Optimization of Cutting Parameters in Face Milling of Waspaloy Superalloy

Oğuzhan Çakmakoğlu, Ahmet Demirer, Yakup Turgut, and Ömer Seçgin

Nomenclature

ANOVA Analysis of Variance

1 Introduction

Waspaloy is a superalloy developed by Pratt and Whitney in the 1950s. It is used in parts that require high strength and good corrosion resistance at high temperatures, such as in the hot parts of turbine machines. Waspaloy's maximum operating temperature is as high as 750 °C. However, it is also an expensive alloy due to its high cobalt content. For this reason, a much cheaper alternative, "Alloy 718" is often used. However, the operating temperature of Alloy 718 is limited to 650 °C. Waspaloy is used in turbine parts, compressor discs, shafts, and turbine boxes of aircraft engines (Olovsjö et al., 2010). These superalloys also have an outstanding combination of toughness, high-temperature strength, creep resistance, excellent thermal fatigue, and resistance to degradation in oxidizing or corrosive media (Isik, 2017). Waspaloy is rich in nickel. It is a superior material because it maintains its high strength at high temperatures due to nano-scale precipitation hardening in the matrix phase. The gamma matrix, a face-centered cubic structure, nickel-based austenitic phase, contains high proportions of chromium, cobalt, molybdenum, and

O. Çakmakoğlu (✉) · A. Demirer · Ö. Seçgin
Technology Faculty, Sakarya University of Applied Sciences, Sakarya, Türkiye
e-mail: ademirer@subu.edu.tr; omersecgin@subu.edu.tr

Y. Turgut
Technology Faculty, Gazi University, Ankara, Türkiye
e-mail: yturgut@gazi.edu.tr

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T. H. Karakoc et al. (eds.), *Green Approaches in Sustainable Aviation*, Sustainable Aviation, https://doi.org/10.1007/978-3-031-33118-3_12

tungsten. Dislocation is inhibited when the amount of precipitates increases. This increases the hardness of the alloy (Veerappan et al., 2018).

In machining, the highest production amount is aimed at the lowest cost. This can be achieved by minimizing the cutting forces. Minimizing cutting forces depends on optimizing cutting parameters. When the literature studies are examined, it can be seen that there are studies on parameter optimization related to the milling process in academic and commercial fields. However, studies on Waspoloy are limited. Yıldırım et al., searched machinability of Nickel-based Waspaloy superalloy in milling. They used Taguchi's L_{16} ($4^2 \times 2^3$) orthogonal array (Yıldırım et al., 2017). As a result, they reported that the minimum cutting force was achieved with a combination of vegetable-based cutting oil, flow rate of 100 ml/s, milling in the opposite direction (up), Type 1 nozzle, and 25 mm spray distance. Yıldırım et al. focused on tool life in milling (Yıldırım et al., 2019). From the experimental results using Taguchi, they determined that the optimum machining parameters for tool life were PVD coating, wet machining, 30 m/min cutting speed, and 0.1 mm/rev feed rate. Thirumalai et al. investigated the effectiveness of chilled coolant in machining the heat-resistant superalloy material Inconel 718. They reported that with the Taguchi experimental design, they reduced the number of experiments by one-third compared to the full factorial experimental setup. Bagci and Aykut used the Taguchi method for low surface roughness value in terms of cutting parameters in the surface milling process of cobalt-based superalloy (stellite 6) material and determined that the cutting speed was the most important parameter (Bagci & Aykut, 2006). Akhyar Ibrahim et al. stated that the most important factor of affecting the tool life of Inconel 718 by turning in dry conditions and at high speed: the depth of cut, feed rate, and cutting speed are respectively (Akhyar Ibrahim et al., 2011).

Motorcu et al. investigated the effects of cutting type, cutting speed, feed rate, and drill bit angle on surface roughness when drilling Waspaloy super alloy with coated (TiN) and uncoated drills. Köksal milled a nickel-based superalloy material named Waspaloy, which is used in the construction of some jet engine parts in the aircraft industry, with CVD-coated and uncoated carbide tips (Köksal, 2000). He measured and examined the subsurface microhardness of the machined surfaces. He discussed the effect of the insert types and process parameters used on this. Venkatesen et al. examined the tool wear of Inconel X-750 and Waspaloy in dry turning. They reported higher machining wear of Waspaloy compared to Inconel X-750 in all experiments. Velmurugan et al. analyzed the turning forces of Inconel X-750 and Waspaloy in dry turning (Vetri Velmurugan et al., 2019). They reported that the cutting force was much higher when processing Waspaloy. Işık investigated the effect of cutting speed on tool life and surface quality while machining Waspaloy (Isik, 2017).

In this experimental study, it was aimed to obtain optimum cutting parameters in the face milling process of Waspaloy superalloy. The effects of cutting parameters on the cutting force in face milling were investigated. The experimental data obtained in the study were optimized using the Taguchi method.

2 Material and Method

2.1 Materials and Experimental Setup

Nickel-based superalloys have high-temperature resistance and high corrosion resistance. Therefore, it is widely used in the aviation industry, especially in gas turbine engines. These alloys are known difficult materials to cut. The reasons for the difficult machining of nickel-based superalloys can be listed as follows (Dudzinski et al., 2004; Ezugwu et al., 1998; Jawaid et al., 2001; Sharman et al., 2001):

1. Due to its high-temperature resistance feature, a large part of its strength is preserved during machining.
2. During machining, work hardening occurs rapidly.
3. It has weak thermal conductivity.
4. During machining, a chemical reaction takes place with the cutting tool material.
5. Nickel alloys tend to bonding of the cutting tool.

In Table 1, physical properties of Waspaloy super alloy material are given.

For the experimental study, Waspaloy super alloy was prepared in the size of 40x40x50 mm. Experiments were made in Johnford VMC-550 CNC vertical machining center. The cutters were supplied by Sandvik company, and the cutting speed ranges recommended by the company for the cutting tool qualities were taken into account. In the study, four-level cutting speeds, two-level federates, and four-level indexable inserts, and a fixed depth of cut were determined (Table 2).

In the experiments, cutting tools (R245-12-T3-E-ML) and tool holder (R245-063Q22-12L) made by Sandvik company were used. The face milling tool diameter was 63 mm, the approach angle was 45°, and the up-milling method was used (Fig. 1). Milling was performed at a radial depth of cut (ae) of 10 mm using a single-edged cutting tool. In Table 3, important dimensions of the cutting tools used are given. In Table 4, coating properties of the used inserts are given.

The experimental setup is shown in Fig. 2. Test piece was attached to the dynamometer. The force data obtained from the experiments were taken from the

Table 1 Physical properties of Waspaloy (Köksal, 2000)

Density (g/cm^3)	8.19
Thermal conductivity (W/m°C)	~11(20 °C)
Hardness (HV)	454
Tensile strength (MPa)	1280
Coefficient of thermal expansion (10^{-6}/°C)	12.1 (21 °C)

Table 2 Cutting parameters

Cutting Speed (m/min)	20, 30, 40, 50
Federate (mm /tooth)	0.1, 0.12
Depth of cut (mm)	0.5
Cutting tool type	GC 1025, GC 1030, GC 2030, GC 2040

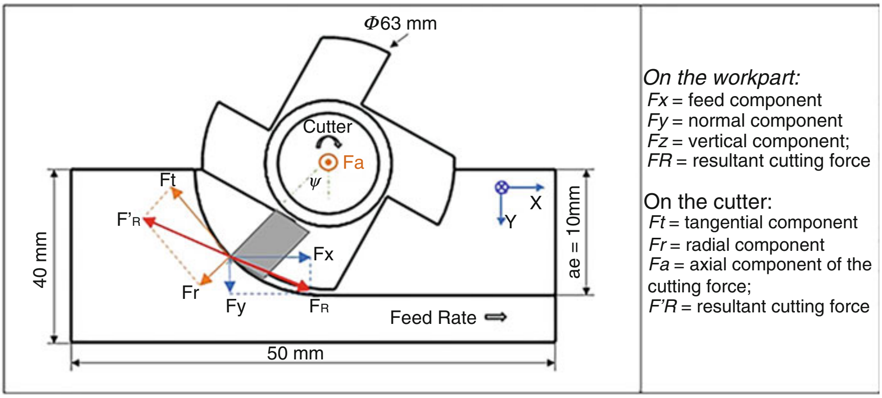

Fig. 1 Cutting forces in up-milling

Table 3 Cutting tool properties (Sandvik Coromant et al., 2010)

	GC 1025	GC 1030	GC 2030	GC 2040
Inscribed circle diameter	13.4 mm			
Cutting edge effective length	10 mm			
Insert thickness	3969 mm			
Wiper edge length	2.1 mm			
Corner radius	1.5 mm			
Major cutting edge angle	45°			

Table 4 Coating properties of inserts (Sandvik Coromant et al., 2010)

Grade	ISO area applications	Cutting material	Coating procedure and compositions	
GC1025	S15	HC	PVD	Ti (C, N) + TiN
GC1030	S15	HC	PVD	(Ti,Al) N + TiN
GC2030	S25	HC	PVD	(Ti,Al)N TiN
GC2040	S30	HC	CVD	MT-Ti (C,N) + Al_2O_3 + TiN

dynamometer. KISTLER 9272A 4 component dynamometer is used in the system. KISTLER Dynoware software was used to process the data and obtain the graphics. Because milling is an intermittent operation and chip thickness changes, cutting forces change. There are many cutting force estimation models. Two reference systems can be used to determine the cutting force components. A table reference system was used in the study (Köksal, 2000).

The cutting force components which occur in the face milling process are shown in Fig. 1. According to the table reference system, the cutting force is calculated according to the following formula (Alauddin et al., 1998; Köksal, 2000). The cutting force (F_R) was calculated from the F_x, F_y, F_z forces obtained from the dynamometer with the help of Eq. (1).

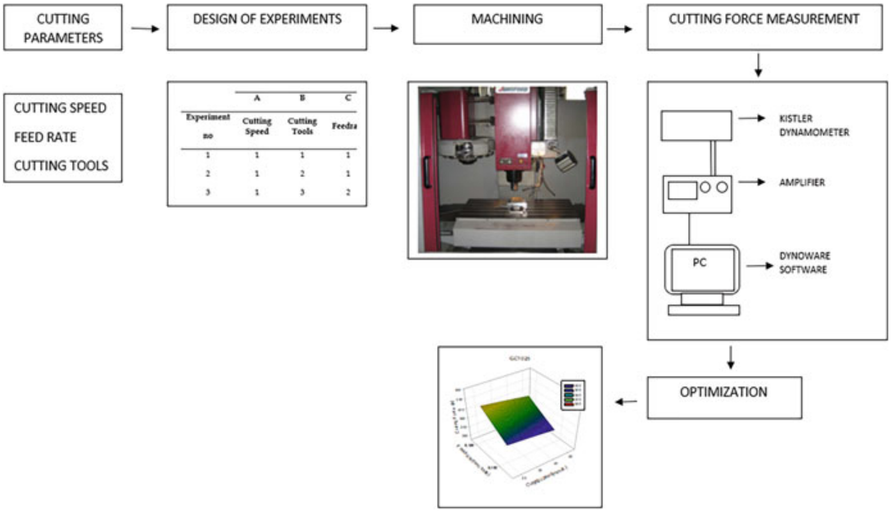

Fig. 2 Schema experimental setup

$$F_R = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2} \tag{1}$$

3 Experimental Design and Optimization

3.1 The Taguchi Method and Design of Experiments

Traditional experimental design procedures are very complex and not easy to use. When the number of parameters increases, many experimental studies are required (Bagci & Aykut, 2006). Increasing the number of experiments means increasing time and costs. To eliminate this negative situation, Taguchi, a well-known academician, developed a method to reduce the number of experiments without affecting the results (Dutta & Kumar Reddy Narala, 2021). Parametric design experiments aim to find the ideal parameter set that optimizes the output and is least sensitive to noise (uncontrollable) factors. In this method, orthogonal arrays (OA) are used to formulate the combination of input variables during experiments (Ekici & Uzun, 2022). The Taguchi method is not only an experimental design technique, but also a useful technique for high-quality system design (Çiçek et al., 2012).

The Taguchi technique includes the following steps:

- Control factors are specified.
- The levels of each control factor are determined, and the appropriate orthogonal sequence is selected.

- Control factors are assigned to the selected orthogonal matrix and experiments are performed.
- Data is analyzed and optimal levels of control factors are determined.
- Validation experiments are performed, and the confidence interval is obtained.

The Taguchi method uses a loss function to determine quality characteristics. Loss function values are also converted to a signal-to-noise (S/N) ratio. In general, there are three different quality characteristics in S/N ratio analysis: "nominal is best," "bigger is better," and "smaller is better." For each process parameter level, the signal-to-noise ratio is calculated based on the S/N analysis (Çiçek et al., 2012; Ekici & Uzun, 2022). In an ideal situation, the cutting force (FR) should be at minimum levels. Therefore, the S/N ratios were calculated with the formula given in Eq. 2.

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

where y_i represents the characteristic value (cutting force) measured under that test conditions and n represents the number of tests performed under that test conditions.

4 Analysis and Evaluation of Experimental Results

4.1 Analysis of the Signal-to-Noise (S/N) Ratio

In this study, cutting tools, cutting speed, and feed rate were selected as control factors and their levels were determined as shown in Table 2. The first step of the Taguchi method is to choose a suitable orthogonal array. L_{16} ($4^2 \times 2^1$) was chosen to determine the optimal cutting parameters and to analyze the effects of these parameters. Cutting parameters were assigned to each column and sixteen cutting parameter combinations were generated as shown in Table 5.

The Taguchi method uses the S/N ratio to measure variations of the experimental design. Since the lowest cutting force values are the desired results for good product quality, the equation "smaller is better" (Eq. 2) was chosen for calculating the S/N ratio. S/N and mean response values for cutting force are shown in Table 5. As a results of sixteen experiments, the average value of the cutting force was calculated as 358.875 N, and the average S/N ratio for the cutting force value was −50.94 dB.

Table 6 gives the S/N (a) and average response table (b) for the cutting forces. This table gives the S/N ratio for the parameters. The level with the biggest S/N ratio indicates the optimum level for that parameter. In the line named "delta," the difference between the maximum S/N ratio of the parameters and the minimum S/N ratio is given. The parameter with the biggest delta value is the most important parameter affecting the cutting force (Sen et al., 2020).

Table 5 Taguchi L_{16} ($4^2 \times 2^{1)}$ experimental design

Experiment no.	Factors and levels						Cutting force (N)	S/N ratio (dB)
	A	B	C	A	B	C		
	Cutting speed	Cutting tools	Feed rate	Cutting speed	Cutting tools	Feed rate		
1	1	1	1	20	GC1025	0.1	323	−50,1841
2	1	2	1	20	GC1030	0.1	415	−52,361
3	1	3	2	20	GC2030	0.12	288	−49,1878
4	1	4	2	20	GC2040	0.12	366	−51.2696
5	2	1	1	30	GC1025	0.1	315	−49,9662
6	2	2	1	30	GC1030	0.1	449	−53,0449
7	2	3	2	30	GC2030	0.12	303	−49.6289
8	2	4	2	30	GC2040	0.12	365	−51,2459
9	3	1	2	40	GC1025	0.12	400	−52,0412
10	3	2	2	40	GC1030	0.12	429	−52,6491
11	3	3	1	40	GC2030	0.1	252	−48,028
12	3	4	1	40	GC2040	0.1	408	−52,2132
13	4	1	2	50	GC1025	0.12	387	−51,7542
14	4	2	2	50	GC1030	0.12	418	−52.4235
15	4	3	1	50	GC2030	0.1	229	−47,1967
16	4	4	1	50	GC2040	0.1	395	−51,9319

Table 6 S/N Response and average response table for cutting force

(a) S/N table			
Level	Cutting speed	Cutting tool	Feed rate
1	**−50.75**	−50.99	**−50.62**
2	−50.97	−52.62	−51.28
3	−51.23	**−48.51**	
4	−50.83	−51.67	
Delta	0.48	4.11	0.66
Rank	3	1	2
(b) Average response table			
Level	Cutting speed	Cutting tool	Feed rate
1	**348.0**	356.3	**348.3**
2	358.0	427.8	369.5
3	372.3	**268.0**	
4	357.3	383.5	
Delta	24.3	159.8	21.3
Rank	2	1	3

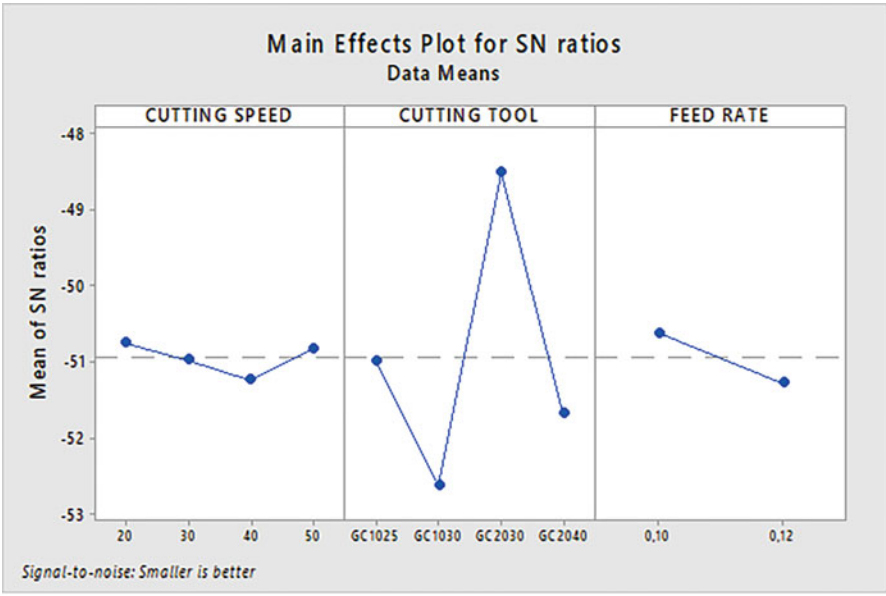

Fig. 3 Main effects plot for S/N ratios

Another requirement in calculating optimum values is to determine optimum levels. The S/N ratios of the cutting force are given in the Fig. 3. Fig. 3 shows the optimum levels at which the lowest cutting force can be obtained in the processing of Waspaloy super alloy: 20 m/ min cutting speed (A1), GC 2030 cutting tool (B3), 0.1 mm/tooth feed rate (C1). Levels and S/N ratios of the factors that give the lowest cut-off value are shown in in Table 7: factor A: Level 1, S/N = −**50.75** dB; factor B: Level 3, −**48.51** dB; and factor C: Level 1, −**50.62** dB.

4.2 *Analysis of Variance (ANOVA) Method*

In this study, ANOVA was used to analyze the effects of experimental parameters on cutting force. ANOVA is a statistical method used to determine the individual interactions of all control factors. Table 7 presents the ANOVA results revealing the effects of cutting speed, feed rate, and cutting tool control factors on cutting force at 95% confidence level and 5% significance level.

ANOVA table shows the importance of the factors. The results showed that factor B (cutting tool) had a high (82.99%) effect on the cutting force. This factor was followed by factor C (feed rate) with a rate of 2.75%. The results of factors and their interactions with a P value less than 0.05 are statistically significant. Factor C (feed

Table 7 Analysis of variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	3	1202	1.83%	1202	400.7	0.39	0.761
Cutting tool	3	54,461	**82.99%**	54,461	18153.8	17.82	**0.001**
Feed rate	1	1806	2.75%	1806	1806.3	1.77	**0.220**
Error	8	8152	12.42%	8152	1019.0		
Total	15	65,622	100.00%				

rate) and factor A (cutting speed) was not found to be statistically significant. The second-order model was used to examine the effectiveness of the parameters used in the experiments and to measure the predictive efficiency of the test results, and the determination coefficient $R^2 = 87.58\%$.

Figure 4 shows the cutting force graphs for four cutting tools. These graphs were obtained from the experiments performed as a result of the Taguchi method (Table 6). It is known that cutting force decreases with increasing cutting speed in conventional materials, but it has been observed in academic studies that cutting force increases with increasing cutting speed in machining superalloys (Mia 2018; Sharman et al. 2001; Thrinadh et al. 2020). In Fig. 4c, it is seen that the GC2030 cutting tool has lower cutting force than other cutting tools. In general, the cutting force increased as the chip volume increased with an increase in the feed rate. This result is in line with the literature (Hoier et al. 2017, 2018).

4.3 *Estimation and Verification Experiment of Optimum Cutting Force*

A validation experiment is required to verify the optimized condition with the Taguchi optimization technique. Figure 3 shows the estimation of the optimum cutting force. The optimum combination of control factors is calculated by the following equation, taking into account A1B3C1.

$$F_{R_{opt}} = F_{R_{avg}} + \left(A_1 - F_{R_{avg}}\right) + \left(B_3 - F_{R_{avg}}\right) + \left(C_1 - F_{R_{avg}}\right) \quad (3)$$

In the Table 6, the average of the cutting forces ($F_{R_{opt}}$) was calculated as *358.875 N*. Calculation result of $F_{R_{opt}}$ was found *246.55 N* with using Eq. 3. Confidence interval is used to validate the quality characteristics of the validation experiment (Mia, 2018; Motorcu et al., 2016). The confidence interval for the estimated optimal values is calculated with the help of Eqs. 4 and 5. The value obtained as a result of the validation experiment should be within the confidence interval (Çiçek et al. 2012; Şen et al. 2020).

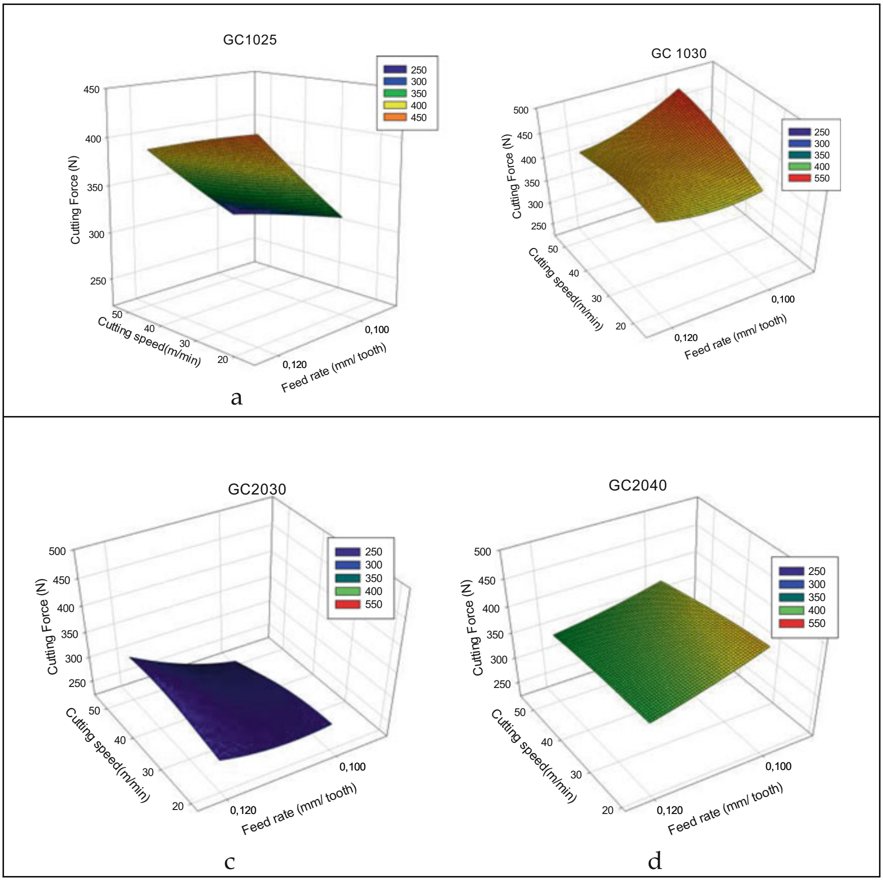

Fig. 4 Effect of cutting speed and feed rate on cutting force for cutting tools

$$CI = \sqrt{F_{\alpha;1;fe}\ \ Ve\left[\frac{1}{n_{\text{eff}}} + \frac{1}{r}\right]} \tag{4}$$

$$n_{\text{eff}} = \frac{N}{1 + T_{\text{dof}}} \tag{5}$$

In Eqs. 4 and 5, $F_{\alpha;1;\ fe}$ is the F ratio at *95%* confidence level (*F distribution table*), α is the significance level, n_{eff} is the effective iteration number, *fe* is the error degree of freedom, *r* is the *number of* validation experiments, *Ve* is the error variance, *N* is the total number of experiments, and T_{dof} is the total master factor degrees of freedom.

Consider that $F_{0.05;1;8} = 5.32$, $Ve = 8152$, $R = 2$, $N = 16$, $T_{\mathrm{dof}} = 7$ and $n_{\mathrm{eff}} = 2$. Confidence interval calculated using Eqs. 4 and 5 is $CI = \pm 208{,}251$. The optimum level of *A1B3C1* was not present in the experiments in the experimental design. Therefore, two replicate verification experiments were performed using the GC 2030 cutting tool, and the cutting force value was found to be *227.94 N*. Estimated average optimum cutting force with 95% confidence interval is as follows:

$$(F_{R\mathrm{opt}} - CI) \le F_{R\mathrm{experimental}} \le (F_{R\mathrm{opt}} + CI)$$
$$(246.55 - 208{,}251) \le 227.94 \le (246.55 + 208{,}251)$$
$$38.298 \le 227.94 \le 454.801$$

5 Conclusions

In this study, optimum cutting parameters in the face milling process of Waspaloy super alloy were obtained, and the effects of cutting parameters on the cutting force in face milling were investigated. The experimental data obtained in the study were optimized using the Taguchi method. The remarkable results of the study are listed below:

- Quadratic model was used to measure the predictive adequacy of the test results and the coefficient of determination was $R^2 = 87.58\%$.
- ANOVA analysis showed that among the cutting parameters (cutting tool, cutting speed, and feed rate) used to determine the cutting force, "cutting tool" was observed to be more effective by 82.99%.
- The optimum levels at which the lowest cutting force was obtained in the machining of Waspaloy super alloy using the Taguchi method were as follows: cutting tool GC 2030, cutting speed 20 m/min, feed rate 0.1 mm/tooth.
- The value obtained as a result of the validation experiment (227.94 N) was within the confidence interval.

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