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Optimization of Thrust Force and Surface Roughness Using Response Surface Methodology (RSM) in Drilling of Al-30Zn Alloy

Al-30Zn Alaşımının Delinmesinde Yüzey Cevap Metodu (YCM) Kullanarak İlerleme Kuvveti ve Yüzey Pürüzlülüğünün Optimizasyonu

Şenol BAYRAKTAR*[a], Ali Paşa HEKİMOĞLU[b]

Recep Tayyip Erdogan University, Faculty of Engineering, Department of Mechanical Engineering, Zihni Derin Campus, 53100, Rize, TURKEY

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Abstract

In this study, Al-30Zn alloy was produced by permanent mold casting method. Drilling tests were performed after the values of hardness, tensile strength and elongation to fracture of the alloy were determined. 80x50x20 mm in dimensions workpiece was prepared from alloy ingot and drilling tests were performed with 8 mm diameter, 30° helix and 118°-point angle uncoated HSS (High speed steel) drills. Drilling tests were performed according to the experimental design obtained in response surface methodology (RSM) statistical analysis software. Independent variables were defined as cutting speed (600, 900 and 1200 rev/min) and feed rate (0.05, 0.15 and 0.25 mm/rev), while dependent variables were defined as thrust force and surface roughness. According to the experimental results, the statistical effect of independent variables on dependent variables was analyzed with ANOVA and optimum cutting parameters were determined. Accordingly, it was observed that the most effective independent variables on thrust force and surface roughness were feed rate and cutting speed, respectively. In addition, optimum cutting conditions according to minimum goal function were determined as cutting speed of 1200 rev/min and feed rate of 0.05 mm/rev. It was found that validation tests and statistical results were quite compatible depending on optimum cutting conditions.

Keywords: Drilling, Optimization, Response Surface Methodology, Surface Roughness, Thrust Force

Öz

Bu çalışmada kokil kalıba döküm yöntemi ile Al-30Zn alaşımı üretilmiştir. Sertlik, çekme mukavemeti ve alaşımın kopma uzaması değerleri belirlendikten sonra delme testleri yapıldı. Alaşım külçesinden 80x50x20 mm boyutlarında iş parçası hazırlanmış ve 8 mm çaplı, 30° helis ve 118° uç açılı kaplamasız HSS (High speed steel) matkaplarla delme testleri yapılmıştır. Delme testleri, istatistiksel analiz yazılımından elde edilen yüzey cevap metodu (RSM) deneysel tasarımına göre yapılmıştır. Bağımsız değişkenler, kesme hızı (600, 900 ve 1200 dev/dak) ve ilerleme miktarı (0.05, 0.15 ve 0.25 mm/dev), bağımlı değişkenler ise itme kuvveti ve yüzey pürüzlülüğü olarak tanımlanmıştır. Deney sonuçlarına göre bağımsız değişkenlerin bağımlı değişkenler üzerindeki istatistiksel etkisi ANOVA ile analiz edilmiş ve optimum kesme parametreleri belirlenmiştir. Buna göre, itme kuvveti ve yüzey pürüzlülüğü üzerinde en etkili bağımsız değişkenlerin sırasıyla ilerleme miktarı ve kesme hızı olduğu gözlenmiştir. Ayrıca minimum hedef fonksiyonuna göre optimum kesme şartları 1200 dev/dak kesme hızı ve 0.05 mm/dev ilerleme miktarı olarak belirlenmiştir. Doğrulama testleri ile istatistiksel sonuçların optimum kesme şartlarına bağlı olarak oldukça uyumlu olduğu tespit edilmiştir.

***Anahtar kelimeler**: Delme, Optimizasyon, Yüzey Cevap Metodu, Yüzey Pürüzlülüğü, İtme Kuvveti*

*[a] Şenol Bayraktar; senol.bayraktar@erdogan.edu.tr, Tel: (0464) 223 75 18, orcid.org/0000-0001-8226-0188
[b] orcid.org/0000-0003-2396-4876

1. Introduction

In recent years, as a result of detailed research and development studies carried out on aluminum-based alloys, many aluminums and/or zinc-based bearing alloys have been developed which can be an alternative to conventional bearing materials such as bronze, brass and cast iron (Gervais et al., 1980; Hekimoğlu and Savaşkan, 2018; Prasad, 2005; Delneuville, 1985). These studies have shown that Al-Zn based alloys have some advantages over these conventional bearing materials. The most important advantages of Al-Zn based alloys are their high specific strength, ease of production and superior friction-wear resistance (Gervais et al., 1980; Hekimoğlu and Savaşkan, 2018; Prasad, 2005; Delneuville, 1985). The high specific strength and ease of production of Al-Zn based alloys is due to the low density of aluminum and low melting point, respectively. High friction-wear resistance of the Al-Zn alloys is explained by the combination of soft and hard phases in their microstructures (Hekimoğlu and Savaşkan, 2016; Savaşkan and Hekimoğlu, 2016; Hekimoğlu and Turan, 2019). It is claimed that the hard phases in the microstructures of these alloys facilitate load-bearing, while the zinc-rich soft phases facilitate the sliding due to the feature of the hexagonal close packed lattice structure (Marczak and Ciach, 1973; Barnhurst and Farge, 1988; Barnhurst, 1990; Prasad et al., 2001). Some studies have been conducted to determine the machinability properties of Al-Zn based alloys. Sanchez et al. investigated the effect of cutting parameters (*V*: 80 m/min, *f*: 0.05-0.3 mm/rev) on chip geometry during turning of UNS A97075 (Al:88.98% and Zn:6.03%) alloy (Sanchez et al., 2015) They found that the feed rate parameter had a significant effect on chip geometry and tool life. It is known that cutting force, surface roughness and BUE and BUL formation decrease with increasing cutting speed and cutting force and surface roughness increase in case of increasing feed rate in the Al-35Zn alloy (Hekimoğlu et al., 2018; Bayraktar et al., 2017). It is also known that uncoated tools perform better in the machining of the Al-Zn alloys (Hekimoğlu et al., 2018; Bayraktar et al., 2017). Martín-Béjar et al. observed that adhesion wear (Built up edge and Built up layer) increased due to increasing of feed rate and depth of cut during dry turning of the Al-Zn alloy (Al:89.13% and Zn: 6.03%) (Martín-Béjar et al., 2017), Bermudo et al. found that tensile strength increases after tensile tests after machined samples and this is caused by residual stresses caused by compression stresses on the machining surface (Bermudo et al., 2017). Yi et al. observed that the micro-milling of Al-6061-T3 alloy decreased surface roughness with increasing cutting speed and increased with increasing feed. In addition, they found that good coherence was obtained between experimental and predicted results with the response surface method optimization (RSM) technique (Yi et al., 2015), Kyratsis et al. studied the effect of independent variables on dependent variables in drilling of Al-7075 alloy with RSM optimization technique (Kyratsis et al., 2018). The results of this study showed that the feed rate parameter on thrust force and cutting torque is more effective than cutting speed and optimization and experimental results are compatible with each other, Dikshit et al. reported that the roughness of the machined surface in milling of Al-2014-T6 alloy increased with increasing feed rate and cutting speed. In addition, they were stated that the mathematical model and experimental results developed by the RSM were statistically compatible (Dikshit et al., 2017). Studies in the literature revealed that structural, mechanical, tribological and machinability properties of Al-Zn based alloys differ according to the zinc content they contain (Hekimoğlu and Turan, 2019; Bican and Savaşkan, 2010; Savaşkan et al., 2009). On the other hand, it has been shown that Al-Zn alloys exhibit the highest strength and/or specific strength values if the zinc content is approximately 30% in the studies conducted to determine the optimal zinc content for Al-Zn based alloys (Hekimoğlu and Turan, 2019; Savaşkan et al., 2009). In these studies, structural and mechanical properties of Al-30Zn alloys are investigated in detail. However, there is no study to determine the most suitable machining parameters of Al-30Zn alloy. However, in the manufacturing of bearings, machining is one of the most important operation because it is the most effective process on the size, tolerance, surface integrity and roughness of the final product. Therefore, in this study, independent variables (Cutting speed and feed rate) were optimized by using response surface methodology in drilling of Al-30Zn alloy with uncoated HSS drills. According to the experimental results, statistical analyzes were performed with ANOVA to determine the numerical effects of independent variables on thrust force and surface roughness. In addition, mathematical models for thrust force and surface roughness were developed and thus the relationship between experimental and mathematical model results were put forward.

2. Materials and Methods

2.1. Preparation of Test Samples, Cutting Tool and Experimental Setup

In this study, Al-30Zn alloy containing 30% zinc was produced by permanent mold casting method. High commercial purity (99.8%) aluminum and zinc were used in the production of the alloy. The alloying elements were melted in a medium frequency induction melting furnace and then solidified by pouring into a mold made of SAE 8620 steel at a casting temperature of approximately 700° C. The technical drawing of the alloy ingot obtained from the casting is given in Figure 1. Hardness, tensile and drilling test samples were prepared from the middle part of the alloy ingot by machining method. Hardness measurements were carried out with Brinell method on the specimens with the dimension of Ø20×15 mm by using 2.5mm diameter ball under 62.5kg×f load. Fifteen hardness measurements were made on the alloy sample and the mean (90 ± 2 HB) of the obtained values was accepted as the hardness of alloy. Tensile tests were performed by using a universal test machine on the samples having the diameter of 8 mm and gauge length of 40 mm at a deformation rate of 10^{-3} s^{-1}. Six samples were used in the tensile tests. The data obtained from these tests were averaged and the values of the tensile strength and elongation to fracture of the alloy were calculated as 290±8 MPa and 7±2%, respectively. Drilling tests were carried out on the samples having the dimension of 50x80x15 mm prepared by milling from alloy ingots. These tests were conducted with Johnford VMC 850 CNC vertical machining center with 7.5 kW and 6000 rpm, Kistler 9273 three-component dynamometer for measuring thrust force, Kistler 5070A signal amplifier and Dynoware software for converting vibration signals into thrust force-times graphics (Figure 2) (Bayraktar and Afyon, 2020). Three different cutting speeds (600, 900 and 1200 rev/min), feed rate (0.05, 0.15 and 0.25 mm/rev) and 20 mm depth of cut were used as cutting parameters. Cutting parameters were determined in accordance with literature research and cutting tool manufacturer's recommendation (Kao et al., 2019; Tosun and Muratoğlu, 2004; Bahçe and Özdemir, 2019). Uncoated HSS (Makine Takım Endüstri A.Ş) drills with 30° helix and 118° point angle of Ø8 mm diameter were used in the experiments.

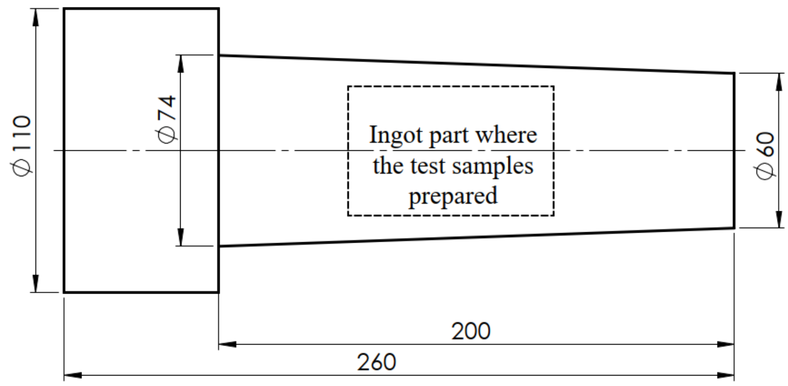


Figure 1. Technical drawing of alloy ingot and drilling test specimen (Dimensions in mm)

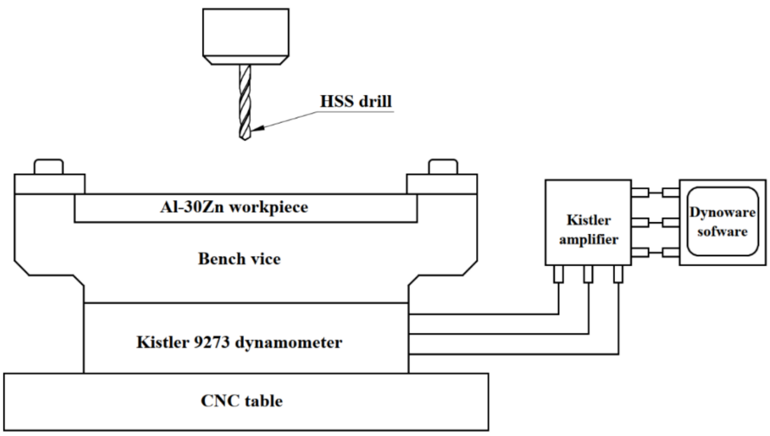


Figure 2. Experimental setup

2.2. Response Surface Methodology (RSM)

The response surface method is an empirical modeling approach based on the determination of the relationship between different independent variables and responses. The aim is to investigate the effect of independent variables on responses and to optimize these responses (Bouzid et al., 2015; Çiçek et al., 2015). In this study, CCD (Central Composite Design) experimental design approach was used to allow the evaluation of linear effects due to the final quadratic interactions between different independent variables. The second order quadratic mathematical model used in the calculation of the response resulting from interactions can be given as follows in Equation (1).

$$Y = a_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \tag{1}$$

i, j, k=1, 2, 3 …. *n* ve a_0, b_i,b_{ij} ve b_{ii} represent the regression coefficients of the model, , X_i and X_j, descriptive variables, and Y represent the desired machinability output in Equation (1) (Chabbi et al., 2017). ANOVA (Analyses of Variance) is used to determine the effect of independent variables on output responses (Meddour et al., 2015; Haiyan and Xuda, 2016). In this study, independent variables were determined as cutting speed and feed (Table 1), while machinability response outputs were determined as thrust force and surface roughness.

Table 1. Independent variables and levels

Level	Cutting speed (rev/min)	Feed rate (mm/rev)
-1	600	0.05
0	900	0.15
1	1200	0.25

3. Statistical Analysis and Modeling

Regression models for thrust force and surface roughness were created in Minitab 17.0 software. These models describe the relationship between independent variables and responses. It also allows the estimation of different responses according to independent variables (Kilic et al., 2019). ANOVA (Analysis of Variance) is used to determine the statistical significance of regression models, model terms, and lack of fit on responses (Kıvak et al., 2016). Accordingly, the statistical significance or effect value of the independent variables on the responses is determined by considering the 95% confidence level or in other words P <0.05 (Labidi et al., 2018). Cutting tests were performed depending on the experimental design according to RSM and the output response results obtained are given in Table 2.

Table 2. Experimental results

	Independent variables		Output response	
Test No	Cutting speed (rev/min)	Feed rate (mm/rev)	Thrust force (N)	Surface roughness (µm)
1	900	0.15	517.580	1.499
2	600	0.25	742.190	1.837
3	1200	0.05	274.621	1.007
4	900	0.15	507.810	1.499
5	900	0.15	478.520	1.482
6	900	0.15	458.980	1.508
7	600	0.15	585.940	1.623
8	900	0.15	468.750	1.439
9	1200	0.25	615.230	1.516
10	600	0.05	348.960	1.317
11	1200	0.15	449.220	1.296
12	900	0.05	322.480	1.256
13	900	0.25	634.770	1.633

Table 3 shows the ANOVA results obtained for thrust force according to output responses. Accordingly, considering the 95% confidence level, it was found that the P <0.05 requirement for V and f was provided, the percentage contributions were 3.820% and 47.482%, respectively, and thus significant parameters on the output were statistically significant. When V^2, f^2 *ve* V x f were examined, it was observed that P <0.05 condition was not fulfilled and their percentage contribution were 0.909%, 0.333% and 0.389%, respectively and it was found that there was no significant effect on the outputs.

Table 3. ANOVA results for thrust force

Source	Degree of freedom	Sum of square	Mean of square	F	P	PC (%)	Observation
Model	5	203848	40769.7	69.07	0.000	22.940	Significant
Lineer	2	91174	40769.7	77.23	0.000	22.940	Significant
V	1	6790	6790.3	11.50	0.012	3.820	Significant
f	1	84384	84384.1	142.95	0.000	47.482	Significant
Square	2	1716	857.9	1.45	0.297	0.482	Not Significant
$V*V$	1	1616	1616.3	2.74	0.142	0.909	Not Significant
$f*f$	1	602	602.0	1.02	0.346	0.338	Not Significant
2-Way interaction	1	692	692.2	1.17	0.315	0.389	Not Significant
$V*f$	1	692	692.2	1.17	0.315	0.389	Not Significant
Error	7	4132	590.3	-	-	-	-
Lack of fit	3	1576	5.253	0.82	0.546	0.0295	Not Significant
Pure error	4	2556	639	-	-	-	-
Total	12	207980	-	-	-	100	-

R^2:0.981; R^2(Adj):0.967 and R^2(Pred):0.901
PC: Percentage contribution

Correlation coefficients for thrust force were determined as R^2:0.981, R^2(Adj):0.967 and R^2(Pred):0.901 and these coefficients are considered to be good in terms of the effectiveness of the model results. The quadratic mathematical model used in calculating the thrust force according to independent variables is given in Equation (2).

$$F = 521 - 0.6067V + 2581f + 0.000269V^2 - 1476f^2 - 0.439Vf \quad (2)$$

The ANOVA results for surface roughness are given in Table 4. When V and f are examined in this table, since P<0.05, it is observed that these independent variables have statistical significance on output response and their percentage contribution is 2.296% and 41.292%, respectively. When V^2, f^2 and V x f were examined, it was found that P <0.05 condition was not provided, and their percentage contributions were 0.592%, 1.399% and 0.0916% respectively, and it was stated that they did not have statistically a significant effect on the output response.

Table 4. ANOVA results for surface roughness

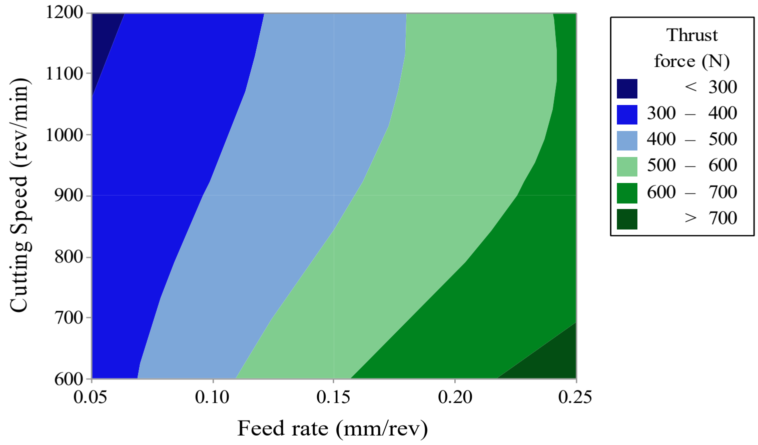
Source	Degree of freedom	Sum of squares	Mean of squares	F	P	PC (%)	Observation
Model	5	0.492457	0.098491	73.41	0.000	30.28	Significant
Lineer	2	0.142189	0.071095	52.99	0.000	21.71	Significant
V	1	0.007289	0.007289	5.43	0.048	2.296	Significant
f	1	0.134900	0.134900	100.55	0.000	41.292	Significant
Square	2	0.009993	0.004997	3.72	0.079	1.598	Not Significant
$V*V$	1	0.001808	0.001808	1.35	0.284	0.592	Not Significant
$f*f$	1	0.004550	0.004550	3.39	0.108	1.399	Not Significant
2-Way interaction	1	0.000030	0.000030	0.02	0.885	0.0916	Not Significant
$V*f$	1	0.000030	0.000030	0.02	0.885	0.0916	Not Significant
Error	7	0.009392	0.001342	-	-	-	-
Lack of fit	3	0.006346	0.002115	2.78	0.174	0.645	Not Significant
Pure error	4	0.003045	0.000761	-	-	-	-
Total	12	0.501848	-	-	-	100	-

R^2:0.986; R^2(Adj):0.973 and R^2(Pred):0.866
PC: Percentage contribution

Correlation coefficients for surface roughness are determined as R^2: 0.986, R^2(Adj): 0.973 and R^2(Pred): 0.866 and it is accepted that these values are statistically effective. The quadratic mathematical model which shows the relationship between the independent variables and the output response for surface roughness is given in Equation (3).

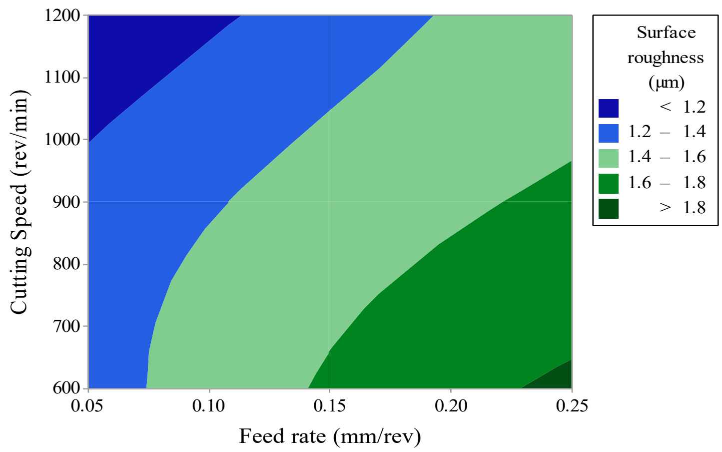
$$R_a = 1.279 - 0.000007V + 3.643f - 0.00012V^2 - 4.06f^2 - 0.000092Vf \qquad (3)$$

Three different validation experiments were performed to test the accuracy of mathematical models developed for thrust force and surface roughness. Validation test conditions were determined in the range of independent variables. According to Table 5, the maximum and minimum error values for F are 1.311% and 0.346% and maximum and minimum error rates for R_a are 2.267% and 0.938%, respectively. The graph showing the change of thrust force depending on the cutting speed and feed rate is given in Figure 3.



◄ **Figure 3.** The effect of cutting speed and feed rate on thrust force

According to Figure 3, it is observed that the thrust force decreases with increasing cutting speed. The thrust force was 348.96 N at the cutting speed of 600 rev/min and the feed rate of 0.05 mm/rev, while it was 276.621 N at the cutting speed of 1200 rev/min and feed rate of 0.05 mm/rev. Accordingly, the thrust force decreased by 26.15%. A similar trend was observed in other feed rate values. This can be attributed to the ease of plastic deformation by reducing the yield stress of the material due to the temperature rise during cutting (Arunachalam et al., 2004; Bouacha et al., 2010; Bayraktar et al., 2020). In addition, it has been observed that the thrust force increases with increasing of feed rate. The thrust force was measured as 274.621 N at the cutting speed of 1200 rev/min and the feed rate of 0.05 mm/rev, while it was measured 615.23 N at the same cutting speed and feed rate of 0.25 mm/rev with an increase of 124.028%. This can be attributed to the increase in the volume of chip that must be removed per unit time due to the increase in feed rate (Suresh et al., 2012; Acır et al., 2009; Bayraktar and Turgut, 2016; Bayraktar et al., 2020). The graph showing the change of surface roughness depending on the cutting speed and feed rate is given in Figure 4.



◄ **Figure 4.** The effect of cutting speed and feed rate on surface roughness

According to Figure 4, the average surface roughness was determined by increasing the cutting speed. Accordingly, surface roughness was measured as 1.317 µm at a cutting speed of 600 rev/min and feed rate of 0.05 mm/rev, while it was measured as 1.007 µm at the cutting speed of 1200 rev/min and same feed rate. The surface roughness was found to be reduced by 30.78%. In addition, it has been determined that surface roughness increases with increasing of feed rate from this graph. Surface roughness was measured as 1.317 µm at the cutting speed of 600 rev/min and feed rate of 0.05 mm/rev, while it was measured as 1.837 µm at the same cutting speed and feed rate of 0.25 mm/rev. According to results surface roughness increased by 39.48%. This can be explained by the increase in surface roughness due to the increasing of feed rate in Equation (4) used in the theoretical calculation of average surface roughness.

$$R_a = \frac{f^2}{32r_e} \quad (4)$$

3.1. Optimization

The selection of the desired target for each independent variable and response was conduct according to which the thrust force and average surface roughness can be minimized. Therefore, desirability function approach was used. The constraints used for the optimization process are given in Table 5.

Table 5. Goals and independent variable ranges for optimization of thrust force and surface roughness

		Constraints			
Independent variables	**Goal**	**Lower limit**	**Upper limit**	**Weight**	**Significance**
V (rev/min)	Limit range	600	1200		
f (mm/rev)	Limit range	0.05	0.25	1	1
F (N)	Minimum	274.621	742.19		
R_a (µm)	Minimum	1.007	1.837		

According to the optimization results, optimum cutting parameters, optimum response and desirability values for thrust force and average surface roughness are given in Table 6. Accordingly, optimum cutting parameters for thrust force and average surface roughness were determined as cutting speed of 1200 rev/min and feed rate of 0.05 mm/rev.

Table 6. Optimum cutting parameters, thrust force and surface roughness

Responses	Cutting speed (rev/min)	Feed rate (mm/rev)	Optimum response	Desirability
F (N)	1200	0.05	279.958	0.988
R_a (µm)			1.027	0.974

In order to validate the results of the study, validation tests were performed depending on the optimum cutting parameters. Accordingly, optimum results and experimental results were found to be highly compatible in terms of percent error rate (Table 7).

Table 7. Comparison of experimental and optimum results

V (rev/min)	*f* (mm/rev)	Response symbol	Experimental result	Optimum response	Error (%)
1200	0.05	*F*	276.542	279.958	1.235
		R_a	1.048	1.027	-2.04

4. Conclusions

In this study, optimization of cutting speed and feed rate parameters which affect thrust force and surface roughness in drilling of Al-30Zn alloy has been conducted by response surface response methodology. The results obtained from the experiments and optimization studies using CCD experimental design can be listed as follows.

- According to ANOVA results, the most important independent variable affecting the thrust force and surface roughness is feed rate and the percentage contributions are 47.482% and 41.292%, respectively, the second most important variable is the cutting speed and the percentage contributions are 3.820% and

2.296%, respectively.

- Correlation coefficients are R^2:0.981; R^2(Adj):0.967 and R^2(Pred):0.901 for thrust force, while they are R^2:0.986; R^2(Adj):0.973 and R^2(Pred):0.866 for surface roughness.

- According to the minimum goal optimum cutting parameters for the thrust force and surface roughness were determined as cutting speed of 1200 rev/min and feed rate of 0.05 mm/rev.

- While the thrust force and surface roughness decreased due to the increase of cutting speed, it was observed that both of them increased with increasing of feed rate.

- As a result of the validation tests performed according to the optimum parameters, the error of 1.235% for the thrust force and 2.04% for the surface roughness indicate that the optimization results are quite successful.

Conflicts of Interest

No conflict of interest was declared by the authors.

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