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OPTIMIZATION OF MULTI-PROCESS PARAMETERS ACCORDING TO THE SURFACE QUALITY CRITERIA IN THE END MILLING OF THE AA6013 ALUMINUM ALLOY

OPTIMIZACIJA MULTIPROCESNIH PARAMETROV V ODVISNOSTI OD KAKOVOSTI POVRŠINE KOT MERILA PRI KONČNEM REZKANJU ALUMINIJEVE ZLITINE AA6013

Hülya Durmuş
Celal Bayar University, Engineering Faculty, Department of Materials Engineering, Muradiye, Manisa-Turkey
hulya.kacar@bayar.edu.tr

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In the study the effects of multi-process parameters on the surface roughness during the machining of the AA6013 aluminum alloy with non-coated cemented carbide milling cutters were investigated by using Taguchi's experimental design method. Experiments were conducted on the basis of Taguchi's L16 orthogonal array (OA) at different levels of the factors relating to the aging process, the cutting speed, the feed rate, the axial depth of a cut and the radial depth of a cut; then they were evaluated through the signal/noise ratio (*S/N*), ANOVA and the main effects' graphic. Accordingly, the lowest surface roughness was estimated to be 0.436 µm and, finally, Taguchi's method allowed the optimization of the system for the verification of the tests.

Keywords: milling, surface roughness, Taguchi's method, aging, experimental design

Raziskan je vpliv multiprocesnih parametrov na hrapavost površine aluminijeve zlitine AA6013, obdelane s karbidnim rezkarjem in z načrtovanjem preizkusov po Taguchijevi metodi. Preizkusi so bili opravljeni na podlagi Taguchijeve ortogonalne porazdelitve L16 po različnem staranju zlitine, pri različnih hitrostih rezkanja, podajanja, aksialne in radialne globine rezov in ocenjeni na podlagi razmerja signal/hrup (*S/N*), ANOVE in grafičnih zapisov glavnih vplivov. Na podagi rezultatov je bila ocenjena kot najmanjša hrapavost površine 0,436 µm, s Taguchijevo metodo pa so bili verificirani preizkusi in optimiziran sistem.

Ključne besede: rezkanje, hrapavost površine, Taguchijeva metoda, staranje, načrtovanje preizkusov

1 INTRODUCTION

Aluminum alloys have been extensively used in aviation, automotive, plastic injection molding and defense industries due to their high resistance/weight ratios, good corrosion/fatigue resistance and high feed rates in recent years. Therefore, studies of the machining of these materials have become more important[1]. Most of the studies have been conducted on milling these materials, frequently focusing on the effects of cutting parameters and tool geometries on surface roughness. The studies conducted on the variation in surface roughness in end milling aluminum are evaluated below.

This is a method, in which effects of only quantitative parameters can be obtained in a small experiment number compared with full factorial experiment design and both the statistical model and the optimization can be obtained. Whang and Chang[2] modeled the effect of cutting parameters and cutter geometry on the surface roughness in milling Al2014-T6 under dry and wet conditions with RSM. It was determined that the factors of the cutting speed, the feed rate, the concavity and the axial gap angle were significant for the variation in the surface roughness under dry conditions, while the feed rate and the concavity angle were significant under wet conditions. Erzurumlu and Öktem[3] modeled the surface roughness of a mold made of AA7075 material with the help of the methods of RSM and artificial neural networks (ANN) and they found that the model based on ANN was higher in accuracy. Routara et al.[4] modeled the machining of the materials of AA6061-T4, AISI 1040 and UNS C34000 with a CVD-coated carbide end mill with RSM. They modeled it as the second-order regression equation for five surface roughness parameters of the depth of a cut, the spindle speed and the feed rate, which were reference parameters in this area, and they accomplished the optimization of the system.

Artificial neural networks, the neural fuzzy logic, fuzzy networks and genetic programming methods are also preferred in this area. Lou and Chen[5] investigated the variation in the surface roughness during the machining of the AA6061 aluminum alloy by considering the cutting parameters (the spindle speed, the feed rate and the depth of a cut) and the vibration criteria through the neural-fuzzy method. Their model predicted the surface roughness at the accuracy rate of 96 %. Chen and Savage[6] predicted the effects of the factors of the spindle speed, the feed rate, the type of the tool material, the tool diameter, and the vibration on the surface roughness in the milling of AA6061 and AISI 1018 materials with the neural-fuzzy approach. The suggested method predicted surface roughness during cutting with a correlation of 90 %. Brezocnik et al.[7] modeled the effect of the process parameters of the spindle speed, the feed rate, the depth of a cut and the vibration on the surface roughness in the end milling of AA6061 alloy with a HSS plain-end mill by using genetic programming.

Taguchi's method can determine effects of the factors on the quality characteristic with the smallest experiment number without any need for complex calculations, accomplishing the optimization of the system at a certain confidence level. The method is very preferable in this area because it requires only a small experiment number and, as a result, a lower cost and shorter time. Yang and Chen[8] determined the effects of the factors of the spindle speed, the feed rate and the tool diameter on the surface roughness during the machining of AA6061 with a HSS plain-end mill and they accomplished the optimization of the system through Taguchi's method. Lo et al.[9] investigated the effects of the factors of the spindle speed, the feed rate, the depth of a cut and the tool material in the high-speed milling of AA6061 by using Taguchi's method. They evaluated the results of the experiments belonging to the L9 orthogonal array of Taguchi through the S/N ratio and the variance analysis, and presented the significance of the factors and their orders. Öktem et al.[10] evaluated the data obtained in a 3-numbered study by using Taguchi's method and the full factorial experiment-design methods for this time. They modeled the surface roughness at the correlation coefficient of 0.96 by using regression analysis. They found, in the analyses conducted with Taguchi, that the machining tolerance was the most significant factor influencing the roughness, followed by the radial depth of a cut, the axial depth of a cut, the feed rate and the cutting speed per thread. Pinar et al.[1,11,12] investigated the effects of the cutting speed, the feed rate, the depth of a cut and the machining pattern on the surface quality in the milling of the alloys of AA5083, 6013 and 7075 by using Taguchi's method. The experiments conducted on the basis of the standard L27 orthogonal array of Taguchi were assessed by using *S/N*, ANOVA and the main effects' graphics so that the system was optimized.

In this study, unlike other studies, the effect of the aging process, which was imposed on the material, was added to the effects of the other cutting factors (the cutting speed, the feed rate, the axial depth of a cut and the radial depth of a cut) influencing the surface roughness to be analyzed by Taguchi's method so that the system was optimized.

2 MATERIAL AND METHOD

The AA 6013 alloy, whose chemical composition is given in **Table 1**, was used as a test sample. The samples to which precipitation hardening had, or had not, been applied were used in the experiments. The pre-tests were conducted to find the situation, in which the mechanical properties were at their maximum. During the first step of the precipitation hardening, the samples were solution treated at 560 °C for 5 h. Then the quenching step was completed. Finally, the samples were aged processed at 190 °C and their hardness was measured for 42 h once every 2 h to find the optimum aging time. The hardness tests were conducted by using Brinell hardness device. The aging time achieving the maximum hardness was determined to be 32 h (**Figure 1**). The end-milling tests of the aged and non-aged samples were conducted in a vertical machining center of First MCV 300 CNC operating in line with Fanuc control unit. The single-insert non-cemented carbide end mill with a 90-degree incidence, a 14-mm diameter and a 0.8-mm insert diameter, recommend by Mitsubishi Company in end milling of aluminum, was used as the cutting tool

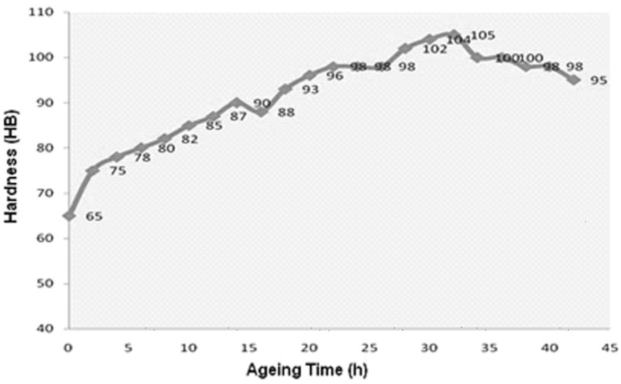


Figure 1: Hardness graph employed in the determination of aging time
Slika 1: Zapis trdote, uporabljen za določitev časa staranja

Figure 2: Cutting tool employed in the experiments
Slika 2: Rezno orodje, uporabljeno pri preizkusih

Table 1: Chemical composition of AA6013 experiment specimen
Tabela 1: Kemična sestava AA6013 raziskanega vzorca

Si	*Fe*	*Cu*	*Mn*	*Mg*	*Zn*	*Cr*	*Al*
1.2	0.339	0.16	0.799	1.01	0.21	0.059	Geri kalan

(**Figure 2**). Machining operations were conducted by up milling with liquid cooling using Ecocool 2030 MB with a 5 % oil emission.

The CNC part programs of the samples were obtained in MasterCAM V10 software as 2½-axial contour machining. The cutting parameters were specified on the basis of the manufacturer's catalog data and bench capacity. The surface-roughness measurements were repeated three times perpendicular to the machining traces through Mitutoyo Surftest SJ 311 profilometer operating on the basis of the insert principle. Their arithmetical means were used in the statistical analyses.

3 EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

Taguchi, which has become prevalently preferable in recent years, only requiring experiments in a small number and allowing system optimization without the need for complex mathematical calculations, was used for the experimental design and the statistical-analysis method[13,14].

The system design is the part, in which the factors affecting the quality characteristic to be investigated and their degrees are determined and it requires technical data related to engineering knowledge in this area. The parameter design is the most comprehensive and important step of Taguchi's method. In this phase, the experiments conducted on the basis of the specified experiment plan are analyzed, the optimum levels for the factors are determined and the optimum dependent variable is predicted for these levels. The final step is the tolerance design, in which the average result of the verification experiments is checked to find out whether or not it is within the specified confidence interval[12].

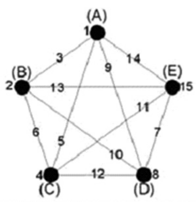
4 APPLICATION OF THE OPTIMIZATION PROCESS

In the present study, the effects of the process parameters, which are the cutting speed, the feed rate, the radial/axial depth of a cut and the aging, as well as their dual interactions on an average surface roughness (R_a/µm) are evaluated and the system is optimized. **Table 2** shows the factors used in the experimental system and their levels.

Table 2: Choosen factors and their levels
Tabela 2: Izbrani faktorji in njihovi nivoji

Factors		Level	
		1	2
Cutting speed (A)	m/min	100	300
Feed (B)	mm/min	100	1200
Axial depth of cut (C)	mm	0.75	2
Radial depth of cut (D)	mm	5	10
Ageing treatment (E)	–	No	Yes

The OA establishing the experimental plan is selected on the basis of the degree of freedom. Accordingly, the freedom degree of the OA to be selected should be higher than, or equal to, the freedom degree of the system[1]. The freedom degree (FD) of the experimental system is obtained by summing up the freedom degrees of the factors and their interactions. The freedom degree of the experimental system is specified according to the number of the factor level interaction. The freedom degree of a factor is specified as the level number of that factor-1. Accordingly, because there are 5 factors, the freedom degree of the factors is 5 × 1 = 5. In case of interactions, individual freedom degrees of the factors establishing interactions are multiplied to calculate the overall freedom degree. Accordingly, because there are 10 interactions, their freedom degree is 10 × 1 = 10. The freedom degree of the system is 15 being the summation of 5 + 10. According to this data, L16 OR with the freedom degree of 15, having 15 columns and 16 rows was selected. If the same factors were investigated by using the full factorial experimental design method, 25 experimental studies would be required. Thus, the saving in terms of the number of experiments is 50 %. Consequently, savings were obtained in time, sample cutters and the power consumed by the bench. The factors and their interactions were transferred to the columns of OA by using the linear graphic method (**Figure 3**). In line with this, the first column was assigned to the cutting speed, while the second was assigned to the feed rate. The forth column was assigned to the axial depth of a cut, the eighth to the radial depth of a cut, the fifteenth to the aging and the remaining columns were assigned to the interactions.



Exp. Number	Column Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	A	B	AXB	C	AXC	BXC	-	D	AXD	BXD	-	CXD	-	-	-
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

Figure 3: Assignment of the factors and interactions to L27 OA by means of linear graph
Slika 3: Porazdelitev faktorjev in interakcij za L27 OA z linearno grafiko

4.1 Analyzing the data

The experimental results given in **Table 3** were evaluated by using the signal/noise ratio (*S/N*), the variance analysis and the main effects' graphic, with the help of Minitab software, at the confidence level of 95 %.

4.1.1 S/N ratio analysis

Taguchi's method uses the signal/noise ratio to measure the existing variation. Description of the *S/N* ratio varies according to the objective function or, in other words, quality characteristic to be investigated. Three different *S/N* ratios are used in the analyses as the nominal values are the best (NB), smaller is better (SB) and bigger is better. Since the average surface roughness was investigated in the study as the quality characteristic and the objective was a minimization of these parameters, the SB was selected as the NB. The following equation refers to it.

$$S/N = -10\lg\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

Herein, n represents the number of measurements and y_i is the measured roughness value. The *S/N* ratio unit is a decibel. **Table 3** shows the results of the experiments conducted on the basis of the L16 orthogonal array, the means and the corresponding *S/N* ratios.

4.1.2 ANOVA

In the study, the influence of the process parameters on the quality characteristic and percentage distributions were established through ANOVA. **Tables 4 and 5** give ANOVA results corresponding to the means and *S/N* ratios. The significance of the process parameters and their interactions are determined in ANOVA by comparing the *F* values (the ratio of the relevant parameter's variance to the error variance) in the fifth column of the tables with the corresponding F_{table}. If a process or an

Table 3: Experimental results, means and corresponding S/N ratios
Tabela 3: Eksperimentalni rezultati, povprečja in ustrezna razmerja S/N

Exp. Number	Cutting speed (A)	Feed (B)	Axial depth of cut (C)	Radial depth of cut (D)	Ageing treatment (E)	R_{a1}	R_{a2}	R_{a3}	R_{aort}	*S/N*
1	100	100	0.75	5	No	0.58	0.58	0.58	0.580	4.731
2	100	100	0.75	10	Yes	0.76	0.76	0.8	0.773	2.230
3	100	100	2	5	Yes	0.8	0.8	0.8	0.800	1.938
4	100	100	2	10	No	0.84	0.81	0.81	0.820	1.722
5	100	1200	0.75	5	Yes	0.9	0.94	0.91	0.917	0.754
6	100	1200	0.75	10	No	0.92	0.95	0.94	0.937	0.568
7	100	1200	2	5	No	1.11	1.12	1.13	1.120	-0.985
8	100	1200	2	10	Yes	1.2	1.2	1.26	1.220	-1.730
9	300	100	0.75	5	Yes	0.38	0.38	0.38	0.38	8.404
10	300	100	0.75	10	No	0.4	0.4	0.4	0.4	7.959
11	300	100	2	5	No	0.62	0.64	0.65	0.637	3.920
12	300	100	2	10	Yes	0.7	0.66	0.67	0.677	3.390
13	300	1200	0.75	5	No	0.78	0.78	0.82	0.793	2.008
14	300	1200	0.75	10	Yes	0.8	0.8	0.84	0.813	1.792
15	300	1200	2	5	Yes	0.9	0.89	0.9	0.897	0.947
16	300	1200	2	10	No	0.9	0.9	0.92	0.907	0.851

Table 4: ANOVA results for means
Tabela 4: ANOVA rezultati za povprečja

Source	SD	SS	V	F	F_{table}	KT'	P
Cutting speed (A)	1	0.172917	0.172917	44.94	4.75	0.169069	22.28
Feed (B)	1	0.402167	0.402167	104.51	4.75	0.398319	52.49
Axial depth of cut (C)	1	0.137517	0.137517	35.74	4.75	0.133669	17.62
Radial depth of cut (D)	(1)	(0.011201)		Pooled	–	Pooled	–
Ageing treatment (E)	(1)	(0.005017)		Pooled	–	Pooled	–
AxB	(1)	(0.000584)		Pooled	–	Pooled	–
AxC	(1)	(0.000034)		Pooled	–	Pooled	–
AxD	(1)	(0.003701)		Pooled	–	Pooled	–
BxC	(1)	(0.000851)		Pooled	–	Pooled	–
BxD	(1)	(0.000951)		Pooled	–	Pooled	–
Error	12	0.046176	0.003848			0.05772	7.61
Total	15	0.758777				0.758777	100

SD: Degree of freedom, SS: Sum of squares, V: Variance, KT': Pure sum of squares, P: Percent of contribution

Table 5: ANOVA results for S/N ratios
Tabela 5: ANOVA rezultati za razmerje S/N

Source	SD	SS	V	F	F_{tablo}	SS'	P
Cutting speed (A)	1	25.104	25.1044	27.42	4.75	24.188	20.85
Feed (B)	1	56.584	56.5838	61.80	4.7	55.668	48.00
Axial depth of cut (C)	1	21.144	21.1439	23.09	4.75	20.228	17.44
Radial depth of cut (D)	(1)	1.524	-	Pooled	-		
Ageing treatment (E)	(1)	0.581	-	Pooled	-		
AXB	(1)	2.295	-	Pooled	-		
AXC	(1)	0.865	-	Pooled	-		
AXD	(1)	0.348	-	Pooled	-		
BXC	(1)	2.493	-	Pooled	-		
BXD	(1)	0.375	-	Pooled	-		
Error	12	10.988	0.9157			15.903	13.71
Total	15	115.987				115.987	100

SD: Degree of freedom, SS: Sum of squares, V: Variance, KT': Pure sum of squares, P: Percent of contribution

interaction parameter has a *F* value higher than this value, it is deemed significant. Thus, it was observed that the process parameters of the cutting speed, the feed rate and the axial depth of a cut were significant, while their interactions did not have a significant effect on surface roughness in the cases of the two ANOVAs. Percentage distributions are given in the last column of the ANOVA table indicating significance degree of each of the process parameters and dual interactions. On the basis of this data, it can be established that the most significant process parameter is the feed rate, followed by the cutting speed and the axial depth of a cut. In Taguchi's method the factor levels indicating the optimum surface roughness are determined by considering ANOVAs, the main effects' and interactions' graphics. Significant parameters are considered in both ANOVAs in the calculation of the optimum surface roughness. According to this, the means of the parameters of the feed rate, the cutting speed and the axial depth of a cut will be considered. The levels to be selected are determined by using the main effects' and interactions' graphics. As none of the interactions in the experimental system is significant, the main effects' graphic will be sufficient in this phase. **Figure 4** shows the main effects' graphic. According to this graphic, surface roughness varies depending on the cutting speed in inverse proportion and also on the feed rate, the axial depth of a cut and the radial depth of a cut in direct proportion. In the case of the aging-state parameter, it was seen that surface roughness increased a bit during the machining of the aged samples. According to this data, the optimum surface roughness was achieved at the cutting rate of 300 m/min, a feed rate of 100 mm/min, an axial depth of a cut of 0.75 mm and a radial depth of a cut of 5 mm in non-aged samples. The optimum surface roughness is obtained through the following equation:

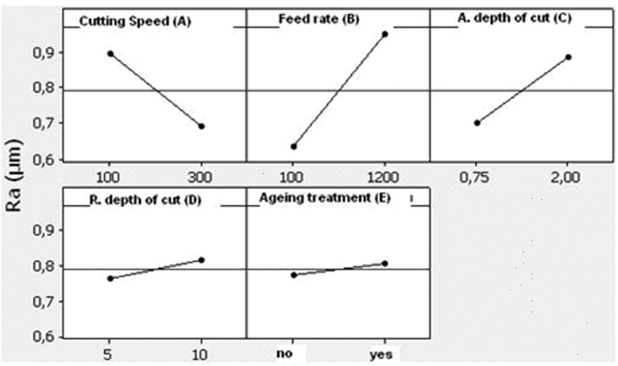


Figure 4: Main effects plot of the factors
Slika 4: Glavne povezave faktorjev

$$P_r = O_{A2} + O_{B1} + O_{C1} - 2K \quad (2)$$

Herein, O_{A3} stands for the means from the experiments conducted at the second level of the cutting speed. O_{B1} stands for the means from the experiments conducted at the first level of the feed rate. O_{C1} stands for the means from the experiments conducted at the first level of the axial depth of a cut. *K* stands for the means from all experiments. **Table 6** shows the relevant means. According to Equation 2, the optimum surface roughness was predicted to be 0.436 μm.

Table 6: Means of factor levels
Tabela 6: Nivoji povprečnih faktorjev

Level	Cutting speed (A)	Feed rate (B)	Axial depth of cut (C)	Radial depth of cut (D)	Ageing treatment (E)
1	0.8958	0.6333	0.6992	0.7654	0.7742
2	0.6879	0.9504	0.8846	0.8183	0.8096
Delta	0.2079	0.3171	0.1854	0.0529	0.0354
Rank	2	1	3	4	5

Overall average (K)=0.792μm

In the last step of Taguchi, called the tolerance design, the confidence interval is determined, in which the upper and the lower limits of the existing predicted surface roughness are determined. The means of the roughness results from the conducted verification tests should be within this interval. The following equation is used to calculate the confidence interval[12,14].

$$CI = \left(F_{CI} \cdot V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right] \right)^{1/2} \quad (3)$$

Herein, F_{CI} is obtained from the standard tables at the significance level of 0.05 according to the freedom degree of 1 including an error and it is 4.75. V_e, is the variance value of the error in the ANOVA table and calculated as 0.003848 (**Table 4**). R is how many times the verification tests are repeated under optimum conditions (3) and finally, n_{eff} is the effective repeat number. This was obtained by using the following equation.

$$n_{eff} = \frac{N}{1+V_t} \quad (4)$$

Herein, N is the total number of the experiments in the experimental plan (16), while V_t is the total freedom degree of the factors existing in the equation, through which the optimum surface roughness is predicted (3). Accordingly, CI was calculated to be 0.103 at the confidence level of 95 % or at the significance level of 0.05. The mean of the results of the verification tests repeated three times should be within the interval of $0.333 < R_a < 0.539$. The average surface roughness was determined to be 0.343 μm (0.35, 0.34 and 0.34 μm respectively) in the verification tests conducted under the optimum conditions. According to this data, it is clearly seen that Taguchi's method optimized the system successfully.

5 CONCLUSION

In the present study, the effects of multi-process parameters (the cutting speed, the feed rate, the axial depth of a cut, the radial depth of a cut and the aging state) and their dual interactions on the surface roughness in the end-milling operations were evaluated and the following conclusions were achieved:

Surface roughness varies depending on the cutting speed in inverse proportion and on the feed rate, the axial depth of a cut and the radial depth of a cut in direct proportion. It was seen that surface roughness increased a bit during the machining of aged samples.

Only the cutting speed, the feed rate and the axial depth of a cut are significant for both ANOVAs. It is seen that the most significant process parameter is the feed rate followed by the cutting speed and the axial depth of a cut.

The optimum surface roughness was predicted to be 0.436 μm found in the case of the second cutting speed (*A* = 300 m/min), the first feed rate (*B* = 100 mm/min), the first axial depth of a cut (*C* = 0.75 mm), the first radial depth of a cut (*D* = 5) and under the non-aging conditions. The average surface roughness was found to be 0.343 μm in the verification tests that were repeated three times, and it existed within the specified confidence interval. Thus, the system was optimized successfully. Furthermore, the minimum surface roughness was found to be 0.38 μm in the nine-number experiment in the experimental plan (*A* = 300 m/min, *B* = 100 mm/min, *C* = 0.75 mm, *D* = 5 mm E: yes). With the result obtained during the verification tests an improvement of 9.74 % was obtained.

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