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EFFECT OF THE MQL TECHNIQUE ON CUTTING FORCE AND SURFACE QUALITY DURING THE SLOT MILLING OF TITANIUM ALLOY

VPLIV TEHNIKE MQL NA SILO REZANJA IN KVALITETO POVRŠINE MED REZKANJEM UTOROV NA TITANOVI ZLITINI

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In this study, the effects of four control parameters, i.e., the cutting speed (v_c), feed per tooth (f), depth of cut (a_p), and flow rate of the cutting fluid (Q), on the surface roughness (R_a) and cutting force (F_c) were investigated in the slot milling of titanium alloys (Ti-6Al-4V). The effects of the control parameters were determined by a statistical analysis. In addition, RSM models for R_a and F_c during machining under three cooling/lubrication conditions, i.e., dry, flood, and minimum quantity lubrication (MQL), were obtained. The results revealed that both R_a and F_c are sensitive to changes in f, a_p and Q. It was found that the MQL condition generates lower values of R_a where the surface roughness value is 0.227 µm. By contrast, F_c values under the MQL condition were close to those of the flood condition and at times even better. The machining performance at a cutting-fluid flow rate of 36 mL/h under the MQL condition was found to be the best under certain machining conditions. MQL was found to be an effective alternative technique for conventional conditions when machining Ti-6Al-4V.

Keywords: sustainable manufacturing, titanium, milling, minimum quantity lubrication

V tem članku avtorji opisujejo raziskavo vpliva štirih kontrolnih parametrov; to je: hitrosti rezanja (v_c), koraka podajanja na posamezni utor (f), globine reza (a_p) in pretoka maziva (Q) na hrapavost površine (R_a) in silo rezanja (F_c) med rezkanjem utorov na titanovi zlitini vrste Ti-6Al-4V. Vpliv kontrolnih parametrov so avtorji določili s pomočjo statistične analize. Na ta način so s pomočjo modelov RSM (angl.: Response Surface Methodology) dodatno dobili vrednosti za R_a in F_c med mehansko obdelavo pri treh različnih pogojih ohlajanja oziroma mazanja. Ti pogoji so bili: na suho oz. brez dodajanja maziva, intenzivno oz. močno (obdelovanec je potopljen v mazivo) in z minimalno količino maziva (angl.: minimum quantity lubrication (MQL)). Rezultati raziskav so pokazali, da sta R_a in F_c občutljiva na spremembe vseh kontrolnih parametrov f, a_p in Q. Avtorji ugotavljajo, da pri preizkusnih pogojih z MQL dobijo manjšo vrednost površinske hrapavosti (R_a = 0,227 µm). Medtem, ko so bile vrednosti za sile rezanja F_c pri MQL podobne tistim, ki so jih dobili pri intenzivnem mazanju oz. v nekaterih primerih celo manjše. Na osnovi izvedenih preizkusov in raziskav avtorji ugotavljajo, da so dosegli najboljše pogoje rezkanja utorov na izbrani Ti zlitini pri MQL oz. hitrosti pretoka maziva 36 mL/h. Ugotavljajo da je MQL učinkovita alternativna tehnika mazanja konvencionalnim pogojem mazanja med mehansko obdelavo zlitine tipa Ti-6Al-4V.

Ključne besede: trajnostna proizvodnja, titan, rezkanje, minimalna količina maziva (MQL)

1 INTRODUCTION

In the field of machining, there is a recent trend toward making machining processes eco-friendly. In this regard, numerous effective strategies have been proposed as alternatives to cutting fluids, including minimum quantity lubrication (MQL), a technique regarded as both economically and environmentally friendly.[1] During machining, large quantities of cutting fluids are supplied to the contact zone between the cutting tool and the workpiece to avoid thermal damage.[2] However, the cost of the cutting fluids relative to the overall manufacturing cost is high. In addition, cutting fluids can have unhealthy impacts on workers and the surrounding environment.[3,4] Therefore, to counter these effects, many sustainable technologies have recently been developed to supply cutting fluids during the machining process using less or no cutting fluids. One of the interesting sustainable technologies is minimum quantity lubrication (MQL), which is considered economically and environmentally friendly.[5–7] MQL consists of a mixture of pressurized air and oil micro droplets applied directly to the cutting zone.[8,9] **Table 1** classifies the flow rates of the cutting fluids applied with the MQL technique.

According to the literature, the MQL technique appears to provide good results and is a promising alternative to conventional cooling and lubricating methods.[15–17] In this context, many researchers have studied the effects of utilizing MQL under various machining processes. In line with these initiatives, Joshi et al.[18] turned an Incoloy

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Table 1: Different ranges for flow rate of air-fluid mixture reported in the literature

References	Flow-rate ranges
10	2–300 mL/h
11, 12	10–100 mL/h
13	50–500 mL/h
14	less than or equal to 1 mL/h

800 alloy using three different lubrication conditions: flood, dry and MQL. Their results revealed that the lowest surface roughness (R_a) and tool wear occured when machining under MQL cooling conditions. Similar results achieved by[19–21] revealed that under MQL conditions, all the values related to the cutting forces (F_c), surface roughness and tool tip temperature were significantly lower than those of the flood condition. J. Sun et al.[22] conducted a milling process on a Ti-6Al-4V titanium alloy with carbide tools under MQL, dry, and flood coolant conditions. This study demonstrated that MQL could be effectively used as a coolant method in end-milling. New advances in cooling techniques along with developments in cutting-fluid types aim at improved machining productivity based on sustainability. Yet, they require predictive models for performance machining processes to create new techniques at low cost.[23] The predictive model helps to clarify the relationship between the quality response and the control parameters. It also includes optimal cutting conditions, coolant or lubricant types, and cutting tools.[24–27] In **Table 2**, a summary of key studies are provided.

Table 2: Literature survey using RSM with MQL technique when machining titanium alloy

ref.	material	machining process	RSM	control parameters	response
28	stainless steel 304	turning	CCD[1)]	v_c f a_p	R_a
29	Cu alloy C360	milling	CCD	v_c f	R_a, machining time
30	Ti alloy Ti-6Al-4V	milling	CCD	v_c f a_p	R_a
31	Ti alloy Ti-6Al-4V	turning	CCD	v_c f a_p	R_a, F_c
32	Ti Grade 2	turning	BB[2)]	v_c f Type of nanofluids	R_a
33	Ti alloy Ti-6Al-4V	milling	CCD	v_c f a_p	power consumption, material removal rate, R_a, tool wear
34	Ti Grade 2	turning	BB	v_c f approach angle	F_c, R_a, tool wear

1) CCD – Central Composite Design
2) BB – Box-Behbkens

2 EXPERIMENTAL PART

2.1 Machine tool, workpiece material and cutting tool

All of the slot-milling experiments were carried out on a three-axis CNC milling machine (VMC 550 JOHNFORD) with a maximum spindle rotation of 8000 min^{-1}. Machining tests were conducted using coated cementite carbide (coated Al-Cr-Ni). The cutting-tool diameter is 10 mm with a flat-end mill and four teeth. In all experiments, the titanium alloy Ti-6Al-4V (grade 5) was used as the workpiece material, together with a nozzle setup, as shown schematically in **Figure 1**. Meanwhile, **Figure 2** shows the experimental setup. Before the experiment, each surface of the test workpieces was machined by face milling at a 1.5-mm thickness. In these experiments, six slots were made along the workpiece block on each surface under different cooling conditions. **Table 3** and **Table 4** list the level parameters and experimental parameters used, respectively.

To measure the machining forces during slot milling, blocks of the titanium alloy Ti-6Al-4V workpiece were

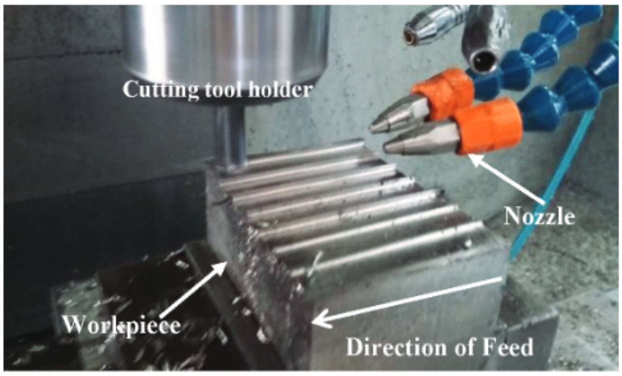


Figure 1: Slot milling with MQL technique

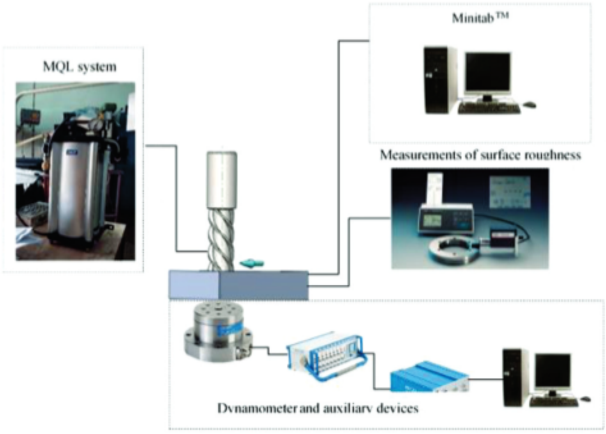


Figure 2: Experimental setup for output measurement and data analysis

mounted and fixed on a three-axis dynamometer (Kistler 9272-A) under the blocks. The setup was arranged for a cutting-force measurement, including a charge amplifier, and was transferred to a PC through the DynoWare software to obtain the values of the real cutting force (F_x, F_y, F_z) and conduct a computational analysis of the signal trends in the slot milling experiments. The mean cutting force (F_c) can be calculated by Equation (1):

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

Measurements of the surface roughness were performed with a Mahr M1 perthometer.

Table 3: Parameters and levels

factor	levels				
v_c/(m/min)	56.835	60	65	70	73.165
f/(mm/tooth)	0.010505	0.02	0.035	0.05	0.059495
a_p /mm	0.6835	1	1.5	2	2.3165
Q/(mL/h)	18.8855	23	29.5	36	40.1145
Coding	–1.633	–1	0	1	1.633

Table 4: Experimental parameters used

machining type	Slot Milling
materials	Ti-6Al-4V
cutting tool	coated cementite carbide (coated Al Cr × Ni)
machining parameters	feed rate: (0.02; 0.03; 0.04; 0.05) mm/tooth
	cutting speed: (50; 60; 70) m/min
	radial depth of cut: 10 mm
	axial depth of cut: (1; 2; 3) mm
cooling technique	flood, dry and MQL
MQL	cutting-fluid type: fetty acid ester
	cutting-fluid flow rate: (18; 29.5; 36; 40) mL/h
	compressed-air pressure: 3 bar

3 RESULTS AND DISCUSSION

3.1 Residual analysis of responses under MQL condition

Residual plots are important tools for evaluating the adequacy of regression models.[16–36] In general, there are four types of plot: normal probability plot, residual-vs.-fitted plot, residual histogram plot, and residual-vs.-observation-order plot.

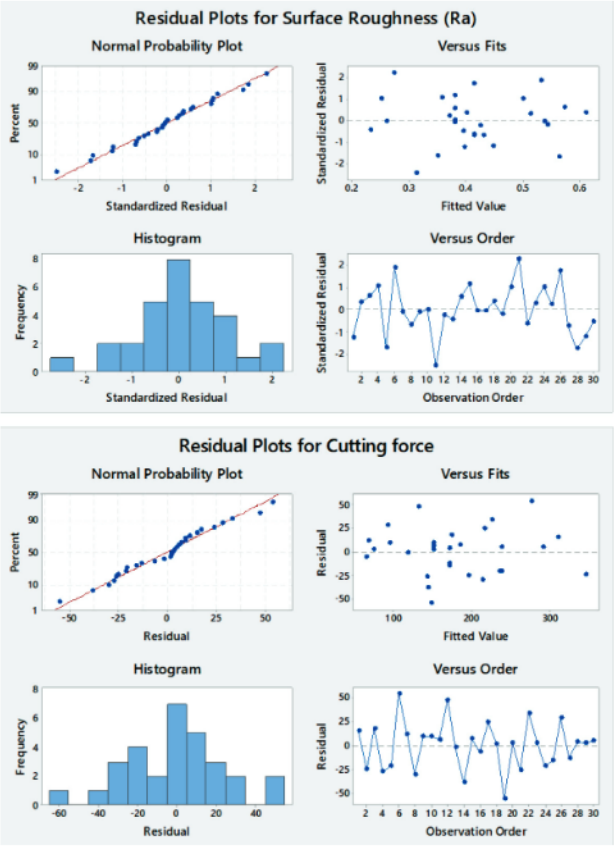


Figure 3: Residual analysis of MQL conditions

Table 5: Analysis of variance (ANOVA) considering F_c values

	flood			dry			MQL		
Source	F-Value	P-Value	Contribution	F-Value	P-Value	Contribution	F-Value	P-Value	Contribution
Model	28.80	0.000	96.97 %	8.87	0.002	90.79 %	7.88	0.000	89.41 %
linear	86.34	0.000	87.20 %	20.32	0.000	62.38 %	25.32	0.000	76.62 %
v_c/(m/min)	0.10	0.757	0.03 %	1.52	0.248	1.56 %	1.55	0.234	1.17 %
f/(mm/tooth)	70.03	0.000	23.58 %	26.87	0.001	27.50 %	43.45	0.000	32.88 %
a_p/mm	188.89	0.000	63.59 %	32.55	0.000	33.32 %	23.17	0.000	17.53 %
Q/(mL/h)	———	———	———	———	———	———	33.10	0.000	25.04 %
S	15.355			37.345			35.212		
R-squared	96.97 %			90.79 %			89.41 %		
Adj R-squared	93.60 %			80.56 %			78.00 %		

Regression models for F_c:
$F_{c\ \mathrm{DRY}} = 5745 – 180.7 \cdot v_c + 14737 \cdot f – 281 \cdot a_p + 1.488 \cdot v_c^2 + 81668 \cdot f^2 + 133.4 \cdot a_p^2 – 276 \cdot v_c \cdot f – 0.41\ v_c \cdot a_p + 671 \cdot f \cdot a_p$
$F_{c\ \mathrm{FLOOD}} = –992 + 26.2 \cdot v_c + 2262 \cdot f + 180 \cdot a_p – 0.173 \cdot v_c^2 – 51692 \cdot f^2 + 13.2 \cdot a_p^2 + 5.6 \cdot v_c \cdot f – 2.79 \cdot v_c \cdot a_p + 2225 \cdot f \cdot a_p$
$F_{c\ \mathrm{MQL}} = 2574 – 74.5 \cdot v_c – 3241 \cdot f – 128 \cdot a_p + 5.7\ Q + 0.602 \cdot v_c^2 – 24353 \cdot f^2 + 91.3 \cdot a_p^2 – 0.066 \cdot Q^2 + 154 \cdot v_c \cdot f – 2.77 \cdot v_c \cdot a_p – 0.105 \cdot v_c \cdot Q + 1468 \cdot f \cdot a_p – 133.4 \cdot f \cdot Q + 1.92 \cdot a_p \cdot Q$

The residual plot for all responses under various cooling/lubrication conditions is shown in **Figure 3**. According to the normal probability plot, the points of the data are in good arrangement on a straight line; therefore, the normality assumptions are valid. The residuals-vs.-experiment data are spread up and down the zero line. Upon examination of all the residual and probability graphs, it was concluded that the models are capable of accurately estimating R_a and F_c for different cooling conditions. The residual-vs.-fitted plots for R_a and F_c revealed that the data points are randomly scattered; as a result, the assumption of constant variance is correct.

3.2 Cutting force (F_c)

A statistical analysis of the data was carried out in the form of a variance analysis using MINITAB™ 17 software. Per the ANOVA results, it is noticeable from **Table 5**, depending on the p-value, that the feed per tooth, depth of cut and cutting fluid flow rate are statistically significant ($p < 0.005$). In addition, the F-value statistics report the same result and contribution value. The feed per tooth and depth of cut were the most effective factors in the cutting force under flood and dry conditions. However, under MQL conditions, the feed per tooth and cutting fluid flow rate were the most effective factors.

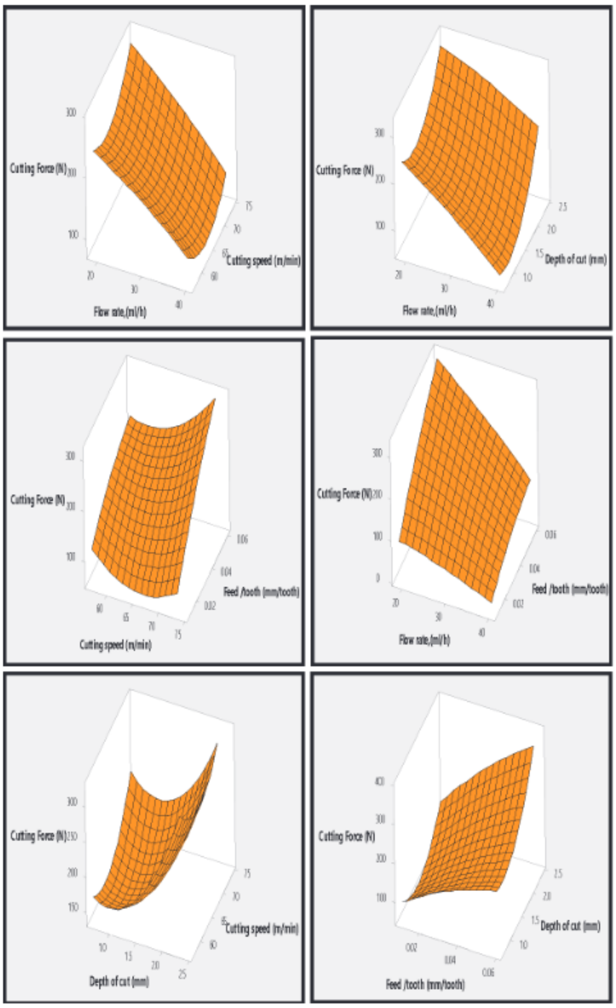


Figure 4: Cutting-force results for MQL condition

The cutting-zone temperature (tool-chip interface) rises to the softening temperature of the titanium alloy, increasing the material removal rate and decreasing the thickness of the chip. Similar effects during the milling of titanium alloy were found in other studies.[31–36] In **Figure 4**, a general trend can be noticed: the F_c increased with an increasing feed per tooth and depth of cutting. In addition, at low machining conditions, F_c was reduced under both MQL and flood conditions. However, F_c increased again when the feed per tooth increased from 0.02 mm/tooth to 0.05 mm/tooth and the cutting depth rose from 1 mm to 2 mm. With the feed per tooth increasing from 0.02 to 0.05 mm/tooth, the material-removed rate also increased. Under such conditions, the cutting tool has to undergo a considerable cutting load, thus generating a high cutting temperature and possibly affecting the physical properties of the cutting tool.[20–37] The outcome is an increased mean F_c for all levels of feed per tooth. More specifically, the maximum values of F_c under dry, flood, and MQL conditions were about (403.25; 287.82; 330.08) N, respectively, and the minimum values of F_c were about (99.71; 54.30; 58.39) N, respectively.

Figure 5 depicts the F_c under different machining conditions. Accordingly, dry conditions produced the highest F_c for all machining conditions. However, the F_c values were equally acceptable under the MQL condition when compared with the flood condition. At higher machining conditions of $v_c = 70$ m/min, $f = 0.05$ mm/tooth, and $a_p = 2$ mm, the lowest F_c was observed with MQL at 216.77 N. The results showed that milling titanium under MQL led to improved F_c values, while the worst values were yielded under dry conditions.

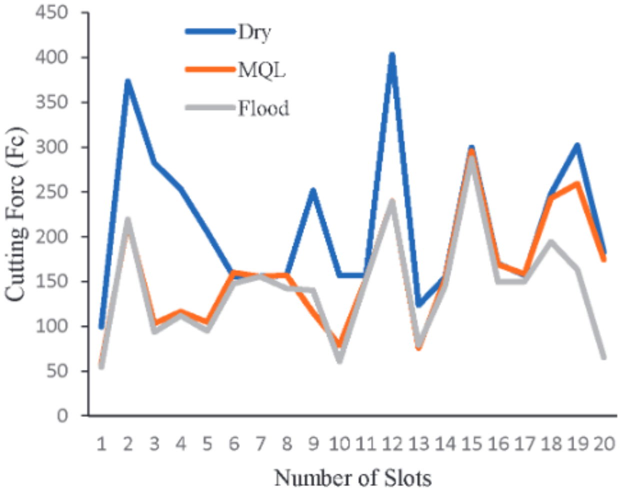


Figure 5: Cutting-force results for different cooling/lubrication conditions

3.3 Surface roughness (R_a)

Per the ANOVA results, it is noticeable from **Table 6**, depending on the p-value, that the feed per tooth, depth of cut and cutting-fluid flow rate are statistically significant ($p < 0.005$). In addition, the F-value statistics report the same results. In the meantime, the values of feed per tooth were the most effective factors in the surface roughness under all conditions. Similar results were reported in.[38]

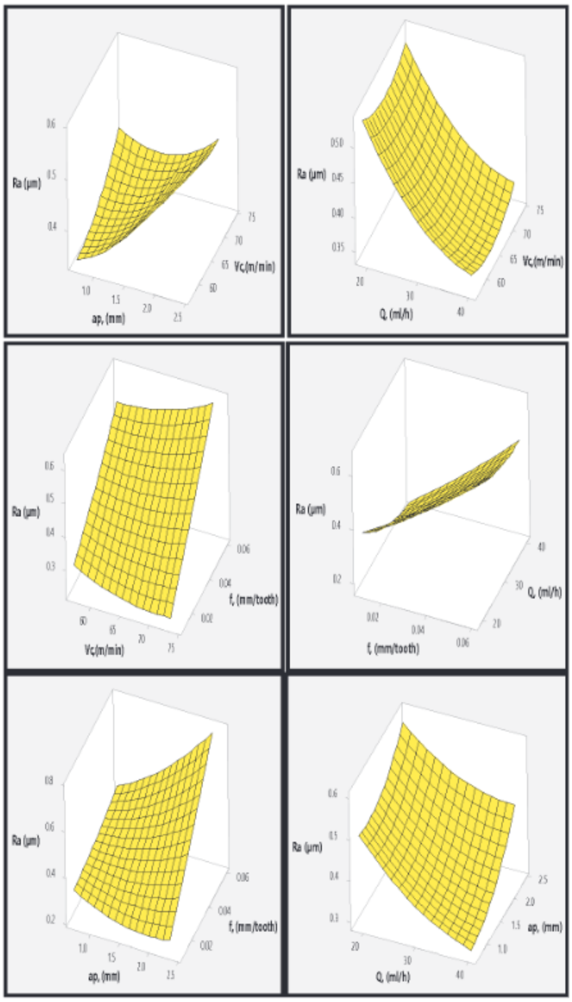
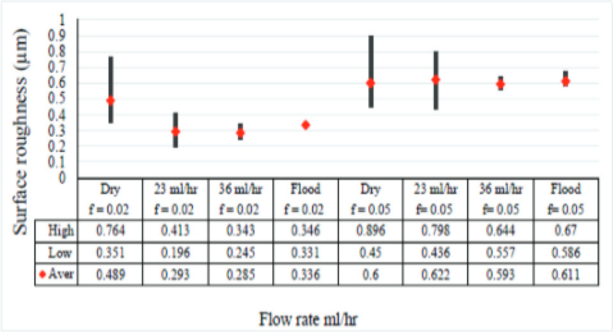


Figure 6: Effects of machining parameters on surface roughness (MQL condition)

The R_a values vs. machining parameters are shown in **Figure 6** under the MQL condition. It is clear that R_a grew quite quickly with increased feed rates from 0.02 mm/tooth to 0.05 mm/tooth and decreased as the cutting.fluid flow (FCs) rate increased. The results for the R_a values were plotted against the flow rates for a 60–70 m/min cutting speed and feed levels of (0.02; 0.05) mm/tooth, as shown in **Figure 7**.

The R_a results were compared in terms of average, maximum, and minimum values for a cutting speed of 70 m/min and feed levels of (0.02; 0.05) mm/tooth. It was observed that machining under MQL and flood conditions yielded better R_a values than the dry conditions. Similar results were shown in other studies.[39,40] The R_a values for MQL of Q = 23 mL/h and Q = 36 mL/h were found to be different from each other. Meanwhile, the values of R_a under MQL at Q = 23 mL/h and the dry condition were very close to each other, but there was an improvement with an increased flow rate to Q = 36 mL/h.



	Dry f = 0.02	23 ml/hr f = 0.02	36 ml/hr f = 0.02	Flood f = 0.02	Dry f = 0.05	23 ml/hr f= 0.05	36 ml/hr f= 0.05	Flood f= 0.05
High	0.764	0.413	0.343	0.346	0.896	0.798	0.644	0.67
Low	0.351	0.196	0.245	0.331	0.45	0.436	0.557	0.586
◆ Aver	0.489	0.293	0.285	0.336	0.6	0.622	0.593	0.611

Figure 7: Surface roughness results at feed rates of 0.02–0.05 mm/tooth and cutting speed of 70 m/min

Table 6: Analysis of variance (ANOVA) considering R_a values

	flood	dry	MQL						
Source	F-Value	P-Value	contribution	F-Value	P-Value	contribution	F-Value	P-Value	contribution
model	13.89	0.000	92.59 %	6.13	0.005	84.65 %	5.45	0.001	85.37 %
linear	32.28	0.000	71.74 %	13.63	0.001	62.99 %	16.00	0.000	66.86 %
v_c/(m/min)	1.34	0.274	0.99 %	2.5	0.145	3.84 %	0.00	0.964	0.04 %
f/(mm/tooth)	77.71	0.000	57.57 %	30.13	0.000	46.26 %	49.59	0.000	51.82 %
a_p/mm	17.79	0.002	13.18 %	8.39	0.016	12.89 %	7.50	0.016	7.84 %
Q/(mL/h)	–	–	–	–	–	–	6.89	0.020	7.20 %
S	0.039			0.0539			0.0644		
R-squared	92.59 %			84.65 %			85.37 %		
Adj R-squared	85.92 %			70.83 %			69.70 %		

Regression models for R_a:

$R_{a\ \mathrm{DRY}} = -4.59 + 0.1529 \cdot v_c + 15.2 \cdot f - 0.548 \cdot a_p - 0.001089 \cdot v_c^2 + 77.3 \cdot f^2 + 0.1611 \cdot a_p^2 - 0.262 \cdot v_c f + 0.00165 \cdot v_c \cdot a_p + 1.22 \cdot f \cdot a_p$

$R_{a\ \mathrm{FLOOD}} = -7.15 + 0.2360 \cdot v_c + 10.9 \cdot f - 0.559 \cdot a_p - 0.001877 \cdot v_c^2 - 126 \cdot f^2 + 0.0673 \cdot a_p^2 + 0.037 \cdot v_c \cdot f + 0.006 \cdot v_c \cdot a_p + 1.23 \cdot f \cdot a_p$

$R_{a\ \mathrm{MQL}} = 0.92 - 0.0177 \cdot v_c - 14.1 \cdot f - 0.009 \cdot a_p - 0.014 \cdot Q + 0.000325 \cdot v_c^2 + 16.2 \cdot f^2 + 0.058 \cdot a_p^2 + 0.00029 \cdot Q^2 + 0.225 \cdot v_c \cdot f - 0.00820 \cdot v_c \cdot a_p - 0.00677 \cdot v_c \cdot Q + 5.93 \cdot f \cdot a_p - 0.136 \cdot f \cdot Q + 0.00804 \cdot a_p \cdot Q$

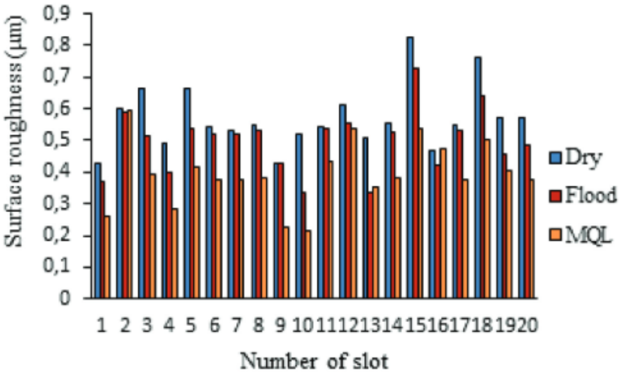


Figure 8: Surface-roughness results under different cooling/lubrication conditions

Figure 8 shows the R_a values under different machining conditions. It can be noted that MQL outperformed the dry and flood conditions under all machining conditions and that the dry condition provided the highest R_a values. This can be explained as follows: the diameter of the droplets is reduced along with an increased fluid flow rate, which can better penetrate the contact zones. Thus, the lubrication improves, as the friction is reduced.[41] However, the latter yielded more satisfactory outcomes at a cutting speed of 60 m/min and feed level of 0.02 mm/tooth.

The better results of MQL (36 mL/h) proved to be an optimum value of the flow rate for this condition. It was important to observe, with respect to the R_a result, that the increase in the cutting-fluid flow rate with MQL of more than 36 mL/h did not provide any improvement. Therefore, there is a concern as to the optimal level of the flow rate. In this respect, a possible contributor may be the lubrication capacity and the associated penetration of the cutting fluid with the MQL technique.[20]

5 CONCLUSIONS

In this study, a titanium alloy was slot milled using different cooling/lubrication conditions (dry, MQL and flood) to investigate the effect of the MQL condition on the cutting force and surface roughness. The main conclusions can be drawn as follows:

The regression model functions were validated by ANOVA analysis with high coefficients of determination (R^2) and at a level of $p < 0.05$ for the three cooling/lubrication conditions. The ANOVA results have indicated that the cutting force and surface roughness are largely affected by the feed rate, depth of cut and cutting-fluid flow rate.

The response surface methodology (RSM) exhibited an acceptable degree of ability to reduce the complexity of the problem by identifying the unimportant factors in the model.

The MQL proved to be an effective technique to achieve sustainability requirements and is an effective alternative approach for conventional cooling conditions during the machining of a titanium alloy (Ti-6Al-4V) in terms of improving the surface roughness and cutting force by eliminating the problems of flood cooling. It was found that the MQL condition generates lower values of surface roughness with values of 0.425 µm, 0.329 µm, and 0.227 µm for dry, flood, and MQL conditions, respectively. Meanwhile, the cutting-force values under the MQL condition were found to be close to those of the flood condition and at times even better.

The flow rates of the cutting fluid increased to 36 mL/h when milling under the MQL technique. This led to a minimization of the cutting force and surface roughness when compared to all the cooling/lubrication conditions. This is, in particular, the case with a low feed rate and low cutting speed. The effects of the flow rate of the cutting fluid seem to be more dominant. A better machining performance was found at a flow rate of 36 mL/h under machining conditions f = 0.02 mm/tooth and v_c = 60 m/min.

Future work may study the improved performance of the milling process under the MQL technique through improved cooling capacity and the lubrication effect of the cutting fluid using nanoparticles. In addition, it is necessary to optimize the MQL parameters for the sustainable machining of titanium alloys. This trend should be studied in detail by carrying out an experiment to identify the optimal combination of parameters for the machining process and MQL technique.

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