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Optimization of cutting parameters in pocket milling of tempered and cryogenically treated 5754 aluminum alloy

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Abstract. Aluminum alloys are widely used today in plastic injection molds in the automotive and aerospace industries due to their high strength and weight ratio, good corrosion and fatigue resistance as well as high feed rates. The 5754 aluminum alloy has high corrosion resistance and a structure suitable for cold forming. In this study, an AA 5754-H111 tempered aluminum alloy with the dimensions of 80×80×30 mm was used, and some of the materials were cryogenically heat treated. For the milling operations, φ12 mm diameter 76 mm height uncoated as well as TiCN and TiAlN coated end mills were used. Different levels of cutting depth (1.25, 2.0, 2.5 mm), cutting speed (50, 80, 100 m/min), feed rate (265, 425, 530 m/min) and machining pattern (concentric, back and forth and inward helical) were used. The number of experiments was reduced from 486 to 54 using the Taguchi L_{54} orthogonal array. The values obtained at the end of the experiments were evaluated using the signal-to-noise ratio, ANOVA, three-dimensional graphs and the regression method. Based on the result of the verification experiments, the processing accuracy for surface roughness was improved from 3.20 μm to 0.90 μm, with performance increase of 71.88%.

Key words: aluminum alloys, cryogenic treatment, surface roughness, Taguchi technique, optimization.

1. Introduction

Along with technological developments, the usage of aluminum in various sectors of the industry is increasing rapidly due to its advantages of durability, lightness, high corrosion resistance, machinability, formability and reusability. In addition, aluminum alloys (AAs) are widely used in the aerospace, automotive, plastic injection molds and defense industries due to their high strength/weight ratios, decent wear/fatigue resistance noted in recent years and high feed rates in terms of workability [1]. The resistance of AA 5754 to corrosion, especially in industrial atmospheres and sea water, is high. In particular, hydraulic equipment is used extensively in the automotive subsidiary industry, shipbuilding and construction equipment, chemical and food industries, and can be handled with conventional methods (turning, milling, drilling and grinding) even if there is no detailed machinability data. AAs machining operations (cutting AAs) are an important production process in the automotive industry for the manufacture of molds and mold parts [2, 3]. The machinability of an engineering material means applicability to machining processes, taking into account factors such as tool wear, cutting temperature, shear force and surface roughness [4, 5]. In particular, surface roughness plays an important role in the quality of the product and is a significant parameter in assessing machining accuracy. For this reason, the optimization and estimation of surface roughness in machining operations has been the focus of some researchers in recent years. Surface roughness is influenced by a variety of factors, including cutting speed, feed rate, cutting tool geometry, microstructure of the workpiece, heat treatments applied to the workpiece, heat treatments applied to the cutting tools, and rigidity of machine tools [6–12]. The effects of these parameters on surface quality can be optimized using the Taguchi method. The Taguchi method is widely used in designing quality engineering, and parameter designing plays an important role in modern engineering. Recently, the Taguchi method has been widely used in a variety of industrial fields and academic research studies [13–25].

Vakondios et al. investigated the effects of milling strategies on surface roughness by means of ball end milling operations on AA 7075-T6, and experimentally confirmed the statistical validity of all models created for milling strategies [26]. Kuram and Özçelik performed micro-milling processes using the AA 7075 material and ball nose end mill cutting tools. In addition, they optimized the cutting parameters using Taguchi-based gray correlation analysis [27]. Rubio et al. carried out turning operations using 90 mm diameter AA 7050 alloy rods, and investigated the effect of machining size on surface roughness [28]. The 6000 series AAs are generally magnesium; they are silicon and copper based and can be used in virtually all production processes, from automotive to construction materials [29]. Dinim et al. investigated the cutting parameters appropriate for best surface quality, and performed finger milling operations on the AA 6061-T6511 material using coated cutting tools. This study included the machinability of AA 6061 series and their work presented the uses of arithmetic average roughness to quantify surface roughness as commonly used in the industry. For this reason, statistical analysis was not included in this study [30]. Kadirgama et al., who evaluated surface roughness statistically, obtained a mathematical predic-

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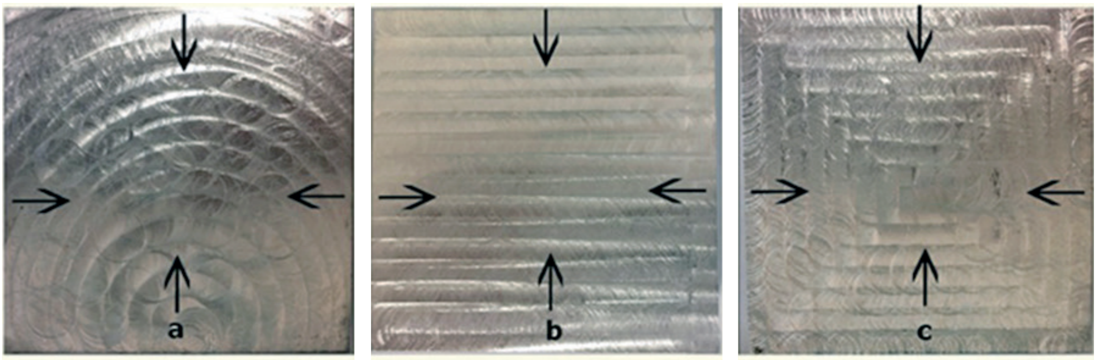

Fig. 1. Surface roughness measurement

tion model for minimum surface roughness in the processing of AA 6061-T6 using response surface methodology (RSM) [31, 32]. Although no special machinability data is available, AA 5083 has good workability properties with conventional methods such as turning, milling, drilling and grinding [33]. Pınar investigated the factor levels determined for experimental design to obtain minimum surface roughness in the pocket milling process on the AA 5083 material and the effect of process parameters on surface roughness, while experiments based on the L27 orthogonal array (OA) were evaluated with ANOVA and signal-to-noise ratios [34].

2. Experimental details

2.1. Experimental setup and pocket milling method. Based on the literature review of aluminum alloys, cryogenic heat treatment can be applied at various temperatures [35–39]. In this study, cryogenic treatment was applied to the AA 5754-H111 [40] material for 12 hours at –145°C with 1°C/min oven temperature change. The hardness of the material after the applied cryogenic treatment was measured as 54.9 Brinell. Hardness measurements were made according to the HB 2.5/62.5 Brinell hardness measurement method. In this study, the pocket milling process was applied to tempered and cryogenically treated AA 5754-H111 aluminum alloy of 80×80×30 mm in dimensions using uncoated as well as TiCN and TiAlN coated end mills of φ12 mm in diameter, 76 mm in height, and 25 mm in helical length along with air cooling. For milling operations, a three-axis DELTA S2 10 vertical milling machine 50A (Fanuc 0i-Mate MC, maximum speed of work shaft of 8000 rpm, operating pressure of 5.5 bar, motor power of 12 kW) was used.

The chemical composition, physical and mechanical properties of AA 5754-H111 are presented in Table 1. While determining the cutting parameters, cutting tools manufacturer's data and the recommendations contained in the ISO 8688-2 standard were taken into consideration. In this study, 486 full factorial experiments were reduced to 54 with the Taguchi technique.

2.2. Surface roughness measurement. Surface roughness measurements were made with the Taylor Hobson Surtronic S25 surface roughness device. Surface roughness values were measured perpendicularly to the edge of the piece at four different points of the workpiece at a sampling length of 4 mm (Lc = 0.80) (Fig. 1). The average of these four measurements was used in the analysis.

In Fig. 1, 'a' denotes a surface with concentric machining pattern, 'b' denotes a surface with back and forth machining pattern, and 'c' denotes a surface with inward helical machining pattern.

Table 1
Properties of AA 5754-H111

Chemical composition									
AL	Fe %	Si %	Cu %	Mn %	Mg %	Zn %	Cr %	Ti %	Other %
Balance	0.40	0.40	0.10	0.50	2.3–3.6	0.20	0.30	0.15	0.15

Physical properties					
Density	Melting point	Thermal expansion	Modulus of elasticity	Thermal conductivity	Electrical resistivity
2.66 gr/cm^3	600°C	24×10^{-6}/K	68 GPa	147 W/m.K	0.049×10^{-6} Ωm

Mechanical properties				
Proof stress	Tensile strength	Elongation	Shear strength	Brinell hardness
60 min MPa	160–200 MPa	12 min %	80–100 MPa	44 HB

3. Experimental design and optimization

3.1. Taguchi method. The Taguchi method is a simple and robust technique that is used to optimize process parameters, including reducing process variability. The aim of the analysis is to investigate how the different process parameters affect the mean and variance of process performance characteristics and which factor contributes significantly. The Taguchi method also uses some functions to determine quality attributes. Loss function values are also converted to a signal-to-noise (S/N) ratio (η). In general, S/N ratio analysis contains three different quality features: 'nominal the best', 'the larger the better' and 'the smaller the better (SB)'. In this study, SB was chosen as the minimum surface roughness that was sought after.

$$\text{SB:} \quad \eta = S/N_S = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where n is the number of observations and y is the observed data [41, 42].

3.2. Determining control factors and OA selection. OA selection is critical since it depends on the number of factors to be investigated for optimization, the number of interactions to be investigated, the number of levels required for each factor, the purpose of the experiment and, evidently, the experimental budget and usability of resources. To ensure that the selected OA design will provide sufficient degrees of freedom for the proposed experiment, the following inequality must be fulfilled: the number of degrees of freedom of the OA $\geq$ the number of degrees of freedom required to study the main effect and interaction [43]. The cutting parameters selected as control factors and their levels were determined as shown in Table 2.

The first step of the Taguchi method is to select an appropriate OA based on the cutting parameters chosen as control factors. The mixed OA $\left[L_{54}\left(3^5\times2^1\right)\right]$ was chosen to determine optimum cutting parameters and to analyze the effects of thus determined parameters [44]. In the experiments based on these 54 trials, each combination of control factors was evaluated. In addition, only 54 trials were conducted, using Taguchi's L_{54} OA, instead of 486 full factorial experiment designs, thus saving both time and experimental resources.

4. Analysis and evaluation of experimental results

4.1. Optimization of experimental results using the S/N ratio. The S/N ratios reflect the variability of the quality characteristic of the system and do not depend on the adjustment of the average. That is, if the target value is changed, the S/N ratio will still be useful for estimating quality [45, 46]. The minimum values of surface roughness obtained according to the experimental results have the greatest effect on the quality of the product and it is desired to reach the minimum value in the experimental study. For this reason, 'the smaller the better' Equation was chosen to calculate the S/N ratio (Equation 1). The S/N ratios calculated using Equation 1 are shown in Table 3. Averages of the four measured values were used for the surface roughness values used herein. As shown in Table 3, the cutting parameters,

Table 2
Cutting parameters selected as control factors and their levels for pocket milling

Symbol	Control factors	Levels		
		1	2	3
A	Material (m)	Tempered	Cryogenic heat treatment	–
B	Cutting tools (t)	Uncoated	TiCN	TiALN
C	Cutting speed (m/min, V)	50	80	100
D	Feed rate (m/min, f)	265	425	530
E	Cutting depth (a)	1.25	2.0	2.5
F	Machining pattern (id)	Concentric	Back and forth	Inward helical

Table 3
S/N ratios of experimental results for surface roughness

Trial No	Control factors						Signal to noise (dB)	
	A	B	C	D	E	F		
	Material (m)	Cutting tool (t)	Cutting speed (V)	Feed rate (f)	Cutting depth (a)	Machining pattern (id)	Ra_m	S/N
1	1	Uncoated	50	265	1.25	1	3.20	–10.10
2	1	Uncoated	50	265	1.25	1	3.20	–10.10
3	1	Uncoated	50	265	1.25	1	3.21	–10.13
4	1	Uncoated	80	425	2	2	2.51	–7.99

Trial No	Control factors						Signal to noise (dB)	
	A	B	C	D	E	F	Ra_m	S/N
	Material (m)	Cutting tool (t)	Cutting speed (V)	Feed rate (f)	Cutting depth (a)	Machining pattern (id)		
5	1	Uncoated	80	425	2	2	2.51	–7.99
6	1	Uncoated	80	425	2	2	2.52	–8.02
7	1	Uncoated	100	530	2.5	3	3.21	–10.13
8	1	Uncoated	100	530	2.5	3	3.21	–10.13
9	1	Uncoated	100	530	2.5	3	3.22	–10.15
10	1	TiCN	50	265	2	2	1.18	–1.43
11	1	TiCN	50	265	2	2	1.18	–1.43
12	1	TiCN	50	265	2	2	1.19	–1.51
13	1	TiCN	80	425	2.5	3	3.31	–10.39
14	1	TiCN	80	425	2.5	3	3.30	–10.37
15	1	TiCN	80	425	2.5	3	3.31	–10.39
16	1	TiCN	100	530	1.25	1	1.23	–1.79
17	1	TiCN	100	530	1.25	1	1.23	–1.79
18	1	TiCN	100	530	1.25	1	1.24	–1.86
19	1	TiAlN	50	425	1.25	3	2.70	–8.62
20	1	TiAlN	50	425	1.25	3	2.69	–8.59
21	1	TiAlN	50	425	1.25	3	2.70	–8.62
22	1	TiAlN	80	530	2	1	1.26	–2.01
23	1	TiAlN	80	530	2	1	1.26	–2.01
24	1	TiAlN	80	530	2	1	1.25	–1.93
25	1	TiAlN	100	265	2.5	2	0.90	–0.91
26	1	TiAlN	100	265	2.5	2	0.90	–0.91
27	1	TiAlN	100	265	2.5	2	0.91	–0.81
28	2	Uncoated	50	530	2.5	2	5.14	–14.21
29	2	Uncoated	50	530	2.5	2	5.13	–14.20
30	2	Uncoated	50	530	2.5	2	5.13	–14.20
31	2	Uncoated	80	265	1.25	3	2.48	–7.88
32	2	Uncoated	80	265	1.25	3	2.49	–7.92
33	2	Uncoated	80	265	1.25	3	2.49	–7.92
34	2	Uncoated	100	425	2	1	2.80	–8.94
35	2	Uncoated	100	425	2	1	2.80	–8.94
36	2	Uncoated	100	425	2	1	2.80	–8.94
37	2	TiCN	50	425	2.5	1	2.81	–8.97
38	2	TiCN	50	425	2.5	1	2.81	–8.97
39	2	TiCN	50	425	2.5	1	2.81	–8.97
40	2	TiCN	80	530	1.25	2	1.61	–4.13
41	2	TiCN	80	530	1.25	2	1.62	–4.19
42	2	TiCN	80	530	1.25	2	1.61	–4.13
43	2	TiCN	100	265	2	3	1.07	–0.58
44	2	TiCN	100	265	2	3	1.08	–0.66
45	2	TiCN	100	265	2	3	1.07	–0.58
46	2	TiAlN	50	530	2	3	2.59	–8.26
47	2	TiAlN	50	530	2	3	2.59	–8.26
48	2	TiAlN	50	530	2	3	2.60	–8.29
49	2	TiAlN	80	265	2.5	1	1.79	–5.05

Trial No	Control factors						Signal to noise (dB)	
	A	B	C	D	E	F	Ra_m	S/N
	Material (m)	Cutting tool (t)	Cutting speed (V)	Feed rate (f)	Cutting depth (a)	Machining pattern (id)		
50	2	TiAlN	80	265	2.5	1	1.79	–5.05
51	2	TiAlN	80	265	2.5	1	1.79	–5.05
52	2	TiAlN	100	425	1.25	2	1.26	–3.04
53	2	TiAlN	100	425	1.25	2	1.26	–3.04
54	2	TiAlN	100	425	1.25	2	1.26	–3.04

Notes: SRa_m (surface roughness total mean value) = 2.28 µm
SRa_m – S/N (surface roughness S/N ratio total mean value) = –6.34 dB

expressed as control factors, were distinguished by considering different levels and probable effects according to the selected OA. After 54 trial runs, the average value of surface roughness was calculated as 2.28 µm and the average S/N ratio was calculated as –6.34 dB.

The average S/N ratios (dB) and the surface roughness values indicated in the control factors shown in Table 4 were obtained according to the control factors and levels of the cutting parameters applied in the experimental study. These levels shows the signal noise ratios (S/N) calculated for the analysis of surface roughness and the average surface roughness values calculated by averaging the total values obtained for surface roughness. As a result of the experimental study, in selecting the appropriate quality characteristic for the determination of minimum surface roughness according to the control factors, the results obtained for 'the smallest (lowest) the best' calculated signal to noise ratios S/N were taken into consideration. Optimum levels can be determined by evaluating different levels of control factors according to the results of the combinations produced by L_{54} OA. As a result, the levels of control factors are determined for the surface roughness shown in Table 4. These levels are used to plot out the surface roughness values and S/N ratios in the main effects plot (Fig. 2).

Table 4
Average S/N ratios (dB) and means of control factors

Control factors	Surface roughness (Ra)			Max-Min
	Level 1	Level 2	Level 3	
S/N ratios (dB)				
A	–5.726	–6.678	–	0.952
B	–9.882	–4.558	–4.165	5.718
C	–8.599	–6.239	–3.766	4.833
D	–4.037	–7.816	–6.752	3.779
E	–5.762	–4.867	–7.977	3.110
F	–6.140	–4.815	–7.650	2.835
Means (µm)				
A	2.165	2.394	–	0.229
B	3.224	1.868	1.748	1.476
C	2.935	2.159	1.746	1.189
D	1.772	2.562	2.505	0.790
E	2.080	1.901	2.859	0.958
F	2.181	2.099	2.559	0.460

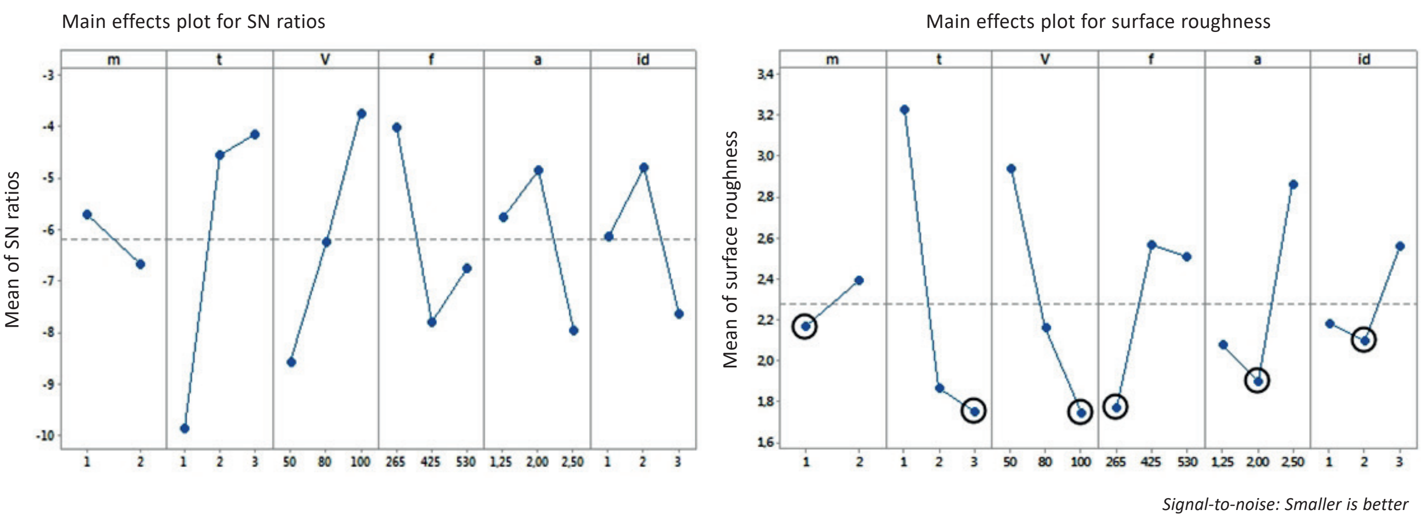

Fig. 2. Mean effects plot for control factors

S/N ratios and mean surface roughness distributions calculated according to the control factors and levels are shown in Fig. 2. Since 'the smaller the better' characteristic was chosen in the study, the lowest mean values for all levels were evaluated to determine the optimum combination of control factors. Similarly, high S/N ratios can be evaluated to determine the optimum combination. The calculated optimum values are suggested for 54 trials and their 486 potential combinations $(2^1 \times 3^5)$. Accordingly, the optimum combination of pocket milling parameters is $A_1B_3C_3D_1E_2F_2$ (A_1 = tempered aluminum, B_3 = TiAlN coated cutting tool, $C_3 = 100$ m/min, $D_1 = 265$ m/min, $E_2 = 2$ mm, F_2 = back and forth).

4.2. Evaluation of experimental results. The average surface roughness variations obtained from the experimental study of the milling process based on the control factors and their variations are shown in Fig. 3. Figure 3a shows the effects of the feed rate and cutting depth on surface roughness. It also shows that there was an increase in surface roughness at a depth of cut value of 1.25 mm and a feed rate of 265 m/min, but there was a decrease in it at the same feed rate and a depth of cut value of 2.5 mm. The practical value of cutting depth varies from applicator to applicator and from one set of milling tools to another. It is also customary to increase the tool radius by increasing cutting depth to achieve the best surface quality in machinability [47]. In Fig. 3a, best average surface roughness was obtained at a cutting depth of 2 mm and a feed rate of 265 mm/min. This is in line with the optimized combinations obtained with the Taguchi technique. In Fig. 3b, the effect of cutting speed and cutting depth on the surface roughness value is shown in a three-dimensional graph. Figure 3b shows that there was a decrease in surface roughness at a depth of cut value of 1.25 mm and cutting speed of 100 m/min. On the other hand, the highest roughness value was achieved at a depth of cut value of 2.5 mm and cutting speed of 50 m/min. In the graph, as the cutting speed increases, the surface roughness values show a decrease. Figure 3c shows the effect of feed rate and cutting speed on surface roughness. Here, the lowest surface roughness was obtained at cutting speed of 100 m/min and feed rate of 265 mm/min. Therefore, the point on the plot where surface

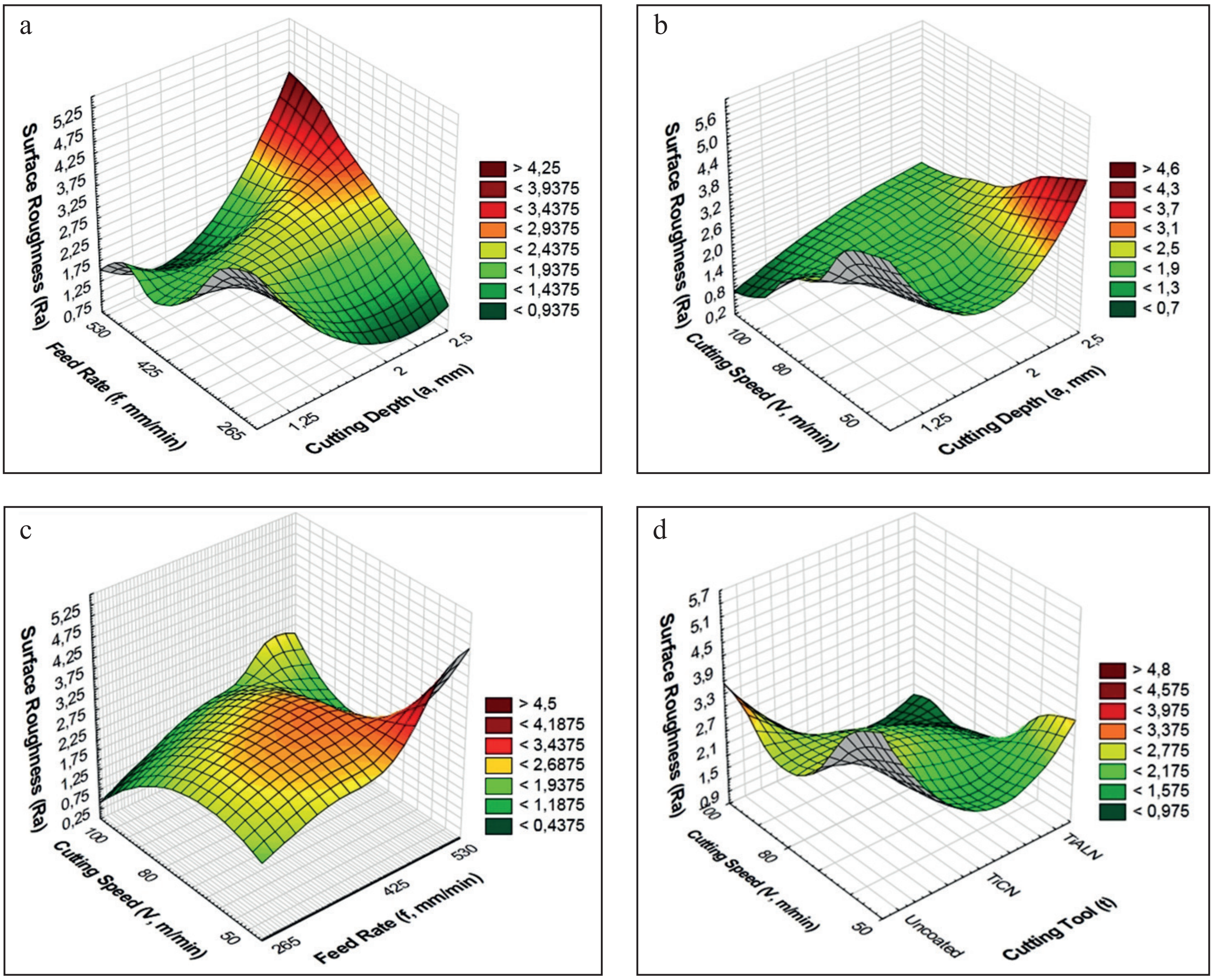

Fig. 3. Effect of cutting parameters on surface roughness

roughness displayed a decrease was at the highest cutting rate (100 m/min) and lowest feed rate (265 mm/min). On the other hand, in the same plot, it may be seen that the roughness values increased at the highest feed rate (530 mm/min) and the lowest cutting speed (50 m/min). While these two observations were in agreement with the literature, a similar study emphasized that the feed rate should be reduced to improve surface roughness [48].

In Fig. 3d, the effect of cutting speed and type of cutting tool on surface roughness is shown in a three-dimensional graph. In this graph, the lowest surface roughness value is obtained with cutting speed of 100 m/min and a TiAlN coated cutting tool. This is in line with the optimum combinations obtained by means of the Taguchi technique. The highest surface roughness values were obtained with the uncoated cutting tool. It was observed that surface roughness decreased at cutting speed of 50 m/min and with the TiCN coated cutting tool.

Consequently, the results that were obtained from three-dimensional plots were in agreement with the optimized parameters that were obtained by means of the Taguchi method. This outcome shows that the Taguchi method was successfully implemented in this study.

4.3. Data analysis using ANOVA. Analysis of variance (ANOVA) is a statistical method used to identify and analyze individual interactions of all the control factors in the Taguchi method. In this study, the effects of the material, cutting tool, cutting speed, feed rate, cutting depth and machining on surface roughness were investigated using the ANOVA method. In the analysis, the percent distributions of each control factor were used to measure their effects on the observed quality characteristics. The test results were evaluated at a confidence level of 95%. The ANOVA values for the test results are shown in Table 5.

In the ANOVA tables in Table 5, the significance status of the control factors was determined by comparing the F value of each control factor with the F0.05 value obtained from an F table for alpha 0.05 [49]. In this case, the factors below the F1.6 and F2.6 values in the table were extracted. Here, the error term (e) is combined with the sum of squares, the degrees of freedom of the extracted factors, the degree of freedom of error and the variance pooling method. Factors marked with '*' were combined to produce an estimated pooled error at a 95% confidence level. In Table 5, material (m), feed rate (f), and machining design (id) were extracted from the table as a result of the F value comparison made by the pooling method at a 95% confidence interval. Percentage distributions were obtained from other effective factors such as the cutting tool (t) (at 37.64%), cutting speed (V) (at 19.43%), cutting depth (a) (at 13.23%), and pooled error (e_t) (at 29.7%). According to the table, the factor with most effect on surface roughness was the cutting tool, at 37.64%. This was followed by cutting speed at 19.43%. In addition, since the variance caused by the material (m) is very small, it can be regarded as mere noise in this study [50].

4.4. Regression method for experimental results. In this study, the response surface regression model was used to determine the relationship between surface roughness and cutting parameters. Multiple regression analyses can be used to derive the estimating Equations of continuous dependent variables obtained through experimental designs with each combination of control factors. The derived equation for the second-order regression model is shown below:

$$\begin{aligned} Ra_m = & -5.716 + 1.166\,m - 2.383\,t + 0.841\,t^2 - \\ & - 0.0197\,V - 0.0012\,V^2 + 0.0433\,f - \\ & - 0.0000608\,f^2 + 13.110\,a - 3.779\,a^2 - \\ & - 10.272\,id + 2.82\,id^2 - 0.567\,mt - \\ & - 0.043\,mV + 0.0637\,tV + 0.010\,mf - \\ & - 0.013\,tf + 0.00026\,Vf \end{aligned} \tag{2}$$

Ra_m expresses the estimating Equation created by using control factors for surface roughness. According to the regression results, the R^2 value of the Equation obtained for surface roughness with the response surface regression model is calculated as 0.99.

Table 5
Results of ANOVA for control factors

Variance source (surface roughness (Ra–µm)	Degree of freedom (DF)	Sum of squares (SS)	Mean square (MS)	F	Contribution (%)
m*	1	0.2358*	–	–	–
t	2	8.0626	4.0313	16.78	37.64
V	2	4.3700	2.1850	9.09	19.43
f*	2	2.3312*	–	–	–
a	2	3.1132	1.5566	6.48	13.23
id*	2	0.7235*	–	–	–
Error (e)	6	–	–	–	–
Pooled error (et)	(11)	(4.7324)	(0.4302)	–	29.7
Total	17	20.2782	–	–	100

4.5. Confirmation experiments and determination of quality losses. Validation experiments and determination of quality losses are the last step of the Taguchi method and the purpose of these applications is to analyze the quality characteristics. The purpose of validation experiments is to verify the validity of the results obtained during the analytic phase. Validation experiments serve the purpose of testing the specific combinations of factors and their levels, and are defined by the total effect produced by the control factors [49]. These factors are equal to the sum of each effect. In the Taguchi optimization technique, a validation experiment must be conducted to verify the optimized condition [43]. Minimum surface roughness is obtained by taking into account the effective factors in the optimum combination evaluated. For this reason, considering the individual effects of the control factors, the minimum surface roughness value (Ra_c) for $A_1B_3C_3D_1E_2$ and F_2 (A_1 = tempered aluminum, B_3 = TiAlN coated cutting tool C_3 = 100 m/min, D_1 = 265 mm/min, E_2 = 2 mm, F_2 = back and forth) is calculated by means of the following equation:

$$Ra_c = B_3 + C_3 + E_2 - 2SRa_m. \tag{3}$$

Here, B_3, C_3 and E_2 are the averages of experimental experiments with different levels of the factors. Ra_m is the average of surface roughness values. In the selection of the most effective factors, Table 5, which is interpreted by F-value comparison using the 95% confidence interval, was taken into account. When these values were taken into consideration, the minimum surface roughness value (Ra_c) was calculated as 0.84 μm. The confidence interval (CI) is used to verify quality of the validation experiments. The confidence interval is a maximum and minimum value between which the true average should fall within the confidence level. The CI used in estimating the optimum values is calculated by means of the following Equation [43, 50–52]:

$$CI = \sqrt{F_{\alpha:1,Ve} x V_{ep} x \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)}. \tag{4}$$

Here, $F_{\alpha:1,v_e}$ is the F ratio of significance level α, α is the significance level, 1:α is the confidence interval, V_e is the degree of freedom of the extracted error, V_{ep} is the variance of the extracted error, r is the number of validation experiments, and n_{eff} is the number of measured results [50].

$$n_{eff} = \frac{N}{1 + V_t}. \tag{5}$$

Here, N is the total number of experiments (54), and V_t is the total degree of freedom of the process parameters in Table 5, where the average is calculated (6). Accordingly, n_{eff} was calculated as 7.71 [23]. Three validation experiments were performed using optimum conditions to evaluatexx the performance of the experimental studies carried out as part of this study. For surface roughness, $F_{\alpha:1}$, v_e = 4.844 was obtained from the table for α = 0.05 and V_e = 11 at the 95% confidence interval. V_{ep} value was found to be 0.4302. Using Equation 4 and Equation 5, CI was calculated as 0.98. The results of the validation experiments carried out for surface roughness are expected to be within the range of (0.84 ±0.98) μm or (0–1.82) μm at the 95% confidence interval. In the validation experiments conducted with the optimum levels ($A_1B_3C_3D_1E_2F_2$), surface roughness values were obtained as 0.96, 0.82 and 0.91 μm, respectively, and their average was calculated as 0.90 μm. Taking the obtained CI value into account, the surface roughness values are in the range of $0 < 0.90 < 1.88$.

In Table 6, surface roughness values are compared according to the optimum combinations obtained by means of experiments and estimation. At the same time, the $A_1B_1C_1D_1E_1F_1$ combination was selected from 54 trials as the initial combination. According to Table 6, the surface roughness values were reduced from 3.20 μm to 0.90 μm and the accuracy developed with the optimum combination was increased to 71.88% ((3.20–0.90)/3.20) for surface roughness. Table 7 lists performance comparisons between the initial and optimum conditions. The mean of the verification experiments is 0.90 μm, i.e. within the estimated range of 0–1.82 μm, which means that the control factors considered in this study are both significant and correct. As a result, 54 experimental trials have been successfully evaluated.

Table 6
Comparison of combinations in terms of means and S/N ratios

	Level	Ra (μm)	S/N (dB)
Initial combination	$A_1B_1C_1D_1E_1F_1$	3.20	–10.10
Surface roughness (Ra_m)			
Optimum combination (experimental)	$A_1B_3C_3D_1E_2F_2$	0.90	–0.91
Optimum combination (prediction)	$A_1B_3C_3D_1E_2F_2$	0.84	–1.51

Table 7
Performance comparison between initial and optimum combination

	Initial combination	Optimum combination	
		Prediction	Confirmation
Level	$A_1B_1C_1D_1E_1F_1$	$A_1B_3C_3D_1E_2F_2$	$A_1B_3C_3D_1E_2F_2$
Ra_m (μm)	3.20	0.84 ±0.98	0.90
Quality loss 11.9%			

As indicated in Table 7, the quality characteristic of this experiment was improved from 3.20 μm ($A_1B_1C_1D_1E_1F_1$, initial combination) to 0.90 μm ($A_1B_3C_3D_1E_2F_2$, optimum combination). For surface roughness, the quality losses between the initial and optimum combinations can be calculated as a quality loss function ratio. This function expresses the following regularity: every 3 dB of quality improvement will reduce half of quality loss. The quality loss function is calculated by means of the following equation [50]:

$$\frac{L_{opt}(y)}{L_{ini}(y)} \approx \left(\frac{1}{2}\right)^{\Delta_\eta/3}. \quad (6)$$

Here, $L_{opt}(y)$ and $L_{ini}(y)$ are the initial and optimum combinations, respectively. Δη is the difference between the S/N ratios of the optimum and initial combinations. The differences in the S/N ratios that can be used to assess the quality loss of the optimum combination for the validation experiments were found to be 9.19 [Δη = 9.19 (= 10.10–0.91)]. The quality loss of the validation test was calculated as 0.119 using Equation 6. This way, the quality loss of the optimum combination is only 11.9% of the initial combination. For this reason, the quality loss for surface roughness in the optimization performed using the Taguchi method is reduced by 88.1%.

5. Results and discussions

Parameter design of the Taguchi method is presented in this study and the second order quadratic fit method is applied along with the response surface method for three-dimensional graphs and statistical methods such as ANOVA and regression to evaluate the effect of cutting parameters on surface roughness. In this study, the Taguchi method was used to obtain the most suitable control factors under air-cooled cutting conditions and to evaluate the quality characteristic of the pocket milling process on cryogenically treated and untreated aluminum 5754-H111 alloy. Also in this study, the selected initial roughness value is 3.20 µm and the optimum roughness value after optimization is 0.90 µm. Thus the surface roughness values were reduced by 71.88%. In the experimental results, the TiAlN coated cutting tool, which was found by using Taguchi analysis, gave the best minimum surface roughness value. When the experimental results and the results optimized with the Taguchi technique were compared, the same results were obtained with all the cutting tools. The results obtained from this study can be listed as follows:

- Based on the test results, the optimum combination of pocket milling parameters was found as $A_1B_3C_3D_1E_2F_2$ (A_1 = tempered aluminum, B_3 = TiAlN coated cutting tool, C_3 = 100 m/min, D_1 = 265 mm/min, E_2 = 2 mm, F_2 = back and forth).
- Test results show that the cutting tool (t) is the most important factor for surface roughness, with the main effect at 37.64%. This factor was followed by cutting speed (V) with a rate of 19.43%.
- According to ANOVA results, the averages and S/N ratios were similar. Validation test results showed that the observed values were within the calculated CI for a significance level of 5% (or 95% confidence interval).
- Using the optimum combination, the quality loss of surface roughness was reduced by 11.9%. Experiments have shown that the TiAlN coated cutting tool has positive effects on better surface roughness.
- As a result of the experiments carried out, the surface roughness value obtained under optimum conditions identified by the Taguchi method was improved from 3.20 µm to 0.90 µm ($A_1B_3C_3D_1E_2F_2$, optimum combination).

Literature review shows that no studies have been conducted to date on the optimization of cutting parameters for surface roughness during the pocket milling process on 5754-H111 tempered AA. As shown in this study, the Taguchi method is successfully used to determine the optimum combinations of cutting parameters and to minimize the machining costs and time of the pocket milling process of the 5754-H111 aluminum alloy widely used in the chemical and food industry, the automotive industry and sub-industry, in hydraulic applications, the nuclear industry, shipbuilding and construction equipment as well as the pressure vessels and boiler manufacturing industry. The method presented in this study can be applied to a variety of machining operations of aluminum alloys.

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