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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Influence of Different Cooling Methods on Tool Life, Wear Mechanisms and Surface Roughness in the Milling of Nickel-Based Waspaloy with WC Tools

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Abstract
Superalloys are generally considered to be difficult to machinability. In recent attempts to facilitate their machinability, minimum quantity lubrication (MQL) has been used due to its positive influence on cutting tool life, the environment and human health. This study focused on the tool life, wear behavior and surface roughness in the milling of nickel-based superalloy Waspaloy. Uncoated carbide tools, PVD (TiAlN)-coated tools and CVD ($TiCN + Al_2O_3 + TiN$)-coated tools were used. Experiments were performed with different cooling methods which included dry, wet and MQL. SEM and EDX were used for tool wear behavior and mechanism analyses. A portable measuring instrument and a 3D optical profilometer were employed for surface roughness analyses. Results obtained from the tests showed that during the milling of the Waspaloy, adhesion and abrasion were effective wear mechanisms for the cutting tools. The main wear behaviors were flank wear, crater wear and BUE (built up edge). In addition to these results, reduction in the tool wear, the wet machining and machining with the MQL system provided improvement at the rates of 37.54% and 29.01%, respectively, when compared to the dry machining.

Keywords Waspaloy · Milling · Tool life · Surface roughness · Taguchi method · MQL

Abbreviations

WC	Tungsten carbide
MQL	Minimum quantity lubrication
V	Cutting speed
f	Feed rate
PVD	Physical vapor deposition
CVD	Chemical vapor deposition
Ra	Average surface roughness
TiCN	Titanium carbonitride
Al_2O_3	Aluminum oxide
TiN	Titanium nitride
TiAlN	Titanium aluminum nitride
ANOVA	Analysis of variance
SEM	Scanning electron microscope
EDX	Energy-dispersive X-ray
S/N	Signal-to-noise ratio
dB	Decibels
CT	Cutting tool
CM	Cooling method
Tl	Tool life
BUE	Built up edge
CI	Confidence interval

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1 Introduction

Waspaloy is a nickel-based superalloy that is suitable for age hardening and is preferred for its high oxidation resistance, perfect high temperature resistance and excellent corrosion resistance. In critical applications, Waspaloy, which has a working temperature of 650 °C, can maintain its properties even at 870 °C. Various engine components such as compressors and rotor disks, bracelets, shafts, felts, and their housings, screws, fasteners, aircraft bodies, petrochemical equipment, chemical plant equipment and missile systems

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are among its current and potential uses [1]. The superalloys among which Waspaloy is included are extremely demanding materials in terms of machinability due to the high cutting strength required and to their low thermal conductivity and tendency to weld to the cutting edge [2].

Machinability can be described as the ease or difficulty in shaping a material using a cutting tool during the machining process [3]. Machinability is generally considered to be a condition originating from the material, but this can vary according to the machining method and parameters. Two of the most important factors used to measure the machinability of a material are tool wear and surface roughness. One of the most important methods used to improve cutting tool performance and extend tool life is to coating the cutting tool. The machining performance of coatings produced by CVD and PVD has been the subject of many studies. Although PVD-coated products gave better results in some studies [4, 5], CVD-coated tools yielded better results in others [6, 7]. One important criterion of machinability is the quality of the machined surface measured by the surface roughness values, which indicate the very small intermittent surface irregularities arising from manufacturing methods or other factors. The ideal surface quality is the result of achieving the least surface roughness using optimum tool geometry and cutting speed. For this reason, it is important to determine the proper cutting tools, coating types and machining parameters that at the same time increase machining performance and reduce production costs.

Another way to improve machining performance is to use cutting fluid. The chemical and physical properties of cutting fluids can ensure the prevention or reduction in thermal or mechanical damage during the manufacturing process [8]. Cutting fluids reduce friction by lubrication in addition to cooling and help to extend tool life and improve surface quality by removing chips from the cutting zone. On the other hand, the usage of classical cutting fluids negatively might affect the environment, health of workers and production expenses. The dangerous nature of the chemicals in the liquid, along with associated challenges of supply, storage and waste disposal, put human health at risk [9]. For this reason, research has been directed toward seeking alternative cooling/lubrication methods. One method of reducing the required amount of cutting fluid is the minimum quantity lubrication (MQL) system.

The MQL, also referred to as semidry machining, is one of the essential elements of environmentally friendly sustainable manufacturing. The main objective of the MQL system is to control resource consumption by minimizing the environmental damage caused by the cutting fluids from the beginning to the end of the chip removal process. In addition to supporting environmental and employee safety, MQL also provides a significant reduction in production costs. The MQL system works by mixing oil droplets with pressurized air and transferring this mixture to the cutting zone via a nozzle. While the lubricating effect is provided by the oil droplets, the cooling effect is also directed to the cutting zone via the pressurized air. In this system, the oil used is vegetable, synthetic or mineral-based and the flow rates are very low (10–200 ml/h) [10]. This amounts to a cutting fluid savings of about 1/10.000 with the MQL compared to the conventional cooling/lubrication systems [11]. Other studies have reported that the MQL system minimizes both the production costs and the negative effects of classical cutting fluid on worker health and the environment.

As machinability studies with Waspaloy are very limited in the literature, some of the studies done with superalloys having similar properties are given below. Olgun and Budak [12] turned 1050 Waspaloy and Ti6Al4V under wet, dry and MQL cooling/lubrication conditions and examined the effects on surface quality, cutting force and tool wear. Sreenivasulu et al. [13] examined the effect of machining parameters in milling of Inconel 718. The authors used Taguchi method to analyze both experimental design and test results. Obikawa et al. [8] examined the performance of cutting fluids used with ordinary spraying and microspraying in terms of tool life in the turning of with multilayer CVD ($TiCN + Al_2O_3 + TiN$)-coated carbide inserts. Sarıkaya et al. [14] observed the changes in surface roughness and tool life based on the machining conditions, by turning cobalt-based Haynes 25 superalloy with uncoated carbide inserts using different cooling methods (dry, wet and MQL system). Ucun et al. [15] researched the effect of the cutting insert coating material on tool inserts wear in the micro-milling of Inconel 718. Kasım et al. [16] evaluated the impacts of cutting speed, rate of the feed and cut depth on surface roughness in the machining of Inconel 718 under the MQL system. Zhang et al. [17] examined the effects of chip removal parameters on cutting force and tool wear in the machining of Inconel 718 with coated carbide tools using the MQL system, dry cutting and biodegradable vegetable-based cutting oil. Hood et al. [18] observed the effects of the cooling/lubrication method (dry, wet, high-pressure air cooling and MQL) and cutting speed (25 and 50 m/min) on tool life and surface roughness in the milling of Udimet 720. In their study, Wang et al. [19] examined the effects of dry cutting and the MQL system on the milling force, temperature at the cutting zone and surface roughness by using uncoated and coated carbide inserts in the milling of Inconel 182, a nickel-based superalloy. Kamata and Obikawa [20] examined the effect of the MQL system on tool wear in the turning of Inconel 718.

The study examined the effects of the cooling method and the milling parameters on tool life and surface roughness in the milling of nickel-based Waspaloy. The Taguchi L_{27} orthogonal array was used in the experiment design, and *S/N* ratio of the Taguchi was performed to obtain the highest

tool life and the lowest surface roughness. ANOVA was employed to determine the relationship between dependent and independent variables. Estimation equations were created by regression analysis, and verification experiments were handled to test the reliability of the developed models.

2 Experimental Procedure

2.1 Material and Milling Tests

The milling tests were performed in a three-axis CNC vertical machining center (DELTA SEIKI CNC-1050A) with 11 kW motor power. The chemical composition of the nickel-based Waspaloy superalloy that was used is shown in Table 1. The test specimens were cut to the dimensions of 150 × 100 × 21 mm. The cut depth was kept constant at 0.5 mm during experiments.

2.2 Cutting Inserts and Tool Holder

The chip removal experiments were carried out with cemented carbide tools having three different coating structures: uncoated, PVD-coated and CVD-coated (Table 2). In addition, a tool holder (R300-025A20-10M) of Ø25X100 mm was selected for the cemented carbide inserts.

2.3 Cooling/lubrication Conditions

The milling tests were made with three cooling conditions: wet, MQL and dry. The Viscol brand semi-synthetic emulsion was used at the rate of 8% as the cutting fluid for the conventional cooling, which is also known as wet machining. The integrated cooling system of the CNC milling machine was used in the conventional machining experiments. For the MQL, the Vario system (SKF Corporation) was used. As a result of the preliminary experiments and the literature survey, the MQL parameters were selected as: 8 bar pressure, vegetable-based cutting oil (density: 0.895 g/cm^3—20 °C, kinematic viscosity: 5 mm^2/s—40 °C, flash point: 170 °C), 100 ml/h flow rate, 25 mm spray distance and 45° spray angle.

2.4 Measurements

In the preliminary experiments conducted, it was observed that the type of wear that occurred in the cutting tool was regular flank wear. The wear limit was assumed to be 0.3 mm in accordance with the tool life standard in ISO 8688-1 milling, and it was assumed that the cutting tool life was completed when the wear reached this value. Cutting tool wearing was measured using a portable digital microscope (Dino-Lite, AM4113ZT) with up to 250 × magnification capability. The cutting tool wearing status was recorded after each pass with Dino-Capture 2.0 software. Each measurement was repeated three times to prevent a possible error. The FEI (Quanta FEG 250) SEM was used to investigate the wear behavior and mechanisms of the cutting tools in more detail. In addition, EDX was performed with the same device to determine the wear characteristics.

At the end of the tests, the mean surface waviness value of the surfaces was determined by a Taylor Hobson Surtronic 25 measuring instrument. The instrument was standardized with calibration blocks before the measurements were taken. Each surface was machined with a tool that had not been previously used. The measurements were made immediately after machining in order to ensure that measured values were not affected by surface oxidation. Surface roughness measurements were taken four times in the machining direction on the machined surface, and the arithmetic average of the measured values was recorded. In addition, a 3D surface topography of the machined surfaces was obtained with the PhaseView camera and sensor, and 2.5 × 2.5 mm measuring points were randomly selected from the machined surfaces. A summary of the experimental procedure is given in Fig. 1.

Table 1 Chemical composition of Waspaloy (wt%)

	Al	B	C	Cr	Co	Fe	Mo	Ni	Ti	Zr
Max	1.20	0.003	0.02	18.00	12.00	–	3.50	–	2.75	0.02
Min	1.60	0.01	0.10	21.00	15.00	2.00	5.00	Balance	3.25	0.08

Table 2 Cutting tool specifications for carbide inserts

ISO Code	Grade	Coating method	Coating material	Hardness (HV3)	Coating thickness (μm)
R300-1032E-KL	H13A	–	Uncoated	1550	–
R300-1032E-PM	GC1030	PVD	TiAlN	1650	3
R300-1032E-MM	GC2040	CVD	TiCN/Al_2O_3/TiN	1300	3

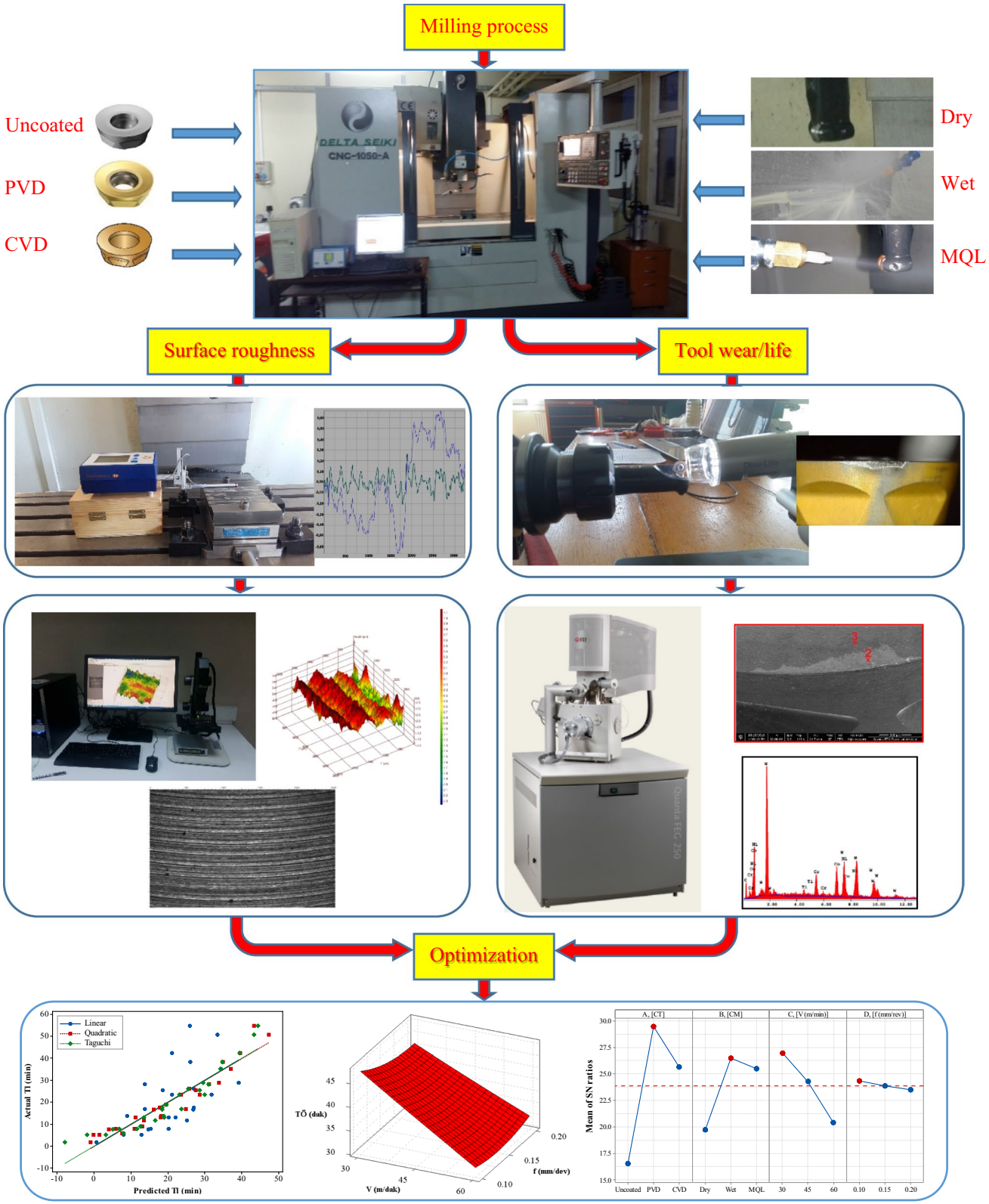


Fig. 1 Schema of measurements and experimental setup

3 Optimization and Experimental Layout

3.1 Design with Taguchi Method

Conventional experimental layout methods are quite complex and difficult to use. In addition, as the number of machining parameters increases, the required number of experiments also increases. A number of experimental design methods have been developed to remove all of this complexity [21]. One of these, the Taguchi method, uses special tables called "orthogonal arrays" for the experimental design and thereby significantly reduces the number of experiments. In addition, the uncontrollable effects on the experiments are also minimized by the use of this method. The major advantages of the Taguchi method include reducing the number of experiments and thus reducing the cost and the time necessary to achieve the target.

The Taguchi method uses a statistical measure to examine the results which called the signal/noise (S/N) ratio. In this method, signal refers to the desired value for the output characteristic, while noise refers to the undesired value. The equations used in the calculation of S/N ratios are as follows: "the higher the better," "the lower the better" and "the nominal the better" [22]. As the purpose of this study was to determine the longest tool life and the lowest surface roughness value, the "the higher the better" was selected for the tool life tests and the "the lower the better" for the surface roughness tests, which were calculated as shown in Eqs. (1) and (2), respectively.

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

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

where *S*/*N* ratio is Signal-to-nose ratio (dB), y_i symbolizes the quality characteristic's value obtained from tests, and n is the test number [23]. The CT, CM, f and V were selected as the control factors, and the levels selected for these factors are shown in Table 3. In this study, three different cooling/lubrication methods, three different cutting tool, three different cutting speeds and three different feed rates were selected as machining parameters. The high number of experiments resulting from the combinations of these parameters causes time losses and increases the experimental costs. Reducing the number of tests has become a necessity to take down the test duration and costs. Thus, the Taguchi L_{27} (3^4) was chosen as the most suitable orthogonal array to determine the optimum cutting parameters.

Table 3 Machining parameters

	Symbol	Level 1	Level 2	Level 3
Cutting inserts	*A*	Uncoated	PVD	CVD
Cooling method	*B*	Dry	Wet	MQL
Cutting speed (m/min)	*C*	30	45	60
Feed rate (mm/rev)	*D*	0.1	0.15	0.2

4 Evaluation of Results of Milling Experiments

4.1 Signal-to-Noise Ratio

Tool life and surface roughness were measured for all combinations of control factors produced by the Taguchi method, and optimization of measured factors was obtained by signal/noise (*S*/*N*) ratios. The experimental results and S/N ratios for tool life (Tl) and surface roughness (Ra) are shown in Table 4.

The *S*/*N* response table was used to analyze the effects of the control factors (CT, CM, V, and f) on tool life and surface roughness (Table 5). In addition, the levels of the control factors for Tl and Ra and the graphical representations of the values corresponding to these levels are shown in Figs. 2 and 3, respectively. The highest *S*/*N* ratio was found in control factor levels to find the best level of each control factor. Accordingly, the levels and *S*/*N* ratios that gave the optimum tool life value were factors *A*, *B*, *C* and *D* (Fig. 2); the levels and *S*/*N* ratios that gave the optimum surface roughness value were factors *A*, *B*, *C* and *D* (Fig. 3).

4.2 Tool Life Results

The 3D surface plots showing the changes in tool life depending on the input parameters are given in Fig. 4. When the correlation of tool life and cutting tool coating type is examined (Fig. 4a), it is seen that the PVD (TiAlN) coated cutting edges had the highest tool life. This can be attributed to the coating properties. With the low thermal conductivity of the Al_2O_3 layer in the CVD-coated tool, it can be said that increasing the thermal resistance of the cutting tool is an important factor in obtaining higher tool life than the uncoated tool [24]. However, the high hardness (1650 HV3) and high wear resistance of the PVD TiAlN coating considerably reduce the tool wear and are thus thought to achieve the highest tool life [25]. The graph presenting the correlation of tool life and cooling–lubrication method (Fig. 4a) shows that the highest tool life value was obtained with wet machining. Friction in the cutting zone is reduced with the use of cutting fluid, thus making positive contributions to tool life by controlling the heat generation [26]. The section in Fig. 4b showing the effect of cutting speed indicates

Table 4 *S/N* ratios values and experiment results

Exp. No.	Control Factors				Tool life (min)	*S/N* ratio (dB)	Surface roughness (μm)	*S/N* oranı (dB)
	A Cutting tool (CT)	*B* Cooling method (CM)	*C* Cutting speed (*V*)	*D* Feed rate (*f*)				
1	Uncoated	Dry	30	0.10	7.9	17.95	0.38	8.87
2	Uncoated	Dry	45	0.15	5.24	14.39	0.38	8.40
3	Uncoated	Dry	60	0.20	1.96	5.85	0.42	7.54
4	Uncoated	Wet	30	0.15	13.12	22.36	0.32	9.90
5	Uncoated	Wet	45	0.20	9.1	19.18	0.33	8.87
6	Uncoated	Wet	60	0.10	5.9	15.42	0.28	10.46
7	Uncoated	MQL	30	0.20	11.8	21.44	0.34	9.37
8	Uncoated	MQL	45	0.10	7.9	17.95	0.29	10.46
9	Uncoated	MQL	60	0.15	5.2	14.32	0.34	9.90
10	PVD	Dry	30	0.15	23.5	27.42	0.40	6.74
11	PVD	Dry	45	0.20	16.9	24.56	0.36	9.37
12	PVD	Dry	60	0.10	13.7	22.73	0.26	10.46
13	PVD	Wet	30	0.20	54.8	34.78	0.28	12.40
14	PVD	Wet	45	0.10	42.4	32.55	0.20	13.98
15	PVD	Wet	60	0.15	28.2	29.00	0.27	12.40
16	PVD	MQL	30	0.10	50.7	34.10	0.23	12.40
17	PVD	MQL	45	0.15	38.4	31.69	0.22	13.15
18	PVD	MQL	60	0.20	25.5	28.13	0.38	7.96
19	CVD	Dry	30	0.20	16.6	24.40	0.40	7.96
20	CVD	Dry	45	0.10	13.1	22.35	0.30	10.46
21	CVD	Dry	60	0.15	7.8	17.84	0.36	8.87
22	CVD	Wet	30	0.10	35.1	30.91	0.20	13.98
23	CVD	Wet	45	0.15	26.1	28.33	0.26	11.70
24	CVD	Wet	60	0.20	19	25.58	0.40	7.54
25	CVD	MQL	30	0.15	28.8	29.19	0.26	11.70
26	CVD	MQL	45	0.20	23.4	27.38	0.30	10.46
27	CVD	MQL	60	0.10	17.6	24.91	0.22	13.15

T_{Tl} (tool life total mean value) = 20.36 min

$T_{Tl\text{-}S/N}$ (tool life *S/N* ratio total mean value) = 23.88 dB

T_{Ra} (surface roughness total mean value) = 0.31 μm

$T_{Ra\text{-}S/N}$ (surface roughness *S/N* ratio total mean value) = 10.31 dB

Table 5 *S/N* respond table for Tl and Ra

Levels	Control factors							
	Tool life (Tl)				Surface roughness (Ra)			
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*
Level 1	16.54	19.72	26.95	24.32	9.38	8.91	10.34	11.81
Level 2	29.44	26.46	24.26	23.84	11.03	11.19	10.82	10.27
Level 3	25.65	25.46	20.42	23.48	10.69	11.01	9.94	9.03
Delta	12.90	6.73	6.53	0.84	1.65	2.27	0.89	2.78

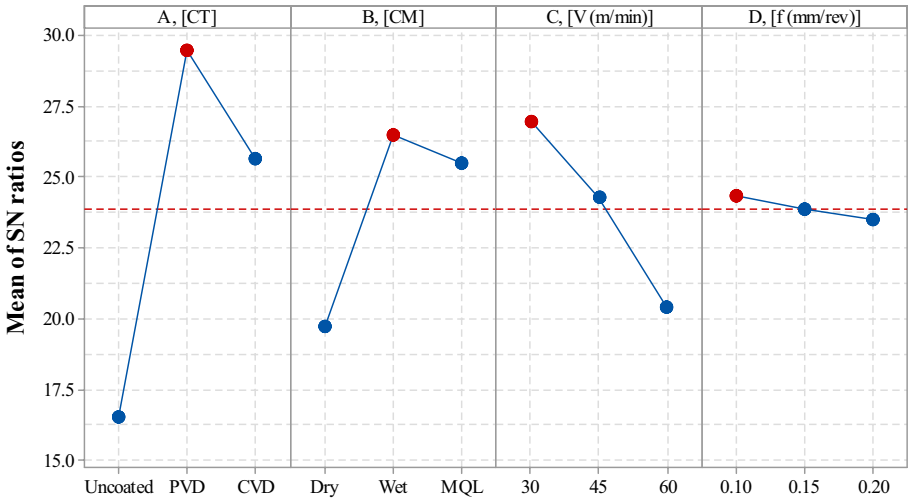


Fig. 2 Effect of machining conditions on *S/N* ratio for Tl

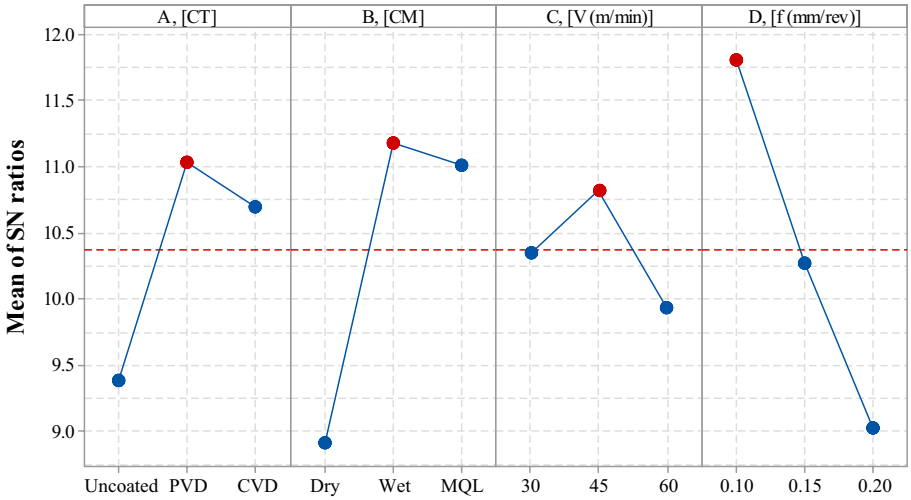


Fig. 3 Effect of machining conditions on *S/N* ratio for Ra

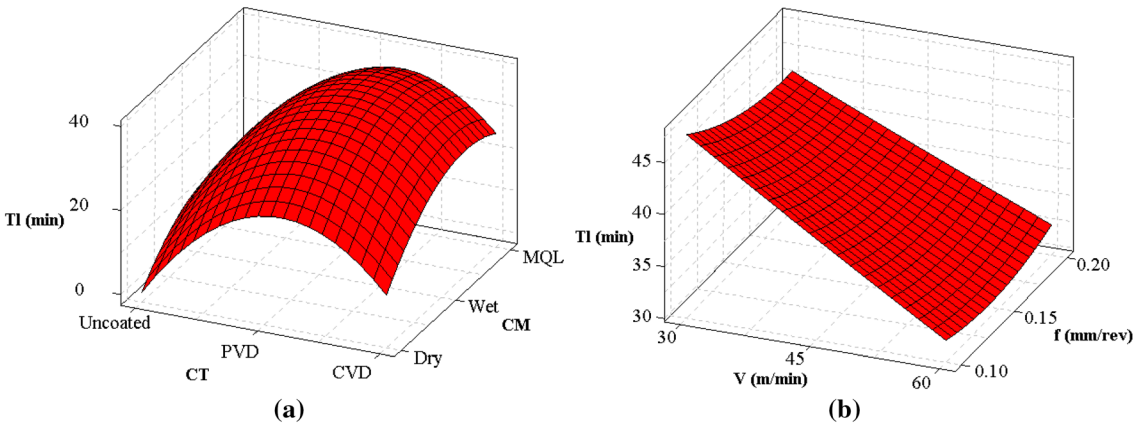


Fig. 4 3D surface plots for effects of **a** coating type and cooling method; and **b** feed rate and cutting speed on tool life (Tl)

that an increase in cutting speed caused a reduction in tool life. With the increase in cutting speed, the volume of chip increases, and therefore, the resulting rise in friction causes an unavoidable increase in wear. In Fig. 4b, the part showing the relation between the cutting tool life and the feed rate indicates that the feed rate had no significant effect on tool life; however, an increase in the feed rate value resulted in some increase in the tool life.

Figure 5 shows the digital microscopic images. The 0.3 mm wear value (ISO 8688-1) was used as a reference, and the time taken to reach this value was determined as the tool life. From the images, it can be seen that the coated tools had a much higher tool life value than the uncoated tools. For example, at a cutting speed of 30 m/min and dry machining, the coated tools (PVD and CVD) exhibited higher tool life despite being tested at higher feed rates than uncoated tools (Fig. 5). This demonstrates the benefits of coating and coating properties. The effect of the cooling–lubrication method showed that wet cutting provided significant improvements in tool life in comparison with dry machining. Moreover, the MQL machining was seen as an important factor in increasing tool life. For example, in tests with uncoated tools at a cutting speed of 30 m/min, although there was an increase in feed rate, a higher tool life was achieved in the MQL and wet cutting conditions according to the dry cutting condition (Fig. 5).

4.3 Characterization of Tool Wear

While carrying out of the experiments, not all the results of the factorial interactions were visible because the experimental design was not fully factorial. For this reason, a series of new experiments was conducted to find the effect of the cutting tool coating type and cooling–lubrication method on wear, based on the optimum cutting parameters (30 m/min and 0.1 mm/rev) that were obtained from the result of the Taguchi optimization. The experiments in the first phase were carried out under dry cutting conditions in

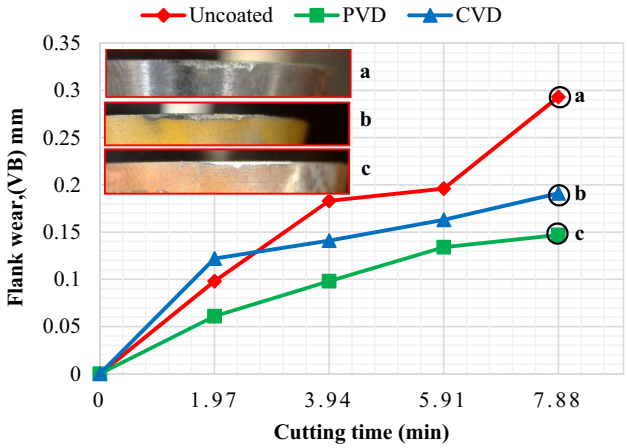
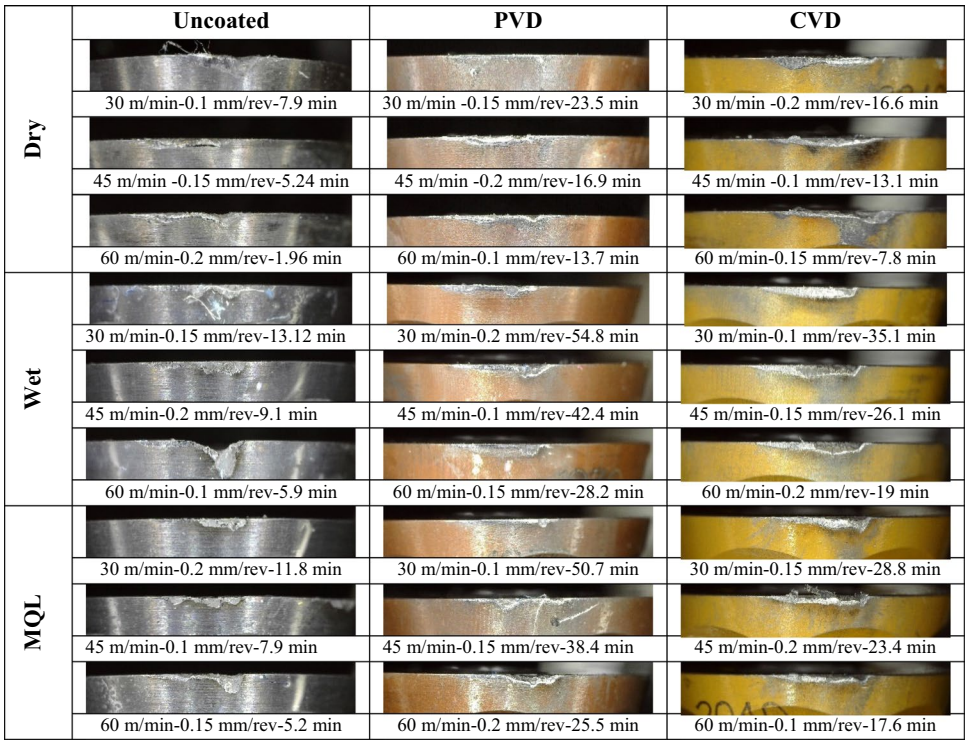


Fig. 6 Changes in the flank wear depending on coating type under dry cutting conditions (30 m/min and 0.1 mm/rev)

Fig. 5 Wear photographs of carbide inserts under different cutting conditions (50×)



order to better analyze the effect of the coating on wear. During the experiments, the machining time was kept constant at 7.9 min. However, with a time interval of 1.96 min, the quantity of wear on the cutting tool was measured via a digital microscope and recorded. The graph in Fig. 6 shows the wear changes due to the cutting tool type under dry cutting conditions. The graph shows that the PVD (TiAlN) coated tool gave the best performance among the three tools. At the end of 7.9 min of machining, the wear quantities were measured as 0.293 mm, 0.191 mm and 0.147 mm for uncoated, CVD- and PVD-coated tools, respectively. Based on these values, when compared to the uncoated tool, the PVD (TiAlN)- and CVD-coated tools provided improvements directed toward decreasing tool wear at the rate of 49.83% and 34.81%, respectively.

The SEM images of cutting tool wear in the machinability tests carried out under dry machining are given in Fig. 7, which shows that the wear occurred in the radius zone of the cutting edge nose of the three different tools and that abrasive and adhesive wear were the effective wear mechanisms. The abrasive properties of MC and M23C6 carbides in Waspaloy are effective in increasing wear. It is known that hard abrasive carbide particles in the superalloys cause abrasive wear with the chip flowing along the cutting edge with the effect of thermal and mechanical loads [27]. The chips which broke off from the workpiece during the chip removal process performed with the uncoated tool adhered to the surface of the tool during a certain cycle, extended and broke off after a certain time. These chip particles which adhered to the cutting tool material also broke off some of the tool material when the tool was withdrawn from the workpiece. The presence of workpiece material which had adhered in micro-dimensions can be detected in the SEM picture (Fig. 7a) of the uncoated tool. Additionally, these adhered particles were confirmed by EDX analysis (Table 6).

Table 6 shows the elements of Ni (54.50%), Cr (19.87%) and Co (13.64%) at Point 1, which correspond to the chemical content of Waspaloy (Table 1) and indicate the extent of the adherence. The high degree of ductility and flow resistance of the Waspaloy caused the material to adhere to the

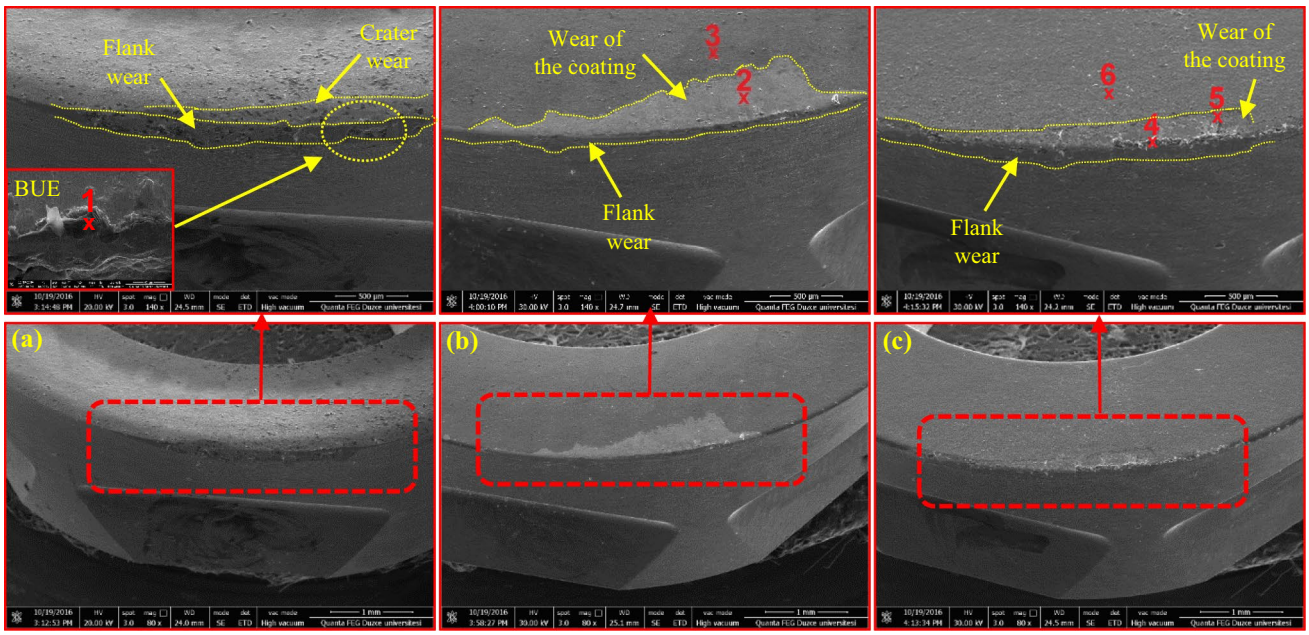


Fig. 7 Tool wear at feed rate $f = 0.1$ mm/rev, cutting speed $V = 30$ m/min and dry machining; **a** uncoated, **b** PVD coated, **c** CVD coated

Table 6 Chemical analysis of wear surfaces on WC inserts (Figs. 7 and 9)

Points	Ti	Cr	Co	Ni	W	C	Al	N	Units
Point 1	3.37	19.87	13.64	54.50	8.62	–	–	–	wt%
Point 2	1.25	5.48	9.30	12.30	53.95	17.73	–	–	wt%
Point 3	26.20	–	–	7.50	18.00	24.14	24.16	–	wt%
Point 4	26.06	0.18	0.71	0.30	1.34	41.69	29.72	–	wt%
Point 5	39.61	0.23	0.12	0.35	0.50	24.14	11.32	23.71	wt%
Point 6	2.55	15.00	10.29	40.36	6.68	23.92	1.21	–	wt%

cutting tool under the high temperature and pressure during machining. The movement of the chip along the chip side surfaces was limited because it could not progress efficiently in the cutting zone with the uncoated tools. Therefore, the wear value of the uncoated tools was higher than that of the coated tools [28]. In contrast to the uncoated tools, the SEM photographs of the PVD (TiAlN) and CVD ($TiCN + Al_2O_3 + TiN$) coated tools (Fig. 7b, c) show that the wear mechanism occurred in the form of flank wear rather than adhesive wear, as an effect of the coating properties. When the coated tools were compared to each other, the PVD (TiAlN) coated tools presented a lower, more controlled wear state since they had a sharper edge profile, a lower coefficient of friction and higher resistance to hardness and abrasion than the CVD ($TiCN + Al_2O_3 + TiN$) coated tools.

From the points given in the EDX analysis of the coated tools in Table 6 (Points 2–6), it can be seen at Point 2 that the surface of the PVD-coated tool was drawn apart from the tungsten at the rate of 53.92%, thus exposing the main material of the cutting tool. In addition, it was observed that at Point 3, the titanium was retained at the rate of 26.20% and the aluminum at the rate of 24.16%. At the points shown in the EDX analysis of the CVD-coated tool, it was observed that the surface coating was drawn apart at Point 4 and adhesion had occurred at the micro level, while the TiN in the coating surface was separated at Point 5 and the Al_2O_3 and the TiCN were retained. At Point 6, the coating had remained intact and abrasion had not reached the selected point in the EDX analysis. Moreover, crater wear had not occurred in the coated tools, whereas it could be observed in the uncoated tool (Fig. 7a). As a result of its low coefficient of friction, the coating reduced the friction at the tool–chip interface, thus reducing the heat buildup in the cutting zone. It is also thought that by increasing the hardness of the cutting tools, the coating was effective in increasing the hardness against the abrasive wear mechanism and in forming a barrier against the chemical affinity between the cutting tool and the workpiece.

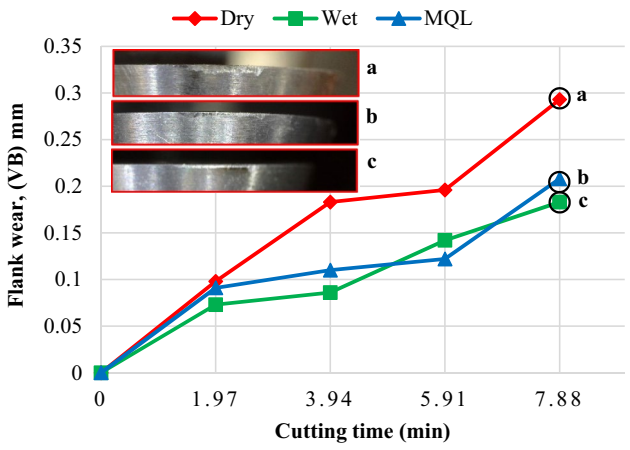


Fig. 8 Changes in the flank wear depending on cooling methods (uncoated insert, 30 m/min and 0.1 mm/rev)

The graph in Fig. 8 shows the effect of the cooling method on wear in the experiments carried out with the uncoated cutting tools. In the graphic, the highest wear value was found with dry machining and the lowest with wet machining. The amount of wear at the end of the 7.9-min machining was 0.293 mm with dry machining, whereas it was 0.183 mm with wet machining and 0.208 mm with machining using the MQL system. On the basis of these values, compared to the dry machining, tool wear reduction was provided by the wet machining at the rate of 37.54% and by machining with the MQL system at 29.01%. Thus, the wet machining and the machining with the MQL system have significantly reduced tool wear compared to dry machining. The main explanation for this could be that because of the low thermal conductivity of the superalloy materials, the high heat generated during cutting attempts to escape the cutting zone via the cutting tool, resulting in thermal destruction to the cutting tool. The use of cutting fluid both in the wet machining and in the machining with the MQL system significantly reduces this damage and thereby provides significant improvements against abrasion.

Figure 9 shows the SEM images of cutting tool wear resulting from the machinability tests carried out under dry machining using uncoated carbide tips. In the figure, it can be seen that the active tool wear for all three tools was regular flank wear, as well as built up edge (BUE) and crater wear (Fig. 9a). The BUE was formed when the chips broken off from the workpiece were welded to the cutting tool surface as an effect of the adhesive wear mechanism. The workpiece material adhering to the cutting tool surface was not fixed and broke off during cutting due to the high-pressure effect. Consequently, the life of the cutting tool was considerably reduced because pieces of the cutting tool were also broken off at the same time. This could explain the BUE formation and high wear value which occurred under the dry machining. No BUE was observed with the wet machining or machining under the MQL system. This shows the effect of cooling and lubrication on BUE formation. However, there was some crater wear during both dry machining and machining with the MQL system (Fig. 9a, c).

Crater wear is a type of wear associated with the diffusion wear mechanism, which is seen extensively at high temperatures and high cutting speeds [29]. As a result of the close contact between the tool, the chip and the workpiece under conditions of extreme heat, the diffusion process accelerates and at the end, a crater is formed on the cutting tip surface. Notch wear was observed along with the flank wear in the chip removal process performed under wet machining (Fig. 9b). Notch wear is a type of wear seen frequently

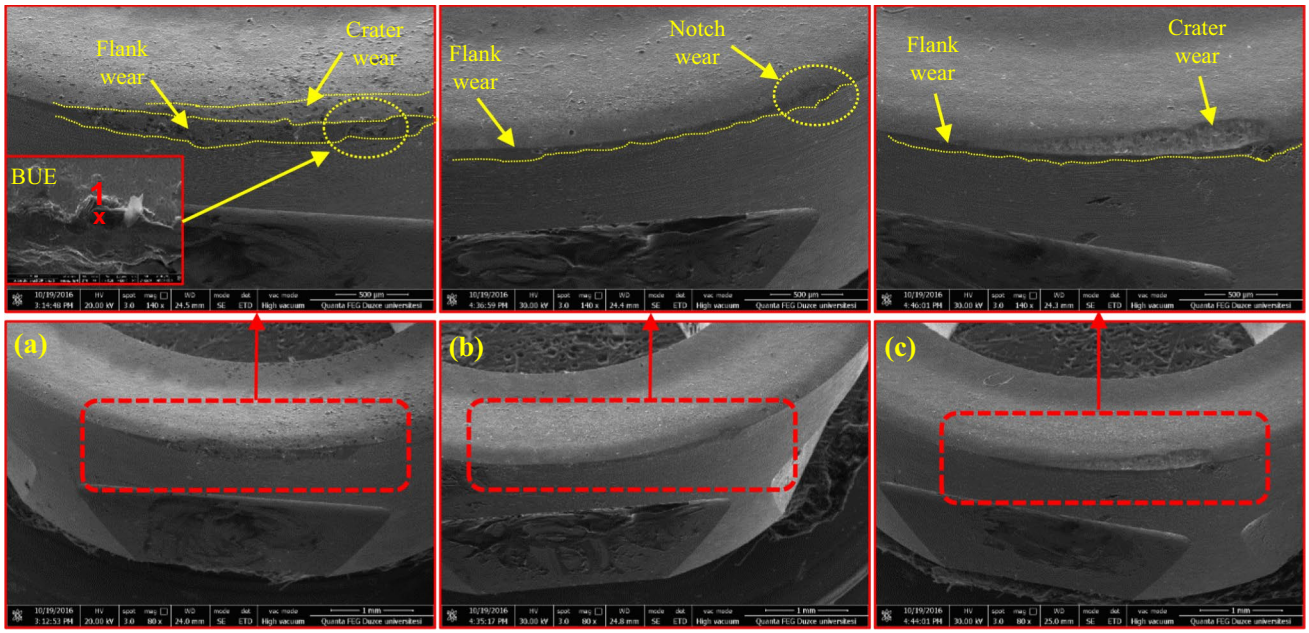


Fig. 9 Tool wear at feed rate $f = 0.1$, cutting speed $V = 30$ m/min and uncoated insert; **a** dry, **b** wet and **c** MQL

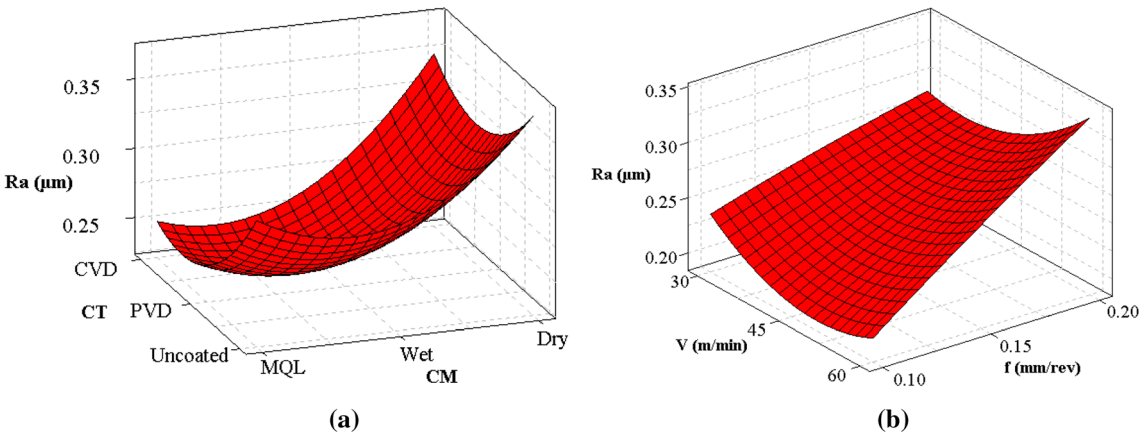


Fig. 10 3D surface plots for effects of **a** coating type and cooling method; **b** cutting speed and feed rate on surface roughness (Ra)

in superalloys, such as nickel-based superalloys, which have high hot hardness values when machined with round geometric cutters [30]. This characteristic feature of nickel-based superalloys is also the main cause of notch wear.

4.4 Experimental Results for Surface Roughness

It is an important process widely used in various sectors such as surface treatment, automobile, aviation and mold/mold industries. [31]. The 3D surface graphic in Fig. 10 shows the changes in surface roughness depending on the input parameters. The cooling/lubrication method which gave the best surface roughness was wet machining (Fig. 10a), while the cutting tool with the lowest surface roughness value was the PVD (TiAlN)-coated tool. During the machining of nickel-based superalloys such as Waspaloy, the low thermal diffusion powers of the uncoated tools cause the cutting temperatures to concentrate at the tool tip. The formation of BUE–adhesion, resulting from the particles breaking loose from the workpiece and welding to the cutting tool, causes the surface to deteriorate [32]. The PVD (TiAlN)-coated carbide tool prevented BUE formation due to its stiffness and low coefficient of friction and thus performed better. Cutting fluids reduce or completely prevent the damage caused by high heat as their physical and chemical properties reduce

the generation of heat during the chip removal process. For this reason, they have an important role in improving machined surface quality [8].

The section showing the relation between the cutting tool type and the cutting speed in Fig. 10b shows that the surface roughness was improved at one point with the increase in the cutting speed; however, the improvement line for surface roughness turned in the negative direction with continued increase in the cutting speed. This can be explained by the rising temperature in the cutting zone accompanying the increased cutting speed. The plastic deformation is easily seen in the first deformation zone, and the flow and shaping of the chip can be easily seen in the second deformation zone. The section in Fig. 10b shows the correlation between the surface roughness, and the feed rate indicates that the best surface roughness value was achieved at a 0.1 mm/rev feed rate and that the surface roughness value increased together with the feed rate. Increasing the feed rate has a negative effect on the surface roughness inasmuch as it causes a high force of feed rate, low angle of shear and increase in removed chip volume. The previous studies have shown that the most effective parameters on surface roughness are the feed rate and the radius of the cutting tool nose [33].

4.5 Characterization of the Machined Surface

In this part of the study, the aim was to examine the effect of the coating type and the cooling–lubrication method on surface roughness. To this purpose, the cutting speed and the feed rate were kept constant at 30 m/min and 0.1 mm/rev, respectively. The dry machining, which was expected to exhibit the most noticeable difference during these experiments, was selected. Knowing the tops and bottoms of the machined surfaces and determining the surface quality parameters are also possible. In general, the surface topography gives an important idea about tribological behavior. For this reason, topographical graphs were drawn of the surfaces obtained by the experiments (Fig. 11). Figure 11 shows the surface roughness changes with the different coatings of the cutting tools.

The best surface was that obtained with the PVD (TiAlN)-coated tools (Fig. 11b), while the highest surface roughness value was obtained with the uncoated tools (Fig. 11a). The main cause of this difference was believed to be the change in the wear initiation process in the cutting tools; as the wear deepened, the fluctuations on the surfaces increased. It can be assumed that the BUE formation occurring due to the adhesion of the uncoated tool had reduced the surface

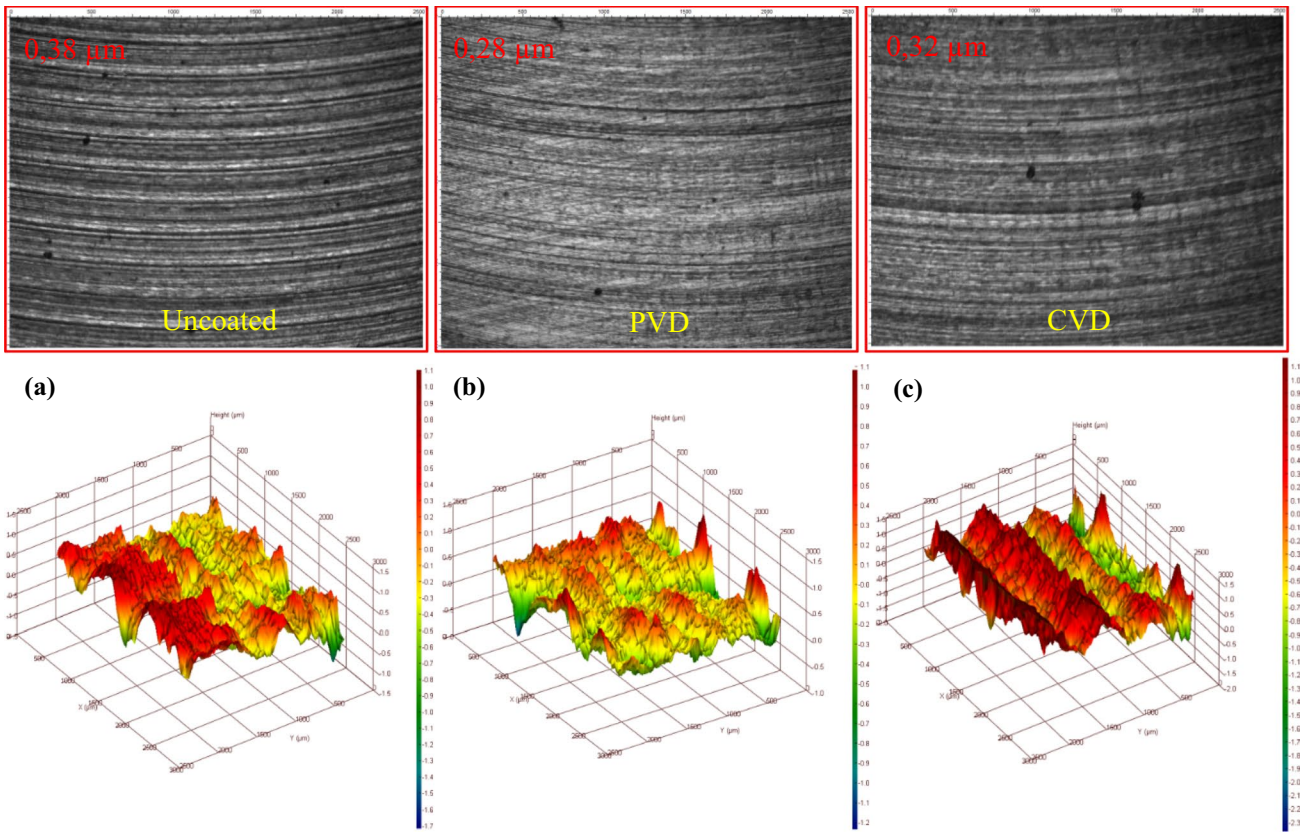


Fig. 11 Topographical graphs of the machined surfaces under dry machining **a** uncoated, **b** PVD coated and **c** CVD coated

quality, while in the coated tool, the reduced adhesion tendency was effective to a great extent in improving the surface quality. This was confirmed by the 3D topography map of the surface machined with the uncoated tool and by the noticeable machining marks on the 2D surface photograph (Fig. 11a).

Cutting tools that are more resistant to abrasion due to coatings also cause significant changes in the quality of the machined surface. The TiAlN coating showed more resistance to wear due to its low coefficient of friction, thermal stability and high hardness, all of which constituted the main reason for the better surface quality. This was confirmed by the 3D topography map showing the result of the surface roughness test with the TiAlN-coated tools in which the indentations and protrusions are fewer than with the others. This finding was also corroborated by the 2D surface photograph showing fewer machining traces than in the others (Fig. 11b). The PVD (TiAlN) coating provided an improvement of 26.32% in the surface roughness value compared to the uncoated tool, while the CVD ($TiCN + Al_2O_3 + TiN$) coating provided an improvement at the rate of 15.79%.

The 2D and 3D topographic maps of the surfaces from the machinability experiments carried out using the uncoated carbide tool under dry machining, wet machining and the MQL system are given in Fig. 12. The uncoated carbide tool was chosen as it was expected to yield the most noticeable differences during experiments in which the cooling–lubrication method effects on the surface roughness were investigated. The figure shows that the best surface roughness was obtained under wet machining (Fig. 12b). In the dry machining (Fig. 12a), the BUE occurring along with chip adhesion during the cutting caused wear to the cutting tool, thus negatively affecting the surface quality. In the wet machining and the machining with the MQL system (Fig. 12a, b), the use of cutting fluid led to significant reduction in cutting tool wear and, in parallel with this, the surface roughness decreased. This also corresponded to the 3D topography of the machined surfaces and the machining traces in the 2D surface photographs. The wet machining provided an improvement of 34.21% compared to the dry machining, while the MQL system provided a 21.05% improvement.

4.6 ANOVA Results

The ANOVA results of the tool life and surface roughness tests are given in Table 7, which shows that the contribution percentages of the factors A, B, C and D on tool life were 54.4%, 19.4%, 14.9% and 0.4%, respectively, and their contribution percentages on the surface roughness were 12.2%, 31.2%, 4.0% and 34.4%, respectively. With the information from this data, the most significant factor that affects tool life was the cutting tool coating type (A), while the most important parameter affecting the surface roughness was the

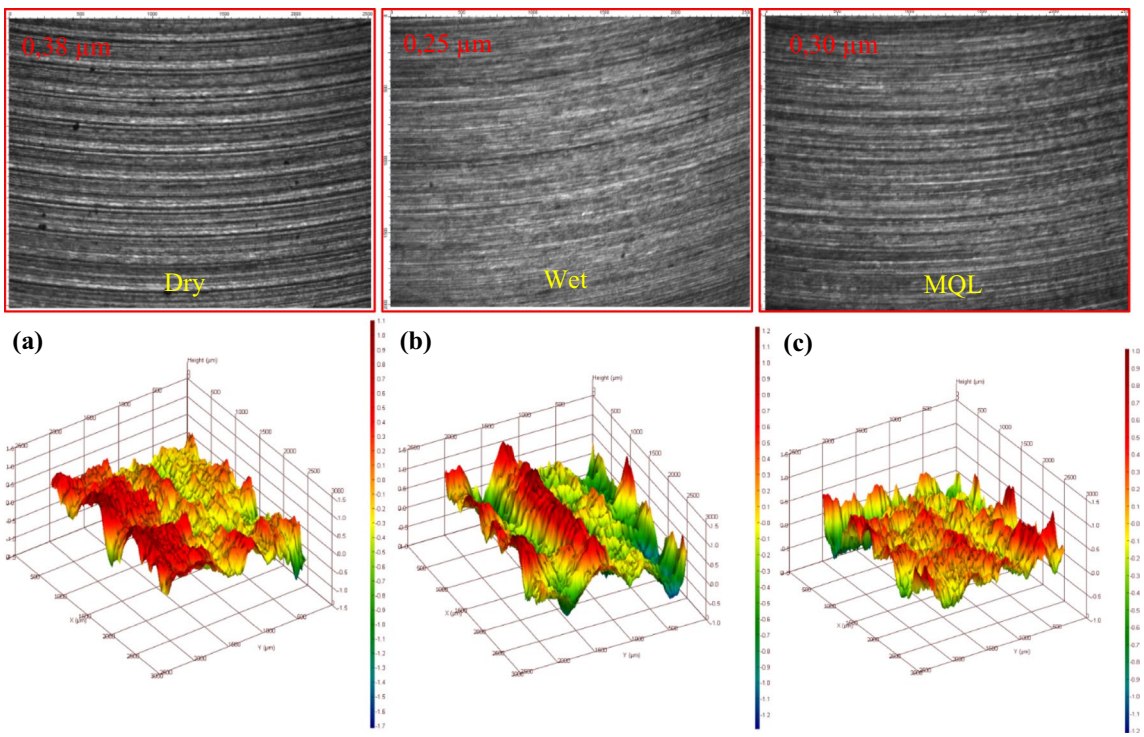


Fig. 12 Topographical graphs of the machined surfaces with uncoated insert; **a** dry, **b** wet and **c** MQL

Table 7 ANOVA results

Source	Degree of freedom	Sum of squares	Mean squares	*F* ratio	*P* ratio	Contribution rate (%)
Tool life						
A	2	2840.08	1420.04	44.94	0.000	54.4
B	2	1009.53	504.76	15.97	0.000	19.4
C	2	776.57	383.29	12.13	0.000	14.9
D	2	20.79	10.40	0.33	0.724	0.4
Error	18	568.77	31.60	–	–	10.9
Total	26	5205.73	–	–	–	100
Surface roughness						
A	2	0.014	0.0071	6.06	0.010	12.2
B	2	0.036	0.018	15.48	0.000	31.2
C	2	0.0047	0.0024	2.01	0.163	4.0
D	2	0.040	0.020	17.10	0.000	34.4
Error	18	0.021	0.0012	–	–	18.1
Total	26	0.11	–	–	–	100

feed rate (D), with an error rate for tool life of 10.9% and for surface roughness of 18.1%.

4.7 Regression Analysis Via Experimental Results

In this study, 27 tool life and surface roughness values obtained from the experiments were used for regression analysis in Minitab software. The regression equations were generated based on the CT, CM, V and f parameters depending on the control levels. Only the linear equations generated with the key effects of the control factors are shown in Eq. (3) for tool life and in Eq. (4) for surface roughness.

$$\mathrm{Tl} = 17.8 + 6.63\mathrm{CT} + 5.7\mathrm{CM} - 0.435V - 16.9f \tag{3}$$

$$\mathrm{Ra} = 0.2665 - 0.0211\mathrm{CT} - 0.378\mathrm{CM} + 0.000444V + 0.0944f \tag{4}$$

The coefficient of determination (R^2) of the obtained linear equations was calculated as 0.410 for tool life and as 0.640 for surface roughness. The differences between the predicted tool life and surface roughness obtained with the first-degree equations at 95% confidence level, and the tool life and surface roughness values found from the experimental studies were both high. Consequently, equations involving factorial interactions were developed. Thus, Eq. (5) represents the tool life and Eq. (6) represents the surface roughness.

$$\begin{aligned}\mathrm{Tl} = {} & -67.3 + 81.6\mathrm{CT} + 43.9\mathrm{CM} - 0.39V - 175f \\ & - 18.48\mathrm{CT}^2 - 8.41\mathrm{CM}^2 + 0.0005V^2 + 459f^2 \\ & + 1.56CT * \mathrm{CM} - 0.073\mathrm{CT} * V - 5.9\mathrm{CT} * f \\ & - 0.098\mathrm{CM} * V - 21.6\mathrm{CM} * f + 1.68V * f\end{aligned} \tag{5}$$

$$\begin{aligned}\mathrm{Ra} = {} & 1.12 - 0.204\mathrm{CT} - 0.24\mathrm{CM} - 0.018V - 0.71f \\ & + 0.032\mathrm{CT}^2 + 0.042\mathrm{CM}^2 + 0.000114012V^2 \\ & - 1.11f^2 - 0.0113\mathrm{CT} * \mathrm{CM} + 0.0006521\mathrm{CT} * V \\ & + 0.03161CT * f + 0.0012\mathrm{CM} * V + 0.018\mathrm{CM} * f \\ & + 0.02933V * f\end{aligned} \tag{6}$$

The coefficient of determination (R^2) for these equations was 0.915 for tool life and 0.948 for surface roughness. The estimated tool life and surface roughness values obtained via linear, quadratic and Taguchi methods at the 95% confidence level and the tool life and surface roughness results obtained from the experimental study and are given and compared in Fig. 13. The closest predictive equation to real values was the equation for the main effects and interactions.

4.8 Optimization

At the end of the milling experiments, the parameter combinations giving the best tool life and lowest surface roughness were found to be $A_2B_2C_1D_1$ and $A_2B_2C_2D_1$, respectively. Equation (7) was used in guessing optimum tool life, and Eq. (8) was used in predicting the optimal surface roughness.

$$\mathrm{Tl}_{\mathrm{opt}} = \left(A_2 - T_{\mathrm{Tl}}\right) + \left(B_2 - T_{\mathrm{Tl}}\right) + \left(C_1 - T_{Tl}\right) + \left(D_1 - T_{\mathrm{Tl}}\right) + T_{\mathrm{Tl}} \tag{7}$$

$$\mathrm{Ra}_{\mathrm{opt}} = \left(A_2 - T_{\mathrm{Ra}}\right) + \left(B_2 - T_{\mathrm{Ra}}\right) + \left(C_2 - T_{\mathrm{Ra}}\right) + \left(D_1 - T_{\mathrm{Ra}}\right) + T_{\mathrm{Ra}} \tag{8}$$

Here, (A_2, B_2, C_1, D_1) and (A_2, B_2, C_2, D_1) represent the optimum level average values of tool life ($\mathrm{Tl}_{\mathrm{opt}}$) and surface roughness ($\mathrm{Ra}_{\mathrm{opt}}$), respectively (Table 3). The T_{Tl} and T_{Ra} state the average of all of the Tl and Ra values obtained

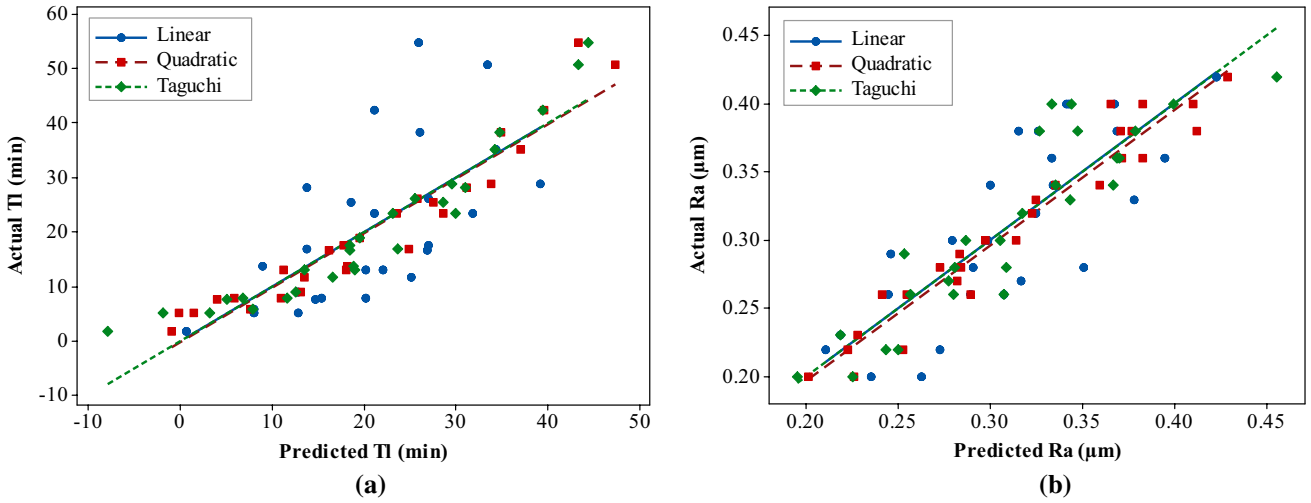


Fig. 13 Comparing of the regression models with results from the experiment

Table 8 Mean response table

Levels	Control factors							
	Tool life (Tl)				Surface roughness (Ra)			
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*
Level 1	7.569	11.856	26.924	21.589	0.3422	0.3622	0.3122	0.2622
Level 2	32.678	25.969	20.282	19.596	0.2889	0.2822	0.2933	0.3122
Level 3	20.833	23.256	13.873	19.896	0.3000	0.2867	0.3256	0.3567
Delta	25.109	14.113	13.051	1.993	0.0533	0.0800	0.0322	0.0944

from the experimental study (Table 8). From the results of the calculations, the Tl_{opt} value was 46.08 min and the Ra_{opt} value to be 0.1966 µm.

Whether the system had realized the optimization accurately enough needed to be evaluated. For this purpose, the CI was calculated by Eqs. (9) and (10) in order to confirm the satisfactory accuracy of the optimization. [24].

$$CI_T = \sqrt{F_{\alpha,1,f_e} V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{9}$$

Here, the 95% reliability ratio is F_α, the level of significance is α, the degree of freedom of the error is f_e, the error distribution is V_e, n_{eff} is the number of repetitive activities, and the number of replications of the validation tests are R.

$$n_{eff} = \frac{N}{1 + T_{dof}} \tag{10}$$

Here, the total number of experiments are N and the total of main factors of the degree of freedom is T_{dof}; $F_{0.05,\ 1,\ 18} = 4.4139$; for tool life, $V = 31.60$; for surface roughness, $V = 0.0012$ (Table 7); $R = 2$ (Eq. 9) and $N = 27$; $T_{dof} = 8$ and $n_{eff\ =}\ 3$ (Eq. 10). By substituting the values obtained in Eqs. (9) and (10), the confidence interval was found as $CI_{Tl} = \pm 10.79$ for the tool life experiments and as $CI_{Ra} = \pm 0.07$ for the surface roughness. The estimated tool life and surface roughness value were at 95% confidence interval.

$$\left[Tl_{opt} - CI_{Tl}\right] < Tl_T < \left[Tl_{opt} + CI_{Tl}\right] \tag{11}$$

$$\left[Ra_{opt} - CI_{Ra}\right] < Ra_T < \left[Ra_{opt} + CI_{Ra}\right] \tag{12}$$

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

$$[46.08 - 10.79] < 56.8 < [46.08 + 10.79] = 35.29 < 56.8 < 56.87$$

and the surface roughness was:

$$[0.1966 - 0.07] < 0.20 < [0.1966 + 0.07] = 0.1266 < 0.20 < 0.2666$$

The experimentally obtained tool life and surface roughness values were in confidence interval limits. Hence, we reach the system optimization at the level of 0.05 significance via the Taguchi method.

Table 9 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									
$A_2B_2C_1D_1$ *(optimum)*	56.8	67.22	18.34	56.8	59.30	4.40	56.8	63.85	12.41
$A_2B_1C_3D_1$ *(random)*	13.7	8.97	34.52	13.7	18.18	37.22	13.7	18.92	38.10
$A_3B_1C_2D_1$ *(random)*	13.1	22.13	68.93	13.1	11.27	13.97	13.1	13.48	2.90
Surface roughness									
$A_2B_2C_2D_1$ *(optimum)*	0.20	0.18	10	0.20	0.20	0.00	0.20	0.20	0.00
$A_1B_3C_1D_3$ *(random)*	0.34	0.16	52.94	0.34	0.34	0.00	0.34	0.37	8.82
$A_3B_1C_2D_1$ *(random)*	0.30	0.19	36.67	0.30	0.30	0.00	0.30	0.29	3.33

4.9 Verification Experiments

In this section, three validation studies were performed to verify the accuracy of the developed models. The test conditions for the confirmation test were selected to be within the predetermined levels range. Confirmation tests for the optimum and randomly selected levels were performed for control factors. The predicted values and the measured experimental values were compared. A comparison of the experimental results with the predicted values is shown in Table 9. Comparison results from evidence that predicted values for each response value are close to experimentally obtained values. Specifically, the error percentage for the quadratic equation is within the allowed limits. Thus, the mathematical models can be successfully use to predict the tool life and surface roughness values for any combination of the cutting tool, cooling method, cutting speed and feed rate within the range of the performed experimentation.

5 Conclusions

In this study, the effects of the cooling/lubrication method and cutting parameters on tool life, wear mechanisms and surface roughness were investigated in the milling of Ni-based Waspaloy superalloy. The following conclusions can be drawn from this study:

- The optimum machining parameters for tool life and surface roughness were found to be $A_2B_2C_1D_1$ (PVD coating, wet machining, 30 m/min cutting speed and 0.1 mm/rev feed rate) and $A_2B_2C_2D_1$ (PVD coating, wet machining, 45 m/min cutting speed and 0.1 mm/rev feed rate), respectively.
- The highest wear value was obtained by the uncoated tool, while the lowest wear value was that of the PVD (TiAlN)-coated tool. In terms of tool wear, the PVD (TiAlN)- and CVD-coated tools provided improvement rates of 49.83% and 34.81%, respectively, in comparison with the uncoated tool. For surface roughness, when compared to the uncoated tool, the PVD (TiAlN) coating provided an improvement rate of 26.32% and the CVD ($TiCN + Al_2O_3 + TiN$) coating an improvement rate of 15.79%.
- The highest wear value was produced with the dry machining, whereas the lowest value was found with the wet machining. In terms of tool wear, the wet machining and MQL system provided improvement rates of 37.54% and 29.01%, respectively, in comparison with the dry machining. For surface roughness, when compared to the dry machining, the wet machining and the MQL showed improvement rates of 34.21% and 21.05%, respectively.
- Although the best results for cooling/lubrication were achieved by wet machining, the results of the machining with MQL were very close to those of the wet machining. Thus, considering production costs, the environment and employee health, the MQL system is recommended in the milling of Waspaloy.
- According to the results of the tool wear mechanism analysis, the dominant type of wear was flank wear, followed by BUE, crater wear and notch wear.

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