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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Determination of MQL Parameters Contributing to Sustainable Machining in the Milling of Nickel-Base Superalloy Waspaloy

Çağrı Vakkas Yıldırım[1] · Turgay Kıvak[2] · Murat Sarıkaya[3] · Fehmi Erzincanlı[4]

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Abstract In addition to reducing production costs, minimum quantity lubrication (MQL) aims to minimize the adverse effects of conventional cutting fluid usage on the environment and human health. Because of the positive effect of the MQL system on both health and production efficiency, sustainable production is increasing daily. Therefore, optimum MQL parameters must be determined in order to obtain maximum efficiency in the manufacturing process. In this study, unlike similar studies in which MQL parameters were evaluated, the scope was widened and the main parameters affecting the efficiency of the system were tested at the same time. For this aim, nickel-base superalloy Waspaloy was machined under MQL using a CNC milling machine with uncoated carbide inserts. In the machining process, the MQL parameters selected were cutting oil type (mineral-, synthetic-, mineral-synthetic- and vegetable-based oils), fluid flow rate (25, 50, 75 and 100 ml/h), milling method (up milling and down milling), spray distance (25 and 50 mm) and nozzle type (Type 1 and Type 2). In order to analyze the effect of MQL parameters on the quality characteristics of tool life and cutting force, the cutting parameters, including cutting speed, feed rate and depth of cut, were kept constant for all experiments. Taguchi's L16 ($4^2 \times 2^3$) orthogonal array was employed to minimize the number of experiments. As a result, both maximum tool life and minimum cutting force were attained via a combination of vegetable-based cutting oil, 100 ml/h flow rate, opposite-direction (up) milling, Type 1 nozzle and a 25-mm spray distance.

Keywords Superalloy · MQL parameters · Tool life · Cutting force · Optimization

✉ Murat Sarıkaya
msarikaya@sinop.edu.tr

1 Bolu Vocational School of Higher Education, Abant Izzet Baysal University, 14300 Bolu, Turkey

2 Department of Manufacturing Engineering, Faculty of Technology, Duzce University, 81100 Duzce, Turkey

3 Department of Mechanical Engineering, Sinop University, 57030 Sinop, Turkey

4 Department of Mechanical Engineering, Faculty of Engineering, Duzce University, 81100 Duzce, Turkey

1 Introduction

Due to the challenging and demanding conditions required to work superalloys, studies on increasing their machinability are continuing to be conducted in the automotive, aerospace, space and other such sectors where these materials are greatly preferred. Materials such as nickel-base superalloys rank among the class of difficult-to-machine materials because of their low thermal conductivity and their high hardness exhibited at high temperatures [1]. The current and potential usage areas of the nickel-base superalloy Waspaloy include compressor and rotor disks, millers, screws, felts, bracelets and their housings, fasteners, airframes, chemical plant equipment, petrochemistry equipment, missile systems and various motor parts [2]. The reason for the preference of Waspaloy despite difficult operating conditions can be explained by its high oxidation resistance and its excellent resistance to high temperature, mechanical and thermal shocks and corrosion [3–5]. Owing to these properties, Waspaloy is among the hardest materials in terms of machinability.

Machinability can be expressed as the degree of convenience or difficulty in processing the material. The machinability of a material is defined by measuring factors such as tool life, surface roughness and cutting force [3]. Tool life is of great importance in most of the sustainability measurements of the chip removal process. In addition, long tool life is extremely important for the quality of the machined surface as well as for production costs and for controlling the forces generated during cutting [6]. Energy consumption is one of the most important factors affecting production cost in the chip removal process. In other words, the power spent during processing directly affects energy consumption. The cutting force required to remove chip is the most important parameter in determining the power consumed, depending on cutting resistance and the cost of energy required for machining [7]. The cutting force is a concept directly related to the other output parameters of machinability which are surface roughness, tool wear and the vibrations that occur during machining. Therefore, research on cutting force is very important [8]. Furthermore, in machining operations, the determination and analysis of the cutting force are very important in terms of increasing the quality of the produced workpiece and reducing the machining costs [9].

Cutting fluid is used extensively in chip removal operations because it improves machinability by reducing heat in the cutting zone. However, the use of conventional cutting fluids adversely affects the environment, human health and production costs [10]. Chemicals in the fluids exert harmful effects on the environment and jeopardize human health when they come in contact with the skin. Moreover, the storage, supply and waste disposal of the liquids also present problems [11]. For all these reasons, in recent years, researchers have been working hard to reduce or completely eliminate the amount of cutting fluid used during chip removal [12]. In order to achieve this goal, many methods have been developed including cryogenic cooling, solid cooling-lubrication, minimum quantity lubrication (MQL), high pressure cooling, cooling with pressurized gases, and applying the cutting fluid through a tool [13,14].

The minimum quantity lubrication method has become increasingly popular because of its low cost and its sensitivity to the environment and human health [15]. The MQL method can be defined as a mixture of dry and conventional cooling-lubrication which combines the advantages of both systems in its own right. The most obvious benefits of the MQL system can be listed as reducing production costs and protecting the health of workers and the environment [14,16]. The use of the MQL system can achieve improvements in total production cost of up to 15% [17]. In addition, the MQL system provides significant contributions to tool life/wear, shear strength and surface roughness. The MQL system can be described in the most general sense as spraying a very small amount (10–100 ml/h) of oil into the cutting zone with the aid of pressurized air [18,19]. When compared to conventional machining and dry machining, this method has many advantages, such as reducing fog and spray, reducing losses due to thermal shocks in the cutting tool, reducing heat at the tool–workpiece interface, reducing wear on the cutting tool and lowering production costs [20].

A review of the literature reveals that studies on the machinability of nickel-base superalloy Waspaloy are very limited. The studies on Waspaloy as well as some of the studies which have chiefly investigated the machinability of superalloy materials under MQL cutting conditions are given below.

Motorcu et al. [21] studied the effect of cutting type, cutting speed, feed rate and drill bit angle on surface roughness in the drilling of Waspaloy superalloy with coated (TiN) and uncoated drills. In their study, Obikawa et al. [22] compared normal spraying and micro-spraying in an investigation of the effects of cutting fluid spraying on chip removal. They observed that micro-spraying by means of specially designed nozzles was very effective in increasing tool life. Wang et al. [23] compared the MQL system to dry machining in the milling of Inconel 182. During the study, the cutting force, the temperature and the surface roughness in the cutting zone were taken as the experimental outputs. During machining, both down milling and up milling were used. The researchers stated in the experimental results that the MQL system was effective on the cutting force, especially for the opposite-direction (up) milling. In this case, they claimed that the MQL system was also effective on tool wear. However, in down milling, this situation showed a change due to vibration. As a result, the researchers claimed that the MQL system in the up milling of Inconel 182 superalloy was effective on tool wear and production costs. Li et al. [24] determined the minimum amount of lubrication by delivering an air–oil mixture at 0.276 MPa pressure through a 0.762 mm diameter hole in the tool holder. The results showed that when the minimum amount of lubrication was used, the cutting force decreased by 24.4% in comparison with dry cutting and by 32.2% in comparison with wet cutting. Davis et al. [25] investigated the effects of the MQL system on titanium machining by comparing the MQL system with dry machining using two different additives. They found that the MQL system used with ionic liquid as additive was 60% better than the dry machining and also that the BMIM-PF6 additive MQL system had 15% better results than dry machining. Lin et al. [26] compared the dry, wet, MQL and cryogenic cooling systems and claimed that MQL and cryogenic machining yielded better results than dry and wet machining. Thamizhmanii and Hasan [27] compared dry machining and the MQL system in the machining of Inconel 718 and found that the MQL system produced better results. Liu et al. [28] milled Ti–6Al–4V superalloy under different MQL parameters (such as air pressure, oil type, nozzle position) and observed that the MQL system had a significant influence on the cutting force and on the reduction in the heat generated in the cutting zone.

The MQL system has many variations in itself such as different oil types, spray types, flow rates, nozzle types, spray angles, spray distances and spray speeds. Optimizing these variables is crucial for a more efficient use of the system. This

Table 1 Chemical composition of Waspaloy

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

Table 2 Mechanical properties of Waspaloy

Melting range (°C)	Elastic modulus (GPa)	Hardness (Rockwell, C)	Tensile strength (MPa)	Elongation (%)
1330–1360	204	38	897–1276	26.6

study aimed to optimize the most appropriate MQL parameters and machining conditions by examining the effect of the MQL parameters on tool life and cutting force in the milling of Waspaloy with cementite carbide cutters. The vertical index of the Taguchi L16 ($4^2 \times 2^3$) was used for the experimental design, and the Taguchi *S*/*N* ratio was applied to determine optimum cutting conditions (cutting oil type, flow rate, milling direction, spray distance and nozzle type) for achieving maximum tool life and minimum cutting force. In addition, linear and quadratic regression analyses were used to assist with subsequent studies and prediction equations were developed. Finally, the reliability of the developed models was tested via verification experiments.

2 Material and Methods

2.1 Material

Waspaloy, a nickel-based superalloy, was used in the milling experiments. Waspaloy is a material with excellent resistance to high temperature and oxidation due to its nickel, chromium and cobalt content. The samples used in the experiments were prepared in dimensions of 150 × 100 × 21 mm. Before beginning the experiments, each sample was cleaned by surface milling in order to prevent the surface oxide and residues from affecting the results. The chemical composition and mechanical properties of the sample material are shown in Tables 1 and 2, respectively.

2.2 Milling Conditions

The DELTA SEIKI CNC-1050 a vertical machining center with a maximum motor power of 11 kW and a maximum rotation speed of 10,000 rpm was used for the milling tests. Figure 1 shows the experimental setup for the milling experiments. The R300-025A20-10M tool holder was chosen and used with H13A-quality uncoated cementite carbide tips (ISO code R300-1032E-KL) produced by Sandvik. The cutting speed (45 m/min), feed rate (0.1 mm/rev) and cutting depth (0.5 mm) were selected based on the recommendations of the cutting tool manufacturer, the literature and preliminary experiments [29,30]. These parameters were kept constant in all experiments since the aim of the study was to investigate the effects of MQL parameters on machinability.

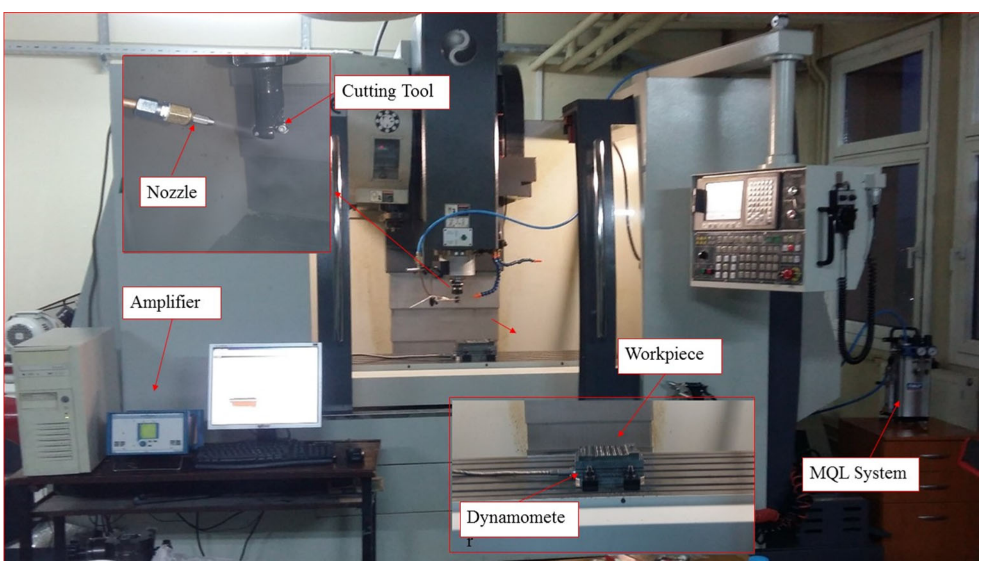

Fig. 1 Experimental setup for milling tests

2.3 Measurements

At the end of the preliminary experiments, the wear conditions of the cutting tools were examined and regular flank and notch wear were observed. In the tool life evaluations, the recommended wear measure (0.3 mm) in the ISO 8688-1 milling standard was taken into account. Thus, the tool life was calculated by considering the time needed to reach 0.3 mm. The wear values were measured at the end of machining periods of 57.3 s and the amount of wear on the cutting tool was checked with a polarized digital AM 4113ZT microscope.

An experimental setup was devised to measure the cutting forces. First, the KISTLER 9257B 4-component piezo-electric dynamometer was specified in the design of the experimental set. In order to transfer the signals from the dynamometer to the data-reading card (KISTLER PCIM DAS 1602/16), the KISTLER 5070-A multichannel amplifier was then added to the experimental design. In addition, the 1677-A5 data cable, 1500-B15 cable and RS232 cable were included for the data transfer. Finally, KISTLER Dynoware 2825A-02-01 software ready-made for processing and graphics and compatible with the Windows operating system was procured. The test sample connected to the dynamometer was perforated from end to end with a hole of 8 mm in diameter between the axes at 120 mm width. The measurement of the cutting forces was taken for each sample by surface milling a 100-mm length according to the predetermined parameters. Cutting force measurements were taken from the middle sections, taking into account the change in cutting forces at the area where the holes were located. When performing the cutting force experiments, attention was also paid to the opposite machining determined in the preliminary experiments.

2.4 MQL System

The Vario model MQL system produced by SKF was used with a constant pressure of 8 bar during the milling experiments. The technical properties of the cutting oils used in the experiments are given in Table 3, and the geometry of the nozzles and their use in the experiments are shown in Fig. 2.

Table 3 Technical properties of cutting oils

Cutting oil	Technical specifications		
	Density (20 °C) (g/mL)	Kinematic viscosity (40 °C) (cSt)	Flash point (°C)
Vegetable oil	0.895	5	170
Synthetic oil	0.797	5.1	160
Mineral oil	0.930	14	180
Mineral-synthetic oil	0.854	10.5	212

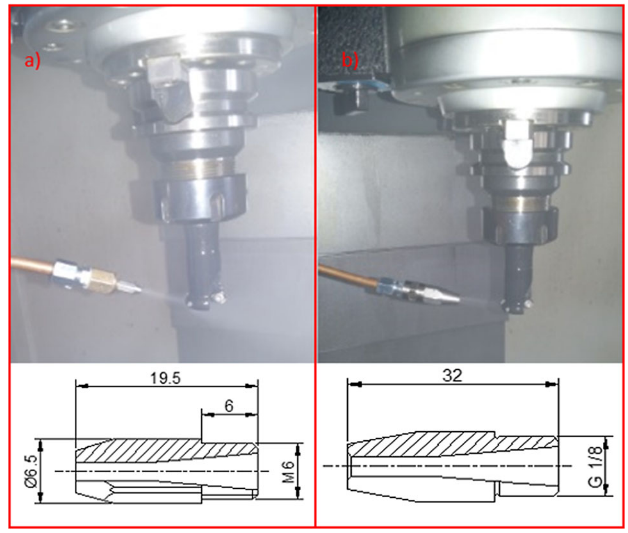

Fig. 2 Nozzles used in experiments: **a** Type 1, **b** Type 2

2.5 Taguchi Method and Experimental Design

The Taguchi method is a technique that examines the results using a statistical measure called the *S*/*N* ratio. In this method, "noise" (*N*) refers to the desired value (mean), while "signal" (*S*) indicates the undesirable value (standard deviation) for the output characteristic [31]. In the analysis of *S*/*N* ratios, there are three main characteristic values: "largest is the best," "smallest is the best" and "nominal is the best" [32]. Since the aim of the study was to calculate the highest tool life and the lowest cutting force, the "largest is the best" (Eq. 1) for the tool life and "the smallest is the best" (Eq. 2) for the cutting force were selected and calculated as follows:

Largest is the best:

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

Smallest is the best:

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

where Y_i is the performance characteristic value (Eq. 1 for tool life, Eq. 2 for cutting force) and n is the number of Y_i values [33].

Cutting oil type, flow rate, milling direction, spray distance and nozzle type were selected as control factors for the milling experiments, and their levels are given in Table 4. Additionally, Taguchi's $L_{16}\,(4^2 \times 2^3)$ experimental setup selected for the system is given in Table 5.

Table 4 Control factors and their levels

A Oil type (OT)	*B* Flow ratio (FR) (ml/h)	*C* Milling type (MT)	*D* Spray distance (SD) (mm)	*E* Nozzle type (NT)
Vegetable	25	Down milling	25	1
Synthetic	50	Up milling	50	2
Mineral	75	–	–	–
Mineral-synthetic	100	–	–	–

Table 5 Orthogonal array of Taguchi L16 ($4^2 \times 2^3$)

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

3 Results and Discussion

3.1 Evaluation of Experimental Results

The three-dimensional surface plots of the tool life resulting from the milling of Waspaloy along with other major factor interactions are given in Fig. 3.

In Fig. 3a, the graph showing the relationship between oil type and tool life shows that the highest tool life was obtained by using vegetable-based cutting oil. The tool life showed a tendency to decrease with the use of synthetic-based, mineral-based and mineral-synthetic-based cutting fluids, respectively. The vegetable-based cutting oil had a more positive impact on tool life than the other cutting oils because its chemical structure and viscosity led to better penetration into the cutting zone, thus absorbing the heat on that area [34,35]. Vegetable-base cutting fluids form a thin, strong and long lasting lubricant layer in the cutting zone due to their chemical structure and high viscosity. In this way, they reduces friction between the tool and workpiece, and tool wear by absorbing the pressure in the cutting zone [36,37]. The results are in parallel with the literature [38–41]. The average tool life values in the experiments with vegetable-based cutting oil were 16.53, 16.53 and 27.54%, respectively, when compared with the experiments made with synthetic-, mineral- and mineral-synthetic-based cutting fluids. The increase in tool life was directly proportional to the increase in flow rate, and the highest tool life was achieved with the highest flow rate of 100 ml/h. As the flow rate decreased, the tool life also decreased together with decreases in the amount of oil reaching the cutting zone (Fig. 3a) [42]. The amount of oil sent to the cutting zone increases with the increase of flow rate and the formed film layer becomes more effective. And thus, it contributes an increase in the tool life with reducing of the friction at the tool–workpiece interface. It is stated in the literature that the decrease in heat and the increase in oil change in direct proportion with the flow rate of the cutting fluid [43–46]. 50 ml/h flow rate provided efficiency at the rate of 7.6%, 75 ml/h flow rate at the rate of 22.81% and 100 ml/h flow rate at the rate of 38.01% in comparison with 25 ml/h flow rate. Depending on the cutting time, the direction of the milling can significantly affect the cutting force and tool life as well [47]. The point where the cutter touches the workpiece is the point where the maximum chip thickness occurs during down milling. This makes up milling more desirable in terms of both cutting force and tool life [48]. Up milling resulted at the rate of 10.18% better than the down milling. Examination of the section that shows the interaction between the tool life and the spray distance revealed that the 25-mm spray distance gave better results because it was closer and transferred the oil to the cutting zone without allowing aerosol dispersion. The improvement in average tool life was at the rate of 3.3%. The relationship between tool life and nozzle type is shown in Fig. 3c. Although the nozzle geometries and measurements were similar, there was no countersink at the mouth of the Type 1 nozzle, while there was countersink at that of the Type 2 nozzle (Figs. 2, 3c). Due to the absence of countersink, the aerosol which reached the cutting zone was more concentrated and without dispersion, so the Type 1 nozzle gave better results in terms of tool life. The increase in efficiency rate is 3.3%. Three-dimensional surface plots of the cutting force and other major factor interactions are given in Fig. 4.

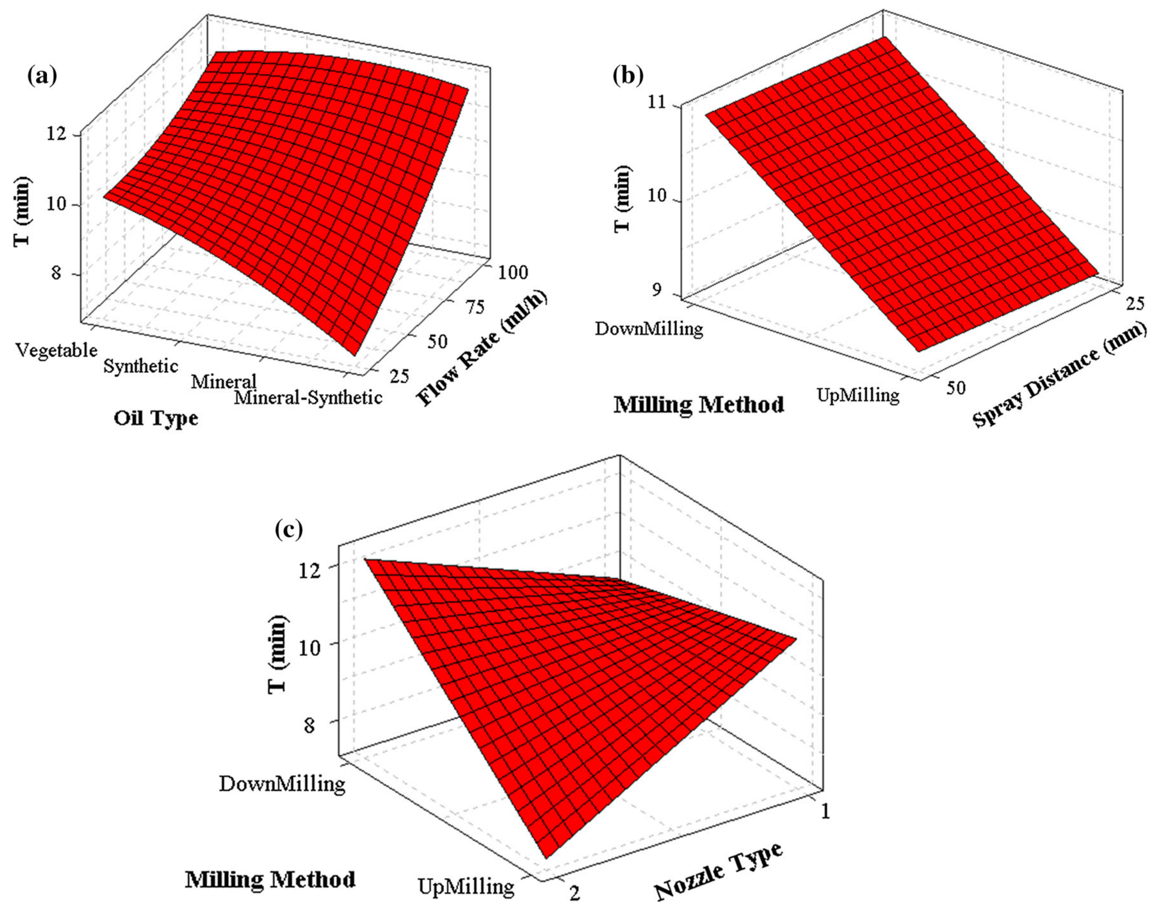

Fig. 3 Effect of the MQL parameters on tool life: **a** flow rate and oil type, **b** milling method and spray distance, **c** milling method and nozzle type

It was determined that the vegetable-based cutting oil created lower cutting force than the synthetic, mineral and mineral-synthetic cutting oils (Fig. 4a). The vegetable-based cutting oils are molecularly long, heavy and bipolar, and thus, the affinity to metal surfaces is chemically increased. Consequently, they reduce the cutting forces, the friction between the tool and workpiece and tool wear by controlling the pressure in the cutting zone [34]. In addition, vegetable-based cutting fluids reduce friction and therefore cutting force since they provide consistent lubricity at high manufacturing temperatures due to their viscosities [38,49,50]. Vegetable-base cutting fluids resulted better in terms of cutting force at the rate of 2.98, 5.14 and 1.18 %, respectively, when compared with synthetic-, mineral- and mineral-synthetic-based cutting fluids. The flow rates in Fig. 4a demonstrate the reduction of cutting forces during the cutting process as a result of the increase in the amount of oil, which in turn affects the cutting zone [51]. This situation is parallel with the literature [42,52,53]. When the rate of increase in flow rate was examined based on 25 ml/h flow rate, 50 ml/h flow rate improved the efficiency at the rate of 0.91%, 75 ml/h flow rate at the rate of 1.3% and 100 ml/h flow rate at the rate of 5.49%. In the down milling, the cutting tool was forced at the point where it started to sink into the workpiece because the greatest amount of the chip section was formed there. In addition, the highest hardness of the workpiece surface was at that point as a result of the oxide and deformation during machining. Therefore, the cutting force was higher in the down milling [13,54]. Up milling resulted at the rate of 1.67% better than the down milling. The effects of the spray distance and nozzle type were in parallel with the tool life experiments. While the 25-mm spray distance improved efficiency at the rate of 0.44%, the 1 numbered nozzle type improved efficiency at the rate of 1.19%. Figure 5 shows the wear condition of the cutting tools at the end of the machining time of 7.9 min.

3.2 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method that was included in the design of the experiment and was used to determine the individual interactions of the control factors [55]. In this study, ANOVA was used to analyze the effects of oil type, flow rate, milling direction, spray distance and nozzle type on tool life. The results of ANOVA for the tool life and cutting force values obtained from the experiments

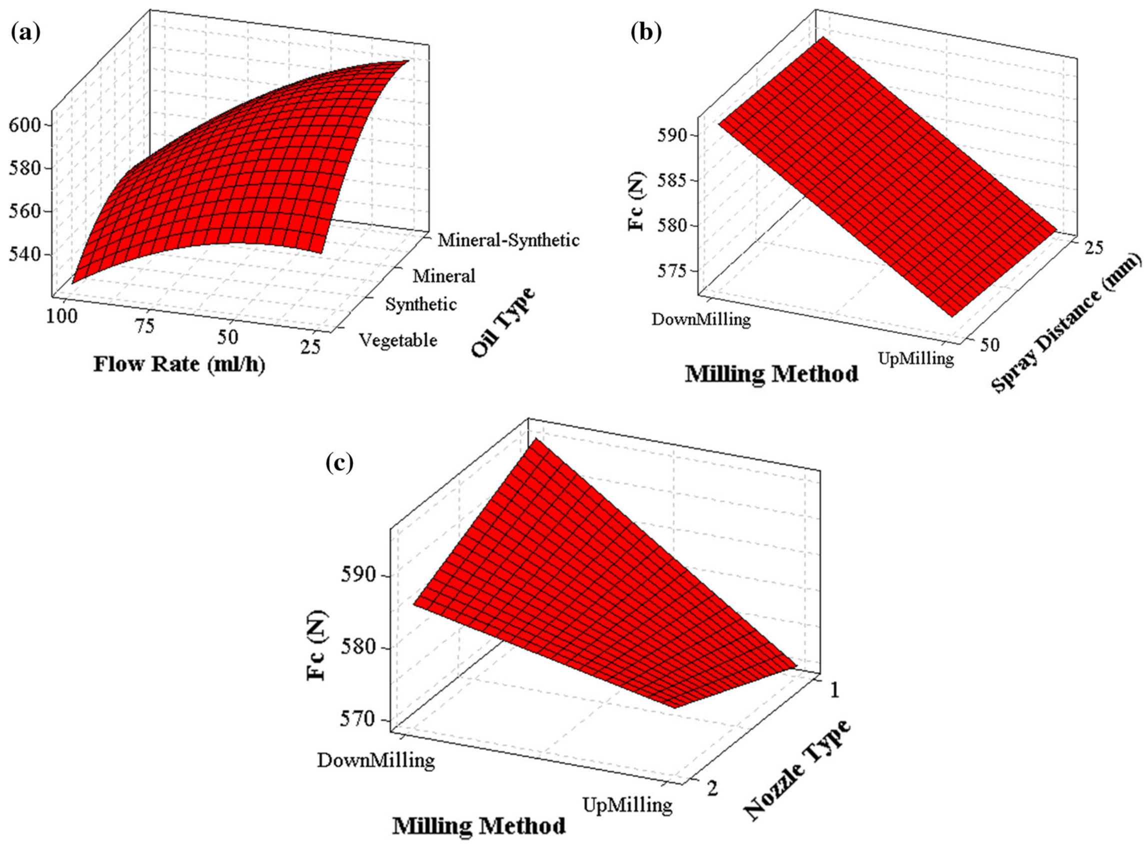

Fig. 4 Effect of the MQL parameters on cutting force: **a** flow rate and oil type, **b** milling method and spray distance, **c** milling method and nozzle type

carried out to find the optimum cutting parameters of the MQL system are given in Table 6.

Analyses were made at the 95% confidence level. A *P* value of less than 0.05 meant that the effect of the factor on the output was regarded as statistically significant [56]. Thus, it can be said that the oil type and the flow rate had a certain effect on both the tool life and the cutting force. The *F* values in the table were taken into consideration when determining the effect levels of the actors (contribution ratios). When Table 6 is examined, it can be seen that the contributions of factors *A*, *B*, *C*, *D* and *E* to tool life were 37.8, 43.7, 6.7, 0.7 and 0.7%, respectively. As for the cutting force, the contribution rate was 33.4, 43.0, 6.5, 0.5 and 3.5%, respectively. In the light of these data, the most important factor affecting tool life and cutting force was found to be the flow rate (B). The error rate was 13.1% for the cutting force, while it was 10.4% for the tool life. This meets the standard of the principle which states that "error level should be less than 20% for reliable statistical analysis" [33].

3.3 Analysis of the *S*/*N* Ratio

The levels of control factors, the tool life obtained from the result of the machinability experiments, the cutting force and the *S*/*N* ratios belonging to these are presented in Table 7. As a result of the milling experiments, the average value of the tool life was found to be 10.1 min while the average value of the cutting forces was 567.4 N. The mean value of *S*/*N* ratios for tool life was 19.80 dB, whereas it was calculated as −55.07 dB for cutting force.

The *S*/*N* responses for tool life and cutting force are given in Table 8. According to the Taguchi method, the highest level for each factor gives the optimum value of that factor. In addition, Figs. 6 and 7 show the main effect graphs of the MQL parameters on *S*/*N* ratios for tool life and cutting force, respectively.

The best level for any control factor loaded into the system is found in accordance with the largest *S*/*N* value in the factor levels. For this reason, the levels of the factors giving the highest tool life value and *S*/*N* ratios were determined for factor *A* as Level 1, $S/N = 21.38$ dB, for factor *B* as Level 4, $S/N = 21.38$ dB, for factor C as Level 2, $S/N = 20.22$ dB, for factor *D* as Level 1, $S/N = 20.05$ dB and for factor *E* as Level 1, $S/N = 20.05$ dB. The levels of the factors giving the lowest value of cutting force and *S*/*N* ratios were determined for the factor *A* as Level 1, $S/N = -54.88$ dB, for factor B as Level 4, $S/N = -54.75$ dB, for factor *C* as Level 2, $S/N = -55.00$ dB, for factor *D* as Level 1, $S/N =$

Fig. 5 Wear condition of the cutting tool at the end of 7.9 min machining time

−55.05 dB and for factor E as Level 1, $S/N = -55.02$ dB. In other words, optimum MQL parameters giving the highest tool life and lowest cutting force values were the vegetable oil (A_1), the flow rate of 100 ml/h (B_4), the up milling (C_2), the spray distance of 25 mm (D_1) and the Type 1 nozzle (E_1).

3.4 Prediction for Tool Life and Cutting Force

The relationship between dependent and independent variables was calculated and analyzed by regression analysis [12]. Tool life and cutting force equations were generated based on the parameters of oil type (OT), flow rate (FR), milling type (MT), spray distance (SD) and nozzle type (NT) depending on the control levels. The linear equations generated by the main effects of the control factors are given in Eq. (3) for the tool life and in Eq. (4) for the cutting force.

$$T = 9.2 + 0.975^{*}\mathrm{OT} - 0.0442^{*}\mathrm{FR} - 0.975^{*}\mathrm{MT} + 0.013^{*}\mathrm{SD} + 0.325^{*}\mathrm{NT} \quad (3)$$

$$\mathrm{Fc} = 583.9 + 3.15 * \mathrm{OT} - 0.39^{*}\mathrm{FR} - 9.5^{*}\mathrm{MT} + 0.1^{*}\mathrm{SD} + 7^{*}\mathrm{NT} \quad (4)$$

The coefficient of determination of the obtained linear equation was calculated as $R^2 = 0.483$ for the tool life and $R^2 = 0.483$ for the cutting force. Since the differences between the predictive values obtained with the first degree equations at the 95% confidence level and the values obtained with the experimental studies were high, new equations including the factorial interactions had to be established, and Eqs. (5) and (6) were used for the tool life and the cutting force, respectively.

$$T = 19.47 - 0.16^{*}\mathrm{OT} + 0.0065^{*}\mathrm{FR} - 8.32^{*}\mathrm{MT} + 0.2^{*}\mathrm{SD} - 11.38^{*}\mathrm{NT} - 0.16^{*}\mathrm{OT}^{2} + 0.00026^{*}\mathrm{FR}^{2}$$

Table 6 Results of ANOVA

Source	Degree of freedom	Sum of squares	Mean squares	*F* ratio	*P* ratio	Contribution rate (%)
Tool life						
A	3	21.5475	7.1825	7.29	0.020	37.8
B	3	24.9275	8.3092	8.43	0.014	43.7
C	1	3.8025	3.8025	3.86	0.097	6.7
D	1	0.4225	0.4225	0.43	0.537	0.7
E	1	0.4225	0.4225	0.43	0.537	0.7
Error	6	5.9150	0.9858	–	–	10.4
Total	15	57.0375	–	–	–	100
Cutting force						
A	3	1854.75	618.25	5.10	0.043	33.4
B	3	2387.25	795.75	6.56	0.025	43.0
C	1	361.00	361.00	2.98	0.135	6.5
D	1	25.00	25.00	0.21	0.666	0.5
E	1	196.00	196.00	1.62	0.251	3.5
Error	6	727.75	121.29	–	–	13.1
Total	15	5551.75	–	–	–	100

Table 7 Results of experiments and *S*/*N* ratios values

E.N	Control factors					Tool life (min)	*S*/*N* ratio (dB)	Cutting force (N)	*S*/*N* ratio (dB)
	A Oil type (OT)	*B* Flow ratio (ml/h)	*C* Milling type (MT)	*D* Spray distance (mm)	*E* Nozzle type (NT)				
1	Vegetable	25	Down milling	25	1	10.5	20.42	571	−55.13
2	Vegetable	50	Down milling	25	1	10.5	20.42	555	−54.89
3	Vegetable	75	Up milling	50	2	13.1	22.35	549	−54.79
4	Vegetable	100	Up milling	50	2	13.1	23.92	543	−54.70
5	Synthetic	25	Down milling	50	2	7.9	17.95	589	−55.40
6	Synthetic	50	Down milling	50	2	7.9	20.42	589	−55.40
7	Synthetic	75	Up milling	25	1	10.5	20.42	565	−55.04
8	Synthetic	100	Up milling	25	1	13.1	22.35	541	−54.66
9	Mineral	25	Up milling	25	2	7.9	17.95	595	−55.49
10	Mineral	50	Up milling	25	2	10.5	17.95	583	−55.31
11	Mineral	75	Down milling	50	1	10.5	17.95	585	−55.34
12	Mineral	100	Down milling	50	1	10.5	20.42	569	−55.10
13	Min.-synt.	25	Up milling	50	1	7.9	17.95	559	−54.95
14	Min.-synt.	50	Up milling	50	1	7.9	17.95	566	−55.06
15	Min.-synt.	75	Down milling	25	2	7.9	17.95	585	−55.34
16	Min.-synt.	100	Down milling	25	2	10.5	20.42	534	−54.55

$$+0.0156^{*}\mathrm{OT}^{*}\mathrm{FR} - 0.0325^{*}\mathrm{OT}^{*}\mathrm{MT} + 0.026^{*}\mathrm{FR}^{*}\mathrm{MT} - 0.00312^{*}\mathrm{FR}^{*}\mathrm{SD} + 0.026^{*}\mathrm{FR}^{*}\mathrm{NT} + 6.17^{*}\mathrm{OY}^{*}\mathrm{NT} \quad (5)$$

$$\mathrm{Fc} = 544.6 + 73.75^{*}\mathrm{OT} - 1.03^{*}\mathrm{FR} + 10.6^{*}\mathrm{MT} - 2.24^{*}\mathrm{SD} + 39.1^{*}\mathrm{NT} - 7.12^{*}\mathrm{OT}^{2} - 0.00760^{*}\mathrm{FR}^{2} - 0.14^{*}\mathrm{OT}^{*}\mathrm{FR} - 12.5^{*}\mathrm{OT}^{*}\mathrm{MT} + 0.48^{*}\mathrm{FR}^{*}\mathrm{MT} + 0.0352^{*}\mathrm{FR}^{*}\mathrm{SD} - 0.2^{*}\mathrm{FR}^{*}\mathrm{NT} - 17.25^{*}\mathrm{MT}^{*}\mathrm{NT} \quad (6)$$

The coefficient of determination of the tool life equation was found as $R^2 = 0.991$ and as $R^2 = 0.998$ in the cutting force equation. Figure 8 shows the comparison of the experimental

Table 8 *S/N* response table

Levels	Control factors				
	A	*B*	*C*	*D*	*E*
Tool life					
Level 1	**21.38**	18.57	19.50	**20.05**	**20.05**
Level 2	19.67	19.19	**20.22**	19.67	19.67
Level 3	19.81	20.29	–	–	–
Level 4	18.57	**21.38**	–	–	–
Delta	2.81	2.81	0.72	0.38	0.38
Cutting force					
Level 1	**−54.88**	−55.24	−55.15	**−55.05**	**−55.02**
Level 2	−55.13	−55.16	**−55.00**	−55.09	−55.12
Level 3	−55.31	−55.13	–	–	–
Level 4	−54.97	**−54.75**	–	–	–
Delta	0.44	0.49	0.15	0.04	0.10

Bold values indicate the optimal levels of control factors

results with the prediction model results for tool life, and Fig. 9 shows the comparison of the experimental values and the prediction models for cutting force. As can be seen in both figures, the predictive equations closest to the real values are the quadratic regression equations belonging to the main effects and their interactions.

3.5 Optimization

The parameter group giving the highest tool life and the lowest cutting force was found to be $A_1B_4C_2D_1E_1$. Eq. (7) was used in predicting optimum tool life, and Eq. (8) was used to predict the optimum cutting force.

$$T_{\text{opt}} = (A_1 - T_T) + (B_4 - T_T) + (C_2 - T_T) + (D_1 - T_T) + (E_1 - T_T) + T_T \quad (7)$$

$$\text{Fc}_{\text{opt}} = (A_1 - T_{\text{Fc}}) + (B_4 - T_{\text{Fc}}) + (C_2 - T_{\text{Fc}}) + (D_1 - T_{\text{Fc}}) + (E_1 - T_{\text{Fc}}) + T_{\text{Fc}} \quad (8)$$

Here, (A_1, B_4, C_2, D_1, E_1) give the optimum level average values of tool life and cutting force (Table 9). The T_T and T_{Fc} values represent the average tool life and cutting force values obtained from the experimental study (Table 7). As a result of the calculations, the T_{opt} value was found to be 14.06 min and the Fc_{opt} to be 524.3 N.

The estimated confidence interval was calculated using Eqs. (9) and (10) to ensure the sufficient accuracy of the optimization [33].

$$\text{CI}_{T\ddot{o}} = \sqrt{F_{\alpha,1,f_e} V_e \left[\frac{1}{n_{\text{eff}}} + \frac{1}{R}\right]} \quad (9)$$

Here, F_α represents the 95% reliability ratio, α is the importance level, f_e is the degree of freedom of the error, V_e is the error variance, n_{eff} is the number of repetitive activities and R is the repetition number of the verification experiments.

$$n_{\text{eff}} = \frac{N}{1 + T_{\text{dof}}} \quad (10)$$

Here, N gives the total number of experiments and T_{dof} is the total main factors of the degree of freedom.

$F_{0.05,1,6} = 5.987$; for tool life $V = 0.9858$; for cutting force $V = 121.29$ (Table 6) and $R = 3$ (Eq. 9) and $N = 16$, $T_{\text{dof}} = 9$, and $n_{\text{eff}} = 1.6$ (Eq. 10). By means of substituting

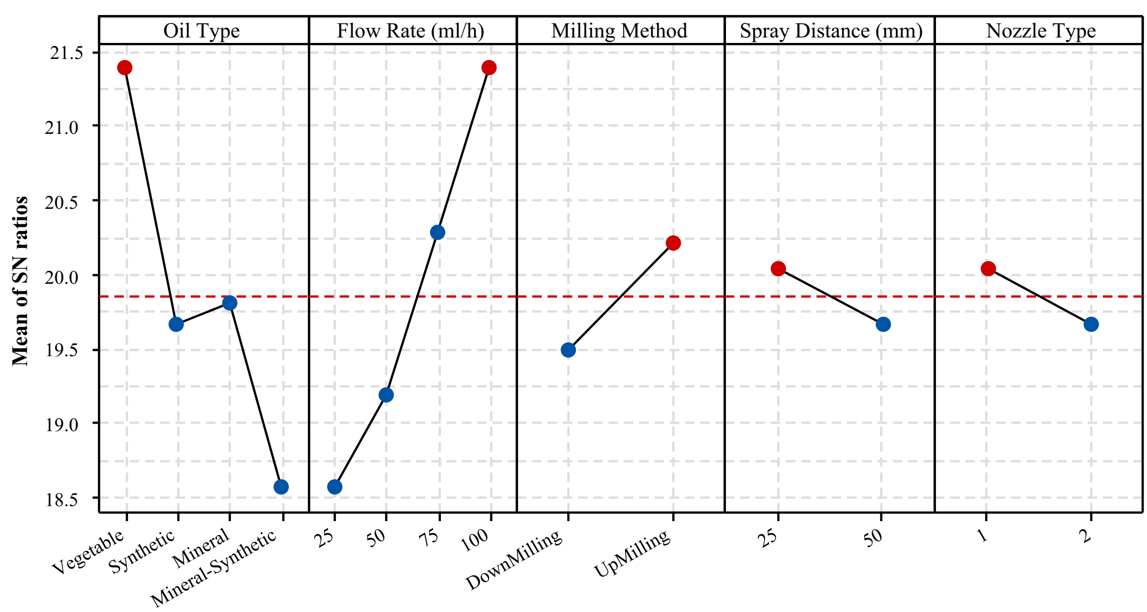

Fig. 6 Effect of process parameters on average *S/N* ratio for tool life

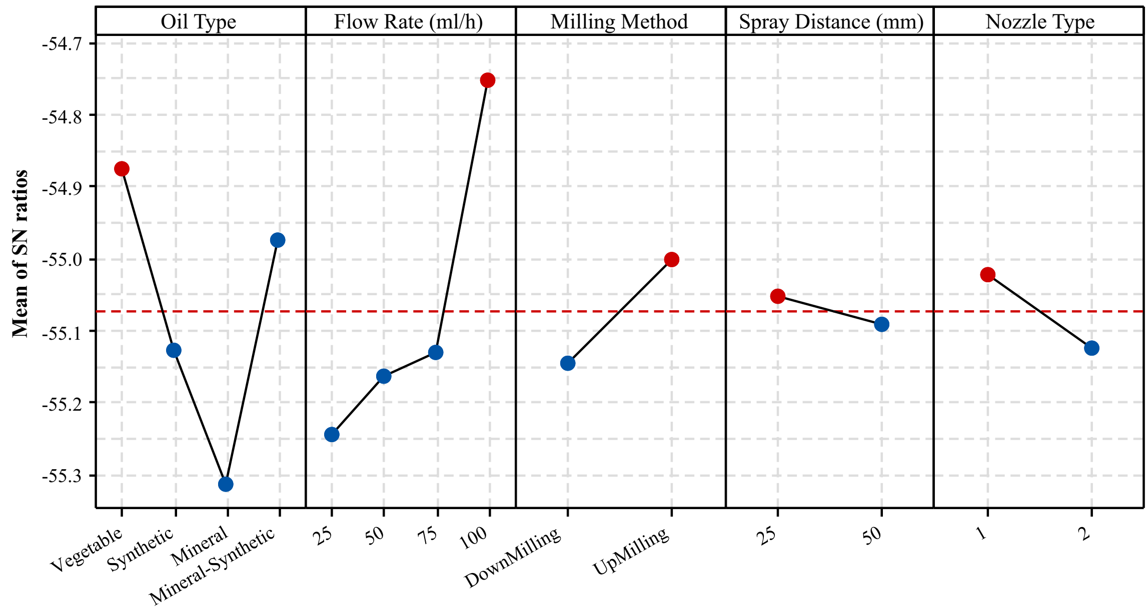

Fig. 7 Effect of process parameters on average *S*/*N* ratio for cutting force

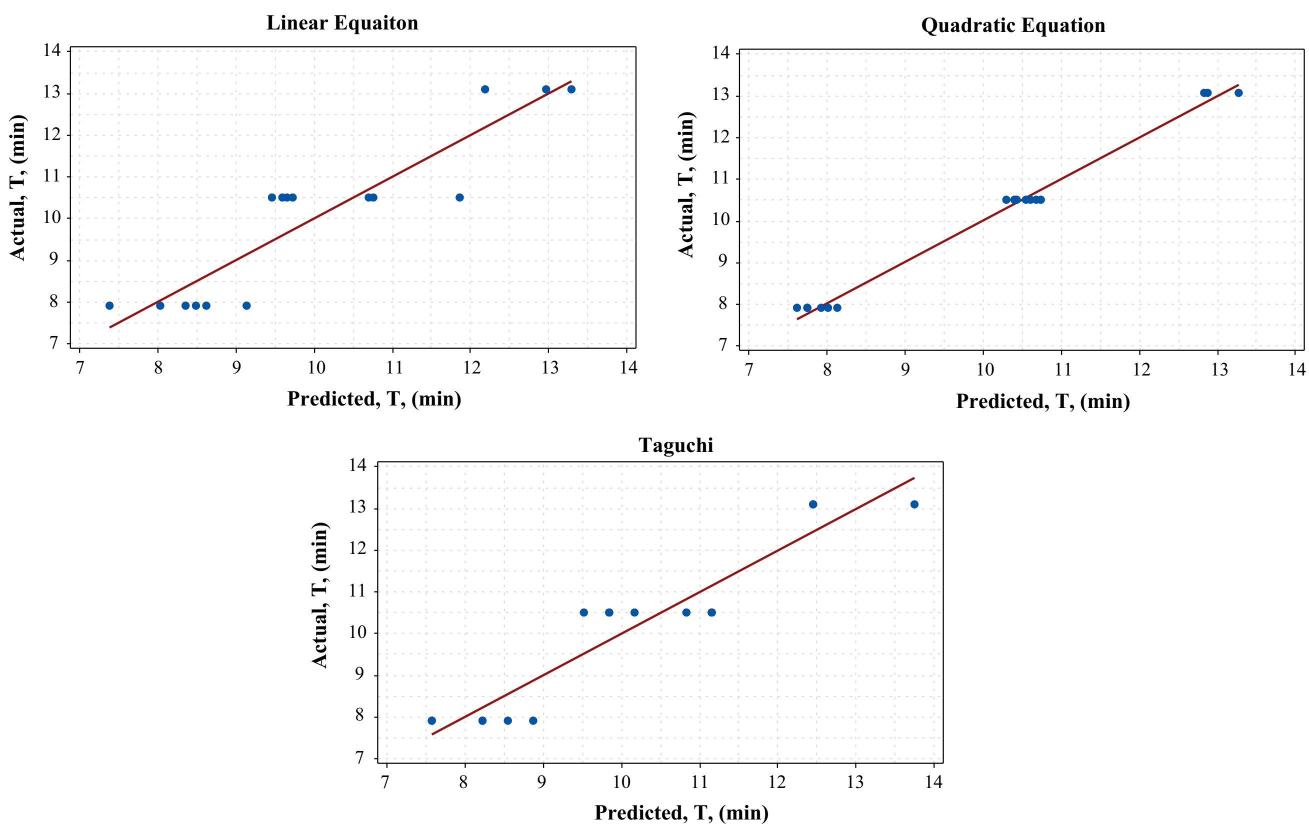

Fig. 8 Comparison of the regression models with experimental results for tool life

the values obtained in Eqs. (9) and (10), the confidence interval was found as $CI_T = \pm 2.378$ for the tool life experiments and as $CI_{Fc} = \pm 26.38$ for cutting force.

$$[T_{opt} - CI_T] < T_t < [T_{opt} + CI_T] \quad (11)$$

$$[Fc_{opt} - CI_{Fc}] < Fc_t < [Fc_{opt} + CI_{Fc}] \quad (12)$$

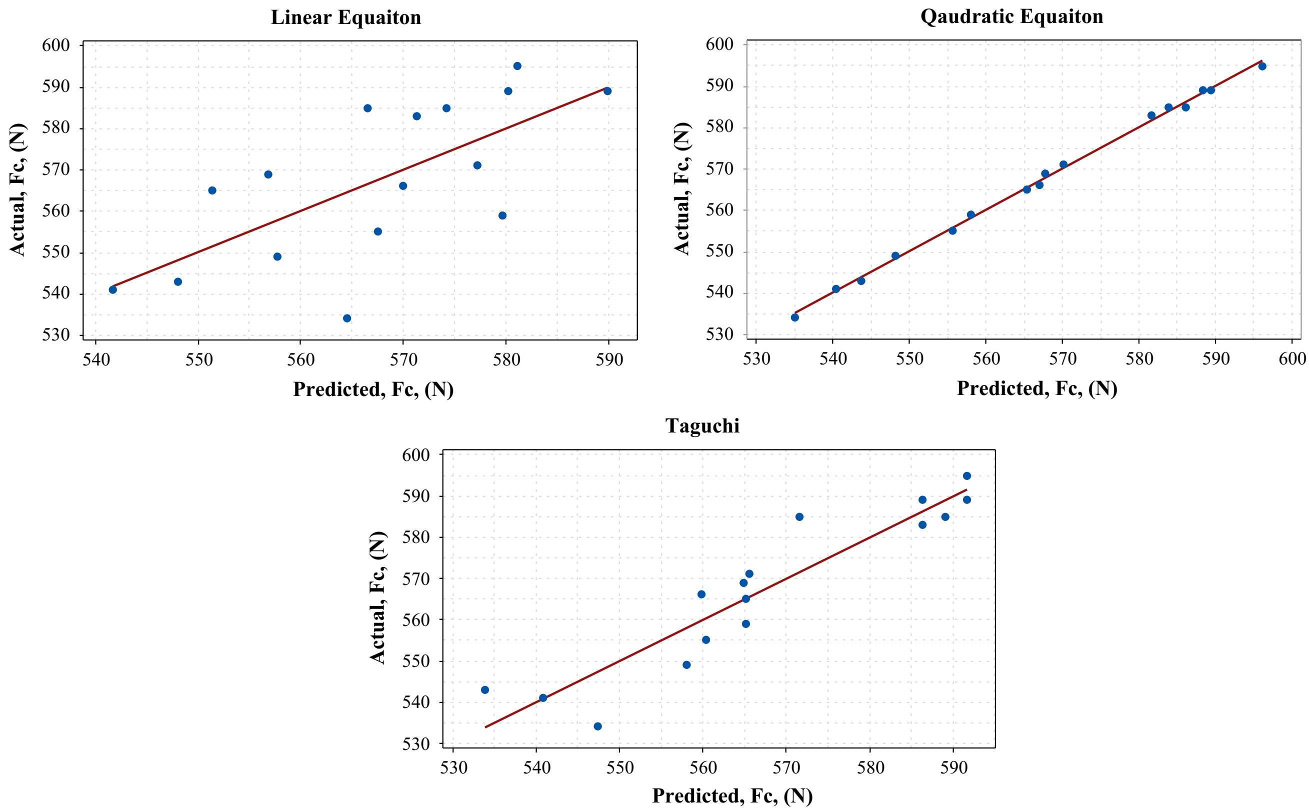

Fig. 9 Comparison of the regression models with experimental results for cutting force

If the values are substituted in Eqs. (11) and (12), the tool life was:

$$[14.06 - 2.378] < 15.7 < [14.06 + 2.378]$$
$$= 11.682 < 15.7 < 16.438$$

and the cutting force was:

$$[524.3 - 26.38] < 526 < [524.3 + 26.38]$$
$$= 497.92 < 526 < 550.68$$

The experimentally obtained tool life and cutting force values were within the limits of the confidence interval. Thus, system optimization was achieved at the level of 0.05 significance using the Taguchi method.

Table 9 Mean response table

Levels	Control Factors				
	A	B	C	D	E
Tool life					
Level 1	**11.80**	8.55	9.53	**10.18**	**10.18**
Level 2	9.85	9.20	**10.50**	9.85	9.85
Level 3	9.85	10.50	–	–	–
Level 4	8.55	**11.80**	–	–	–
Delta	3.25	3.25	0.98	0.33	0.33
Cutting force					
Level 1	**554.5**	578.5	572.1	**566.1**	**563.9**
Level 2	571.0	573.3	**562.6**	568.6	570.9
Level 3	583.0	571.0	–	–	–
Level 4	561.0	**546.8**	–	–	–
Delta	28.5	31.8	9.5	2.5	7.0

Bold values indicate the optimal levels of control factors

3.6 Confirmation Tests

Verification experiments for control factors were performed at optimum and randomly selected levels. A comparison was made of the experimental results, the regression equations and the predicted values obtained by the Taguchi method (Table 10).

When Table 10 is examined, it is seen that the closest predicted values were obtained with quadratic equation in terms of both tool life and cutting force. For example, while the deviation rate of the parameter group $A_1B_4C_2D_1E_1$ giving the highest tool life was 4.14% in the linear equation, this rate was 1.91% in the quadratic equation, and 3.18% in the estimation made by the Taguchi program. In the same way, while the deviation rate of the parameter group $(A_1B_4C_2D_1E_1)$ giving the smallest cutting force was 1.14% in the linear

Table 10 Predicted values and confirmation test results by regression equations

Level	Linear equation			Quadratic equation			Taguchi equation		
	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
Tool life									
$A_1B_4C_2D_1E_1$	15.7	15.1	4.14	15.7	15.4	1.91	15.7	15.2	3.18
$A_2B_1C_1D_2E_2$	13.1	13.0	0.99	13.1	12.8	2.29	13.1	12.5	5.34
$A_4B_3C_1D_1E_2$	10.5	9.6	8.67	10.5	10.6	0.95	10.5	9.9	6.67
Cutting force									
$A_1B_4C_2D_1E_1$	526	532	1.14	526	525	0.19	526	519	1.33
$A_2B_1C_1D_2E_2$	589	590	0.16	589	589	0.00	589	592	0.51
$A_4B_3C_1D_1E_2$	585	574	1.88	585	584	0.17	585	572	2.22

equation, this rate was 0.19% in the quadratic equation, and 1.33% in the estimation made by the Taguchi program. When the confirmation test results were examined, it was found that the results obtained were sufficient and the Taguchi optimization was successful.

4 Conclusions

In this study, unlike similar studies in which MQL parameters were evaluated, the scope was widened and the main parameters affecting the efficiency of the system were tested at the same time. Taguchi method was chosen to determine the optimum MQL parameters in the milling of the Waspaloy superalloy based on nickel. The Taguchi L_{16} orthogonal index was used for the experimental design. Verification experiments were conducted to confirm the specified optimum cutting parameters. The results obtained in the light of the ANOVA and *S*/*N* analyses are presented below.

- According to the results of ANOVA, the main factor affecting tool life and cutting force was flow rate, and the percentage of the effect was determined as 43.7 and 43.0% for tool life and cutting force, respectively. The contribution rates of cutting oil type, flow rate, milling direction, spray distance and nozzle type on tool life were 33.4, 43.0, 6.5, 0.5 and 3.5%, respectively, whereas these percentages for cutting force were found to be 37.8, 43.7, 6.7, 0.7 and 0.7%, respectively.
- Based on the *S*/*N* ratio, the optimum MQL parameters for tool life using "the largest is the best" approach and for cutting force using "the smallest is the best" were determined to be $A_1B_4C_2D_1E_1$ (vegetable cutting oil, 100 ml/h flow rate, up milling, 25 mm spray distance and Type 2 nozzle).
- Vegetable-based cutting oil gave higher tool life and lower cutting force values than other types of oil. This result is very important for sustainable manufacturing, as mineral- and synthetic-based cutting oils are regarded as having adverse effects on the environment and human health.
- When vegetable-base cutting fluid was compared with synthetic-, mineral- and mineral-synthetic-based cutting fluids in terms of tool life, it resulted better at the rate of 16.53, 16.53 and 27.54%, respectively, whereas in terms of cutting force, the efficiency rates were 2.98, 5.14 and 1.18%, respectively.
- As the flow rate increased, the values of both tool life and cutting force were improved. When compared the effect of flow rates in terms of tool life, 50 ml/h flow rate improved efficiency at the rate of 7.6%, 75 ml/h flow rate at the rate of 22.81% and 100 ml/h flow rate at the rate of 38.01% when compared with 25 ml/h flow rate. This rate for cutting force was 0.91% for 50 ml/h flow rate, 1.3% for 75 ml/h flow rate and 5.49% for 100 ml/h flow rate when compared with 25 ml/h flow rate.
- The up (opposite-direction) milling yielded better results compared to the down milling. While up milling resulted better at the rate of 10.18% in terms of tool life, this rate was 1.67% in cutting force.
- As a result of the experiments, the effectiveness levels of the spray distance and the nozzle type on the tool life and the cutting force were very low.
- The advanced quadratic regression model revealed a very good correlation between the measured value for tool life and cutting force and the estimated value, with the high correlation coefficients of 99.1% for tool life and 99.8% for cutting force.
- The values measured according to the verification test results were within the 95% confidence interval.

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