughness.
- ✓ It has been observed that the effect of the change in cutting speed on surface roughness is more unstable due to the difficulty experienced in chip evacuation during drilling (especially in dry cutting and external cooling conditions).
- ✓ According to the "Smallest is the best" approach. the L9 vertical index was used in the Taguchi experiment design and the number of 27 experiments was reduced to 9. At the end of these experiments, the optimum conditions obtained in the Signal/Noise (S/N) tests for the measured Ra data describe the best machining performance. According to the results obtained from the S/N tests, the internal MQL method (A1), which is the first level of cooling conditions, 100 m/min (B1), the first level of the cutting speed and 0.10 mm/rev (C1), the first level of the feed parameter, are the optimum

conditions. The 0.5 µm surface roughness amount measured under these conditions is the smallest Ra value measured under all conditions.

- ✓ In the SEM images of the tools used in the experiments, results consistent with the Ra data obtained under the conditions in which the corresponding tools were used were observed. It is observed that the chisel edge form is usually preserved in tools used in internal MQL conditions where small Ra values are observed. Due to the effect of the reduction of the cutting speed from the tool circumference to the tool center during drilling operations, more built-up edge (BUE) was observed. especially in the tool center than around it.
- ✓ In addition, ANN and Taguchi analyses were successfully applied to the data obtained from the experiments. At the end of these analyses, a 97% concordance was observed between the results obtained in the experiments and the estimated data obtained using the Taguchi approach, while a 99% concordance was observed between the estimated data obtained using the ANN approach. According to these results, it can be said that the estimates made with the ANN approach can give closer to the correct results.

As a result, it has been demonstrated by this study that the MQL method can be effective not only in turning and milling operations. But also, in drilling when the correct method is used. In this way, it is thought that by encouraging the MQL method to be used more frequently in the field of manufacturing. It can be ensured that environmentally friendly and sustainable production becomes widespread.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person/institution in the article prepared.

Acknowledgments

The authors would like to thank the Technological Research Council of Turkey (TUBITAK) for this study supports under the program 1002-115M106 coded project finance. Also. the authors would like to thank the Turkish Aerospace Industries Corporation (TUSAŞ/TAI) for the possibility of using machines and equipment in their experiments.

Declaration of author contributions

Ayşegül Çakır Şencan: Experimental research, Methodology, Analysis, Writing, Original draft.
Abdullah Duran: Methodology, Review, Editing
Ulvi Şeker: Funding acquisition, Project management Methodology, Review, Editing.
Müberra Rüveyda Koçak, Writing, Editing, Original draft.
Cevdet Şencan: Review, Editing, Analysis.

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