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Optimization of MQL Parameters Using the Taguchi Method in Milling of Nickel Based Waspaloy

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ABSTRACT

This study aimed to investigate the effect of the minimum quantity lubrication (MQL) parameters such as cutting oil type, flow rate, milling method, pulverization distance and nozzle type on average surface roughness (Ra) in milling of nickel based Waspaloy super alloy. During milling experiments, constant cutting speed (45 m/min), feed rate (0.1 mm/rev) and depth of cut (0.5 mm) were selected as machining parameters. Four different types of oil (vegetable, synthetic, mineral and mineral-synthetic), four different flow rates (25, 50, 75 and 100 ml/h), two different milling methods (down milling and up milling) two pulverization distances (25 and 50 mm) and two different nozzle types were chosen as MQL parameters. The results were analyzed using 3D surface graphs, signal-to-noise ratio (S/N) and main effect graphs of means. Optimal MQL parameters were determined using the S/N ratio. Mathematical models have been created for surface roughness. The analysis results indicated that the dominant factors were oil type and flow ratio on surface roughness. In addition, confirmation test results showed that the Taguchi method was very successful in the optimization of MQL parameters in order to obtain minimum surface roughness in milling of Waspaloy super alloy.

1. INTRODUCTION

The properties of Waspaloy include high thermal stress, high hardness, machining strain under high cutting force, low thermal conductivity causing high heat, a high abrasive carbide particle content, and a higher tendency for welding onto the tool and built up edge (BUE) formation [1]. Due to its high performance in resistance to oxidation, corrosion, high temperature and mechanical and thermal shocks, Waspaloy is preferred in several applications including gas turbines, jet motors, port accessories, steam generator installment parts and structural parts of nuclear reactors [2]. Waspaloy exhibits high heat resistance as a result of the molybdenum, cobalt and chromium elements in the alloy [3]. Waspaloy resembles Inconel 718 from the structural point of view, but its stability is higher than Inconel 718 and its machinability is relatively more difficult [4].

Machinability is defined as the ability of a material to be machined or the ease or difficulty of shaping the workpiece with a cutting tool. The most important parameters used for the evaluation of machinability are tool life, cutting force and the quality of the machined surface (surface roughness) [5,6]. Surface roughness is defined as the amount of small surface irregularities generally limited by other irregularities that emerge during manufacturing processes or from other factors. In the machining industry, one of the most widely used methods to improve surface quality is through the use of cutting fluids [7,8].

Cutting fluids have been used in cutting operations for the last two hundred years [9]. In spite of all of the positive developments, cutting fluid usage creates some negative and hazardous effects in terms of

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*Corresponding author, e-mail: cagriyildirim@ibu.edu.tr production costs, the environment and human health. As an example, a study conducted by Ford Motor Company in 2012 stated that cutting fluid had a share of approximately 13% in the production costs [10]. According to another study, the USA uses more than 100 million gallons of cutting fluid each year, while nearly 1.2 million workers are faced with potential health risks from exposure to these cutting fluids [11]. Cryogenic, high speed cutting (HSC) and minimum quantity of lubrication (MQL) techniques are being used to address these problems. Dry machining is an ecologically friendly and low-cost production method. However, it is not very desirable under heavy cutting conditions where high machining performance and better surface quality are required [12], nor can cryogenic machining give great results at high cutting speeds [13]. Pressure cooling provides good results under both dry and wet conditions [14]. For this reason, the MQL system, in which cutting fluids are used in very low amounts, is considered important for practical operations.

The MQL system is a cooling-lubrication technology which is widely used in today's manufacturing processes [15]. This technique is extensively used in the main manufacturing processes of turning (lathing), milling and drilling as well as in grinding [16, 17]. The lowering of costs and the safeguarding of workforce health are the most distinctive benefits offered by the use of the MQL system [18]. The MQL cooling-lubrication method requires 10-150 ml/h of oil [16] or cutting fluid, which provides a savings of 1/10000 [19] of the conventional cooling-lubrication system. Apart from this high-pressure aerosol cooling and lubricating, another function of the cutting fluids is to remove the chips from the cutting area [20]. In MQL systems, cutting fluids can be conveyed to the cutting area either from inside by way of channels in the tool or externally via constant spraying through a nozzle [12, 21].

In this study, the effect of MQL parameters on surface roughness was investigated in the milling of Waspaloy. Uncoated carbide (1550 HV3) H13A Sandvik tools were chosen for use during the tests. For the experimental design, the Taguchi L_{16} (4^2 2^3) vertical index was used. The Taguchi signal/noise ratio was employed to specify the optimum cutting conditions (cutting oil type, flow ratio, milling method, spraying distance and nozzle type) needed to achieve the minimum surface roughness. In addition, linear and quadratic regression analyses were employed for the estimation of the test results. Lastly, the reliability of the developed models was confirmed with verification tests.

2. EXPERIMENTAL METHODS

2.1. Milling tests

Milling tests were carried out at DELTA SEIKI CNC-1050 A triaxial CNC vertical machining center having 11 kW motor power and 10000 rev/min maximum number of revolutions. CNC vertical machining center and the testing apparatus are given in Fig 1. Test sample Waspaloy super alloy was cut in the size of 150x100x21 mm and its chemical composition is given in Table 1. In the milling tests, according to the advice of the cutting tool company , literature survey and advanced tests, H13A Sandvik uncoated carbide tool selected. It was kept constant in all the tests by choosing 45m/min cutting speed and 0.1 mm/min feed rate.

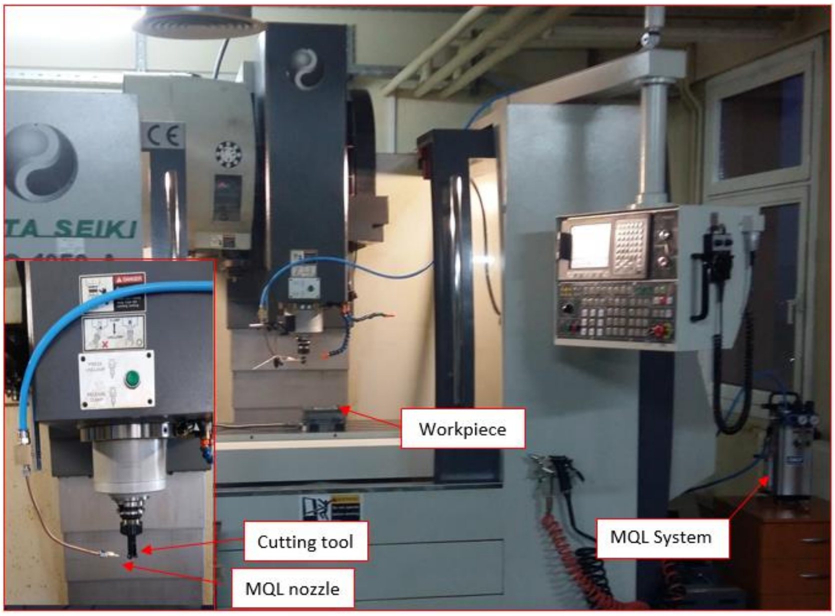


Figure 1. *Experimental setup for milling tests*

Table 1*. Chemical composition of Waspaloy.*

Al%	%B	%C	%Cr	%Co	%Fe	%Mo	%Ni	%Ti	%Zr
1.40	0.010	0.050	19.50	13.00	1.00	4.30	57.00	3.00	0.70

2.2. Measurement of surface roughness

The average surface roughness values were measured using a Taylor Hobson (Surtronic 25) portable measuring device which was calibrated before beginning the measuring process. Each surface was machined with a fresh unused tool. The measurement was carried out immediately after machining in order to avoid oxidation of the surfaces which would affect the measurement values. Surface roughness measurements were made from each of four points in the machining direction and the arithmetic mean of the measured values was taken. Measurement of surface roughness with the testing apparatus can be seen in Figure 2.

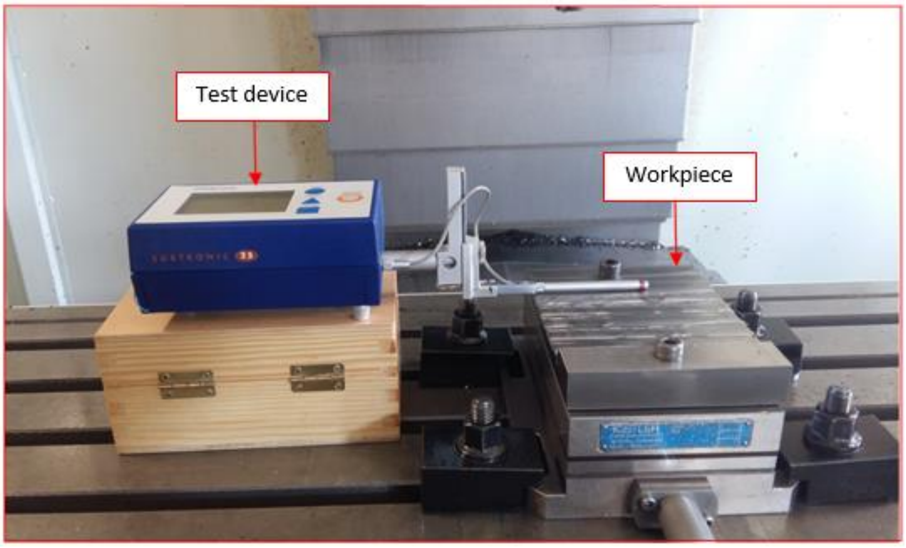


Figure 2. *Surface roughness measurements.*

2.3. Minimum quantity lubrication (MQL) system

In the tests, the cutting fluid was sprayed onto the cutting area using pressurized air at 8 bar. The technical properties of the vegetable oil, synthetic oil, mineral oil and mineral-synthetic oil used in the tests are given in Table 2. In addition, the nozzles and their geometries are shown in Figure 3.

Table 2. *Technical properties of cutting oils*

Cutting Oil	Technicial Specifications		
	Density (20 ºC)	Kinematic Viscosity (40 ºC)	Flash Point
	g/mL	cSt	ºC
Vegetable Oil	0.895	5	170
Synthetic Oil	0.797	5.1	160
Mineral Oil	0.930	14	180
Mineral-Synthetic Oil	0.854	10.5	212

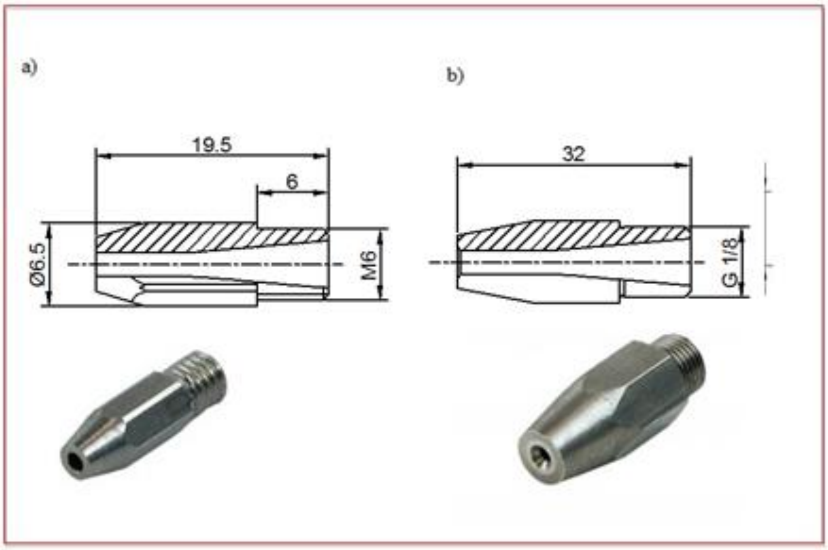


Figure 3. *Nozzles used in experiments; type 1 (a), type 2 (b)*

3. EXPERIMENTAL DESIGN AND OPTIMIZATION

3.1. Taguchi method and experimental design

The Taguchi method employs a statistical measurement called the S/N ratio to examine the results. In this method, the "signal" (S) indicates the unwanted value (standard deviation) for the output characteristic, while the "noise" (N) is the desired value (average) [22]. In the analysis of S/N ratios, there are three main characteristic values: "the biggest the best", "the smallest the best" and "nominal the best" [23]. Since the purpose of the study is to calculate the lowest surface value, "the smallest the best" was chosen and calculated as shown in the equation 1;

$$S/N = -10\cdot\log\left(\frac{1}{n}\cdot\sum_{i=1}^{n}Y_i^2\right) \tag{1}$$

Here,

Y: Performance characteristic value (surface roughness),

n: number of Y values [24]

The control factors chosen for the tests and their levels are given in Table 3. The L_{16} (4^2 2^3) vertical index chosen for the optimizations of the machining parameters is presented in Table 4.

Table 3. *Control factors and their levels.*

A Oil Type (OT)	B Flow Ratio (ml/h)	C Milling Method (MM)	D Pulverization Distance (mm)	E Nozzle Type (NT)
-Vegetable	25	Down Milling	25	1
-Synthetic	50	Up Milling	50	2
-Mineral	75			
-Mineral-Synthetic	100			

Table 4. *Orthogonal array of Taguchi* L_{16} (4^2 2^3).

Experiment No	Factor A	Factor B	Factor C	Factor D	Factor E
1	1	1	1	1	1
2	1	2	1	1	1
3	1	3	2	2	2
4	1	4	2	2	2
5	2	1	1	2	2
6	2	2	1	2	2
7	2	3	2	1	1
8	2	4	2	1	1
9	3	1	2	1	2
10	3	2	2	1	2
11	3	3	1	2	1
12	3	4	1	2	1
13	4	1	2	2	1
14	4	2	2	2	1
15	4	3	1	1	2
16	4	4	1	1	2

3.2. Evaluation of experimental results and analysis

The surface roughness results obtained at the end of the tests and their S/N ratios are given in Table 5. In the milling tests, the average surface roughness value emerged as 0.228 μm, whereas the average S/N ratio value was calculated as 12.67 dB.

Table 5. *The results of experiments and S/N ratios values.*

	Control factors						
Exp No.	A Oil Type (OT)	B Flow Ratio (ml/h)	C Milling Method (MM)	D Pulverization Distance (mm)	E Nozzle Type (NT)	Surface Roughness (µm)	S/N Ratio (dB)
1	Vegetable	25	Down milling	25	1	0.240	11.70
2	Vegetable	50	Down milling	25	1	0.220	13.15
3	Vegetable	75	Up milling	50	2	0.210	13.35
4	Vegetable	100	Up milling	50	2	0.200	13.98
5	Synthetic	25	Down milling	50	2	0.250	11.87
6	Synthetic	50	Down milling	50	2	0.220	12.40
7	Synthetic	75	Up milling	25	1	0.220	13.15
8	Synthetic	100	Up milling	25	1	0.210	13.98
9	Mineral	25	Up milling	25	2	0.240	12.40
10	Mineral	50	Up milling	25	2	0.230	12.40
11	Mineral	75	Down milling	50	1	0.230	12.40
12	Mineral	100	Down milling	50	1	0.220	12.40
13	Mineral- Synthetic	25	Up milling	50	1	0.240	12.40
14	Mineral- Synthetic	50	Up milling	50	1	0.250	12.04
15	Mineral- Synthetic	75	Down milling	25	2	0.255	11.87
16	Mineral- Synthetic	100	Down milling	25	2	0.220	13.15

The Taguchi method was used for analysis of the S/N values, and the optimum levels of the control factors were then determined. The S/N response table for surface roughness with the optimum levels of the control factors for the optimum surface roughness values are shown in Table 6.

Table 6. *S/N response table for surface roughness.*

Levels	Control factors				
	A	B	C	D	E
Level 1	**13.27**	12.31	12.71	12.80	12.83
Level 2	12.97	12.78	**12.98**	**12.89**	**12.86**
Level 3	12.77	12.84			
Level 4	12.36	**13.46**			
Delta	0.91	1.15	0.27	0.08	0.04

The best level for each control factor was found according to the greatest S/N ratio in all levels of that control factor. Thus, the levels and S/N ratios of factors giving the best surface roughness value were specified as: Level 1, S/N = 13.27 dB, Level 4, S/N = 13.46 dB**,** Level 2, S/N = 12.98 dB, Level 2, S/N = 12.89 dB and Level 2, S/N = 12.86 dB for the factors A, B, C, D and E, respectively (Table 6). In addition, control factors for surface roughness values and factor level values are given in Figure 4.

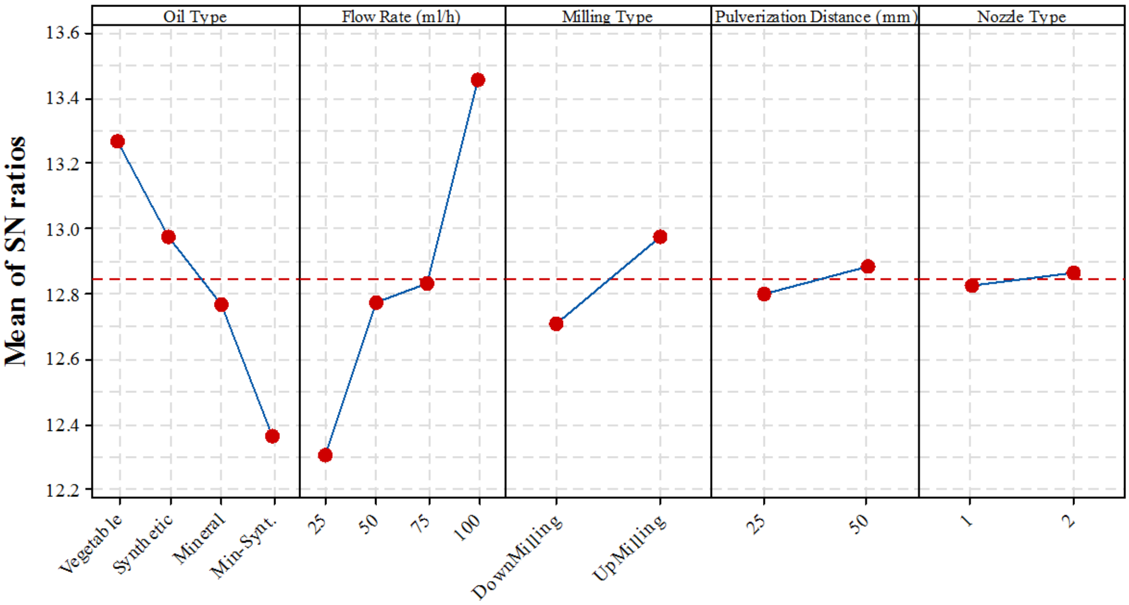
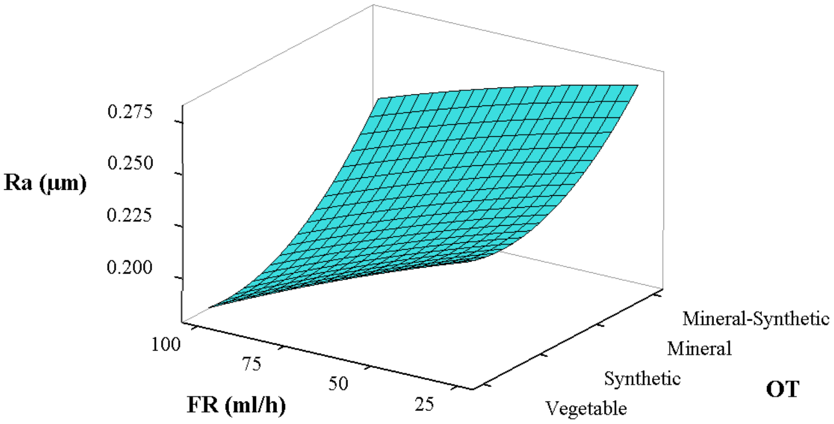


Figure 4. *Effect of process parameters on average S/N ratio.*

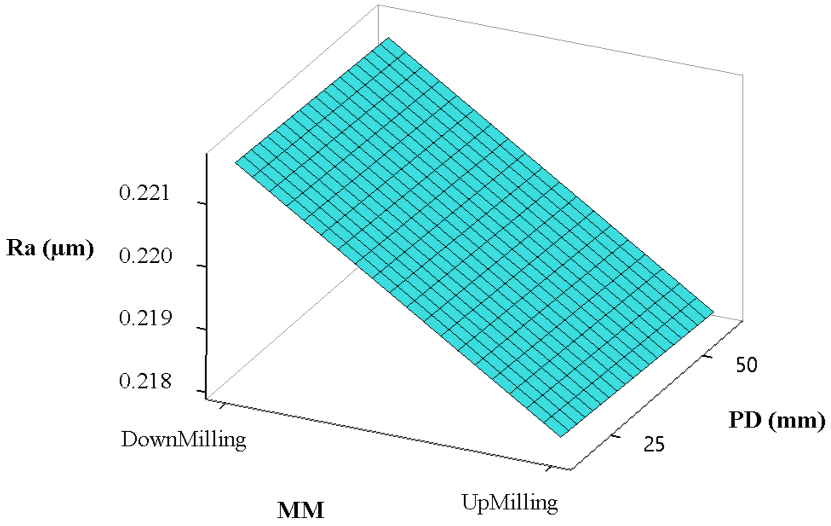
Figure 4 shows that the MQL parameters having the lowest surface roughness values were vegetable oil (A_1), a flow rate of 100 ml/h (B_4), up milling (C_2), a spraying distance of 50 mm (D_2) and the Type 2 nozzle (E_2).

3.3. Evaluation of test results

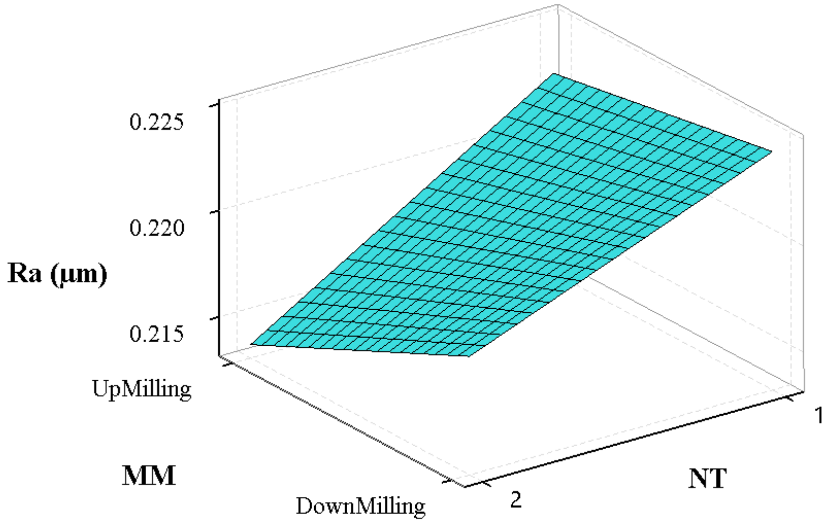
Three-dimensional surface graphs of the surface roughness of Waspaloy obtained as a result of milling under the MQL system and other main factor interactions are given in Figure 5.



a)



b)



c)

***Figure 5.** Effect of the MQL parameters on surface roughness. **a)** Flow ratio and oil type **b)** Milling method and pulverization distance **c)** Milling method and nozzle type.*

Figure 5a shows that the lowest surface roughness value was obtained when using vegetable-based cutting oil [23]. Surface roughness values obtained from experiments with vegetable base cutting fluid gave better results than synthetic, mineral and mineral-synthetic cutting fluids at rates of 3.5%, 5.75% and 10.94%, respectively. When the relationship between the flow rate and surface roughness is examined, it can be observed that the surface roughness value decreased with the increase of the flow rate. This decrease in surface roughness can be explained by the decrease in friction at the tool-chip interface due to the increased amount of oil directed to the cutting area [24]. When the effect of flow rate on was analyzed, according to flow rate of 25 ml/h it was seen that flow rates of 50 ml/h, 75 ml/h and 100 ml/h provided an improvement with percet of 5.2%, 5.7% and 12.38%. Figure 5b shows that up milling gave better results compared to down milling. When Fig. 5b was examined, it was seen that up milling gave better result than down milling at percent of 3.02%. As for the spraying distance, it was thought that the further spraying distance of 50 mm produced better results, as the aerosol reached the cutting area wider angle. However, this improvement was occurred by 0.9%. The graph for nozzle type indicates that the Type 2 nozzle gave better results. The reason for this was that the counterbore at the mouth of the nozzle dispersed the cutting fluid over a wider area, thus creating a better film layer. Graph showing nozzle type was analyzed, type 2 nozzle gave 0.3% better result.

3.4. Analysis of Variance (ANOVA)

The ANOVA results (95% confidence level) for surface roughness are given in Table 10. In the Table, a P value of less than 0.05 indicated that the effect of the factor on the output was considered to be statistically meaningful; therefore, it can be said that the oil type and flow factors had a certain effect on the surface roughness. In the determination of effect levels (contribution ratio) of F factors, again the F values in the Table were taken into consideration. Consequently, the contribution percentages of factors A, B, C, D and E on the surface roughness were found to be 30.7%, 46.7%, 4.9%, 0.4% and 0.1%, respectively (Table 7). The most important factor affecting surface roughness was the flow rate (B). The percentage of error was found to be 17.2%. Examination of the statistical analysis results revealed that they verified the results of the experimental study.

Table 7. Results of ANOVA for surface roughness.

Source	Degree of freedom	Sum of squares	Mean squares	F ratio	P ratio	Contribution rate (%)
A	3	0.001192	0.000397	3.55	0.087	30.7
B	3	0.001817	0.000606	5.41	0.038	46.7
C	1	0.000189	0.000189	1.69	0.242	4.9
D	1	0.000014	0.000014	0.13	0.735	0.4
E	1	0.000002	0.000002	0.01	0.910	0.1
Error	6	0.000672	0.000112	-	-	17.2
Total	15	0.003886	-	-	-	100

3.5. Regression analysis

Minitab software was used for the regression analysis of the surface roughness results. Surface roughness equations were formulated on the basis of the parameters of oil type, flow rate, milling method, spraying distance and nozzle type. The first degree equation (Eq. 2) was developed with only the main effects of the control factors and is given below:

$$Ra = 0{,}25 + 0{,}0076.OT - 0{,}00036.FR - 0{,}0069.MM - 0{,}00075.PD - 0{,}00063.NT \qquad (2)$$

The coefficient of determination of the obtained first degree equation was calculated to be $R^2 = 0.781$. Since the difference between the estimated surface roughness values obtained by the first degree equations at a 95% confidence level and the test results would be greater, a new equation (Eq. 3) covering the factor interactions had to be formulated and is given below:

$$\begin{aligned} Ra = {} & 0{,}28 - 0{,}007.OT - 0{,}0014.FR - 0{,}013.MM - 0{,}0009.PD + 0{,}032.NT + 0{,}008.OT.OT \\ & -0{,}000002.FR.FR + 0{,}00007.OT.F - 0{,}0131.OT.MM + 0{,}00075.FR.MM + 0{,}000014.FR.PD \\ & -0{,}0005.FR.NT - 0{,}003.MM.NT \end{aligned} \qquad (3)$$

The coefficient of determination of this equation was found to be $R^2 = 0.989$. The estimated surface roughness values obtained by the first degree equation at 95% confidence level (including control factors and their interactions), the surface roughness values from the experimental study and the differences between them are given in Table 8, in addition to both of the estimation model values which were made via the Taguchi program using Minitab software. Here, the estimation values closest to the test results were the values obtained by the equation containing both control factors and interactions. A comparison of the experimental results and the values obtained by the estimation models is given in Figure 6. The estimation equation closest to the real values was the equation belonging to the main effect and its interactions.

Table 8. *Predicted values and confirmation test results by regression equations.*

Exp. No	Experimental surface roughness (μm)	Linear equation estimation (μm)	Difference	Quadratic equation estimation (μm)	Difference	Taguchi estimation (μm)	Difference
1	0.240	0.235	0.005	0.24073	-0.001	0.23625	0.004
2	0.220	0.226	-0.006	0.21778	0.002	0.22375	-0.004
3	0.210	0.208	0.002	0.20835	0.002	0.213125	-0.003
4	0.200	0.199	0.001	0.19415	0.006	0.196875	0.003
5	0.250	0.241	0.009	0.24738	0.003	0.24125	0.009
6	0.220	0.231	-0.011	0.22118	-0.001	0.22875	-0.009
7	0.220	0.218	0.002	0.21487	0.005	0.223125	-0.003
8	0.210	0.209	0.001	0.20742	0.003	0.206875	0.003
9	0.240	0.243	-0.003	0.24156	-0.002	0.24125	-0.001
10	0.230	0.234	-0.004	0.22711	0.003	0.22875	0.001
11	0.230	0.231	-0.001	0.2289	0.001	0.233125	-0.003
12	0.220	0.221	-0.001	0.2132	0.007	0.216875	0.003
13	0.240	0.250	-0.010	0.23932	0.001	0.25125	-0.011
14	0.250	0.240	0.010	0.24912	0.001	0.23875	0.011
15	0.255	0.239	0.016	0.25179	0.003	0.245625	0.009
16	0.220	0.230	-0.010	0.21534	0.005	0.229375	-0.009

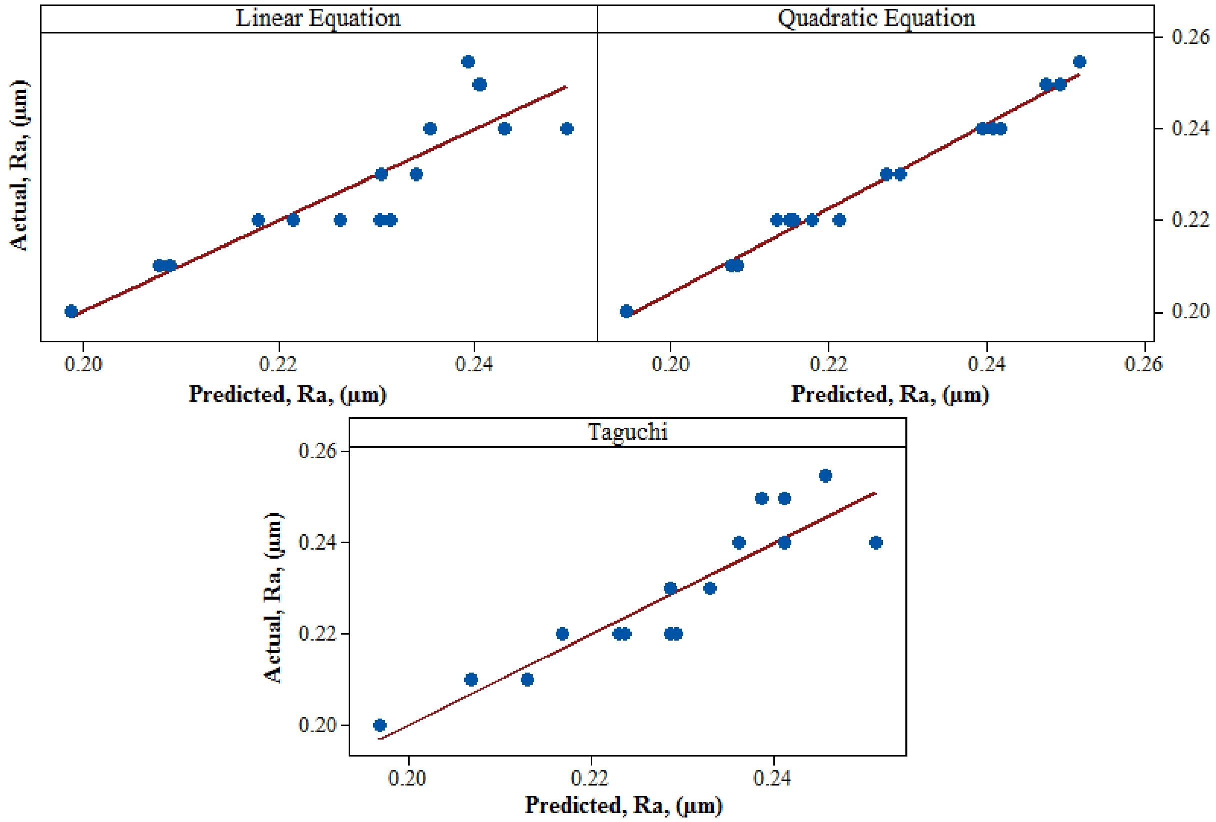


Figure 6. *Comparison of the regression models with experimental results.*

3.6. Estimation of optimum surface roughness

The parameter group of the lowest surface roughness has been obtained as $A_1B_4C_2D_2E_2$. In the estimation of optimum surface roughness equation 4 was used.

$$Ra_{ort} = (A_1 - T_{Ra}) + (B_4 - T_{Ra}) + (C_2 - T_{Ra}) + (D_2 - T_{Ra}) + (E_2 - T_{Ra}) + T_{Ra} \quad (4)$$

Here, (A_1, B_4, C_2, D_2, E_2) represent the average values of surface roughness at the optimum level (Table 9). The T_{Ra} value represents the average surface roughness value obtained from the experimental study (Table 5). As a result of the calculations, the T_{Ra} value was found to be 0.1981 μm.

Table 9. *Mean response table for Ra.*

Levels	Control Factors				
	A	B	C	D	E
Level 1	**0.2175**	0.2425	0.2319	0.2294	0.2287
Level 2	0.2250	0.2300	**0.2250**	**0.2275**	**0.2281**
Level 3	0.2300	0.2288			
Level 4	0.2412	**0.2125**			
Delta	0.0238	0.0300	0.0069	0.0019	0.0006

In order to verify the optimization values, the estimated confidence interval had to be calculated by using the following equations [25]:

$$CI_{Ra} = \sqrt{F_{\alpha,1,f_e} V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (5)$$

and

$$n_{eff} = \frac{N}{1 + T_{dof}} \quad (6)$$

Here, $F_{\alpha,1fe}$ gives the 95% confidence ratio, α is the level of importance, f_e is the degree of freedom of error, V_e is the error variance, n_{eff} is the number of replications and R is the number of replications for the verification tests (Eq. 5); N gives the total number of tests and T_{dof} is the total main factors of freedom degree (Eq. 6); $F_{0.05,1,6} = 5.987$, $Ve = 0.000112$ (Table 10); $R = 2$ (Eq. 5); $N = 16$, $T_{dof} = 9$ and $n_{eff} = 1.6$ (Eq. 6). The obtained values were inserted into Equations 5 and 6, and in this way the confidence interval for surface roughness tests was found to be $CI_{Ra} = 0.037$. The estimated surface roughness value (95% confidence interval) was calculated as follows:

$$\left\lfloor Ra_{opt} - CI_{Ra} \right\rfloor < Ra_t < \left\lfloor Ra_{opt} + CI_{Ra} \right\rfloor \quad (7)$$

$$[0.1981 - 0.037] < 0.20 < [0.1981 + 0.037] = 0.1611 < 0.20 < 0.2351$$

The Ra value obtained through the tests was within the confidence interval limits. Thus, the system optimization for surface roughness was obtained at the 0.05 significance level by using the Taguchi method [26,27].

3.7. Verification tests

The verification tests of the control factors were carried out for the Taguchi method and regression equations with the optimum levels and randomly selected levels. In Table 10, a comparison of the test results and the estimated values obtained by the regression equations is presented. The estimated and real values were close to each other. When the verification test results are examined, it can be said that the results were satisfactory and the Taguchi optimization was successful.

Table10. *Predicted values and confirmation test results by regression equations.*

Level	Linear equation			Quadratic equation			Taguchi equation		
	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
$A_1B_4C_2D_2E_2$	0.200	0.1931	3.45	0.200	0.2031	1.55	0.200	0.1954	2.30
$A_2B_1C_1D_2E_2$	0.250	0.2410	3.60	0.250	0.2474	1.04	0.250	0.2413	3.48
$A_4B_3C_1D_1E_2$	0.255	0.2390	6.27	0.255	0.2518	1.25	0.255	0.2456	3.68

4. CONCLUSIONS

In this study, in the milling process of Waspaloy with MQL system and uncoated carbide tools Taguchi method was used for the description of optimum MQL parameters on surface roughness. ANOVA was used to evaluate the test results and the following results were obtained;

For the surface roughness optimum parameter group was found to be $A_1B_4C_2D_2E_2$. In other words, combination of vegetable based cutting oil (A_1), 100 ml/h flow (B_1), up milling (C_2), 50 mm pulverization distance (D_2) and number 2 nozzle type (E_2) gave minimum surface roughness value.

Vegetable based cutting oil gave better result compared to other cutting oils.

According to analysis results, flow exhibited the greatest effect on the surface roughness by 46.7% and then came oil type by 30.7%.

The developed quadratic regression model put forward a very good relationship between the measured value for surface roughness and the estimated value with a higher correlation coefficient (98.9%).

According to the verification test results were measured in the 95% confidence interval.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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