lubricants

MDPI

Article

Implementation of Sustainable Vegetable-Oil-Based Minimum Quantity Cooling Lubrication (MQCL) Machining of Titanium Alloy with Coated Tools

Salman Pervaiz [1,*], Naveed Ahmad [2], Kashif Ishfaq [3], Sarmad Khan [3], Ibrahim Deiab [4] and Sathish Kannan [5]

[1] Department of Mechanical and Industrial Engineering, Rochester Institute of Technology—Dubai Campus, Dubai P.O. Box 341055, United Arab Emirates
[2] Department of Industrial Engineering, College of Engineering and Architecture, Al Yamamah University, Riyadh 11512, Saudi Arabia
[3] Department of Industrial & Manufacturing Engineering, University of Engineering & Technology, Lahore 54890, Pakistan
[4] School of Engineering, University of Guelph, Guelph, ON N1G 2W1, Canada
[5] Department of Mechanical Engineering, School of Engineering, American University of Sharjah, Sharjah P.O. Box 26666, United Arab Emirates
* Correspondence: sxpcad@rit.edu; Tel.: +971-4-371-2036 or +971-506-355-390

Abstract: The lubrication capacity and penetration ability of the minimum quantity cooling lubrication-based strategy is linked with lubrication specific parameters (oil flow rates and air pressure), cutting conditions, and chip formation. It points out the complex selection involved in the MQCL-assisted strategy to attain optimal machining performance. Lubrication during metal cutting operations is a complex phenomenon, as it is a strong function of the cutting conditions. In addition, it also depends on the physical properties of the lubricant and chemical interactions. Minimum Quantity Lubrication (MQL) has been criticized due to the absence of cooling parts; MQCL is a modified version where a cooling part in the form of sub-zero temperatures is provided. The aim of this paper was to investigate the influence of different lubrication flow parameters under minimum quantity cooling lubrication (MQCL) when machining aeronautic titanium alloy (Ti6Al4V) using Titanium Aluminum Nitride – Physical Vapor Deposition (TiAlN-PVD) coated cutting inserts. The machining experiments on the MQCL system were performed with different levels of oil flow rates (70, 90, and 100 mL/h) and the performance was compared with the conventional dry cutting and flood cooling settings. A generic trend was observed that increasing the oil flow rate from 70—mL/h to 100 h/h improved the surface finish and reduced thermal softening at a low feed of 0.1 mm/rev. The results revealed that many tool-wear mechanisms such as adhesion, micro-abrasion, edge chipping, notch wear, built-up edge (BUE), and built-up layer (BUL) existed.

Keywords: MQCL; metal cutting process; lubrication strategies; Ti6Al4V

Citation: Pervaiz, S.; Ahmad, N.; Ishfaq, K.; Khan, S.; Deiab, I.; Kannan, S. Implementation of Sustainable Vegetable-Oil-Based Minimum Quantity Cooling Lubrication (Mqcl) Machining of Titanium Alloy with Coated Tools. *Lubricants* **2022**, *10*, 235. https://doi.org/10.3390/lubricants10100235

Received: 12 July 2022
Accepted: 20 September 2022
Published: 24 September 2022

1. Introduction

The manufacturing sector is considered as a backbone of economy, and metal removal processes have played a vital role in the manufacturing sector. Nowadays, due to excessive market competition and stiffer environmental safety rules and regulations, companies are stressed to manufacture higher-quality products with a low environmental impact. Titanium alloys are referred to as heat-resistant alloys due to their inherent characteristics of low thermal conductivity and high hot-hardness [1]. Due to the previously mentioned problems, these are referred to as difficult-to-cut alloys. Due to the cyclic nature of forces, segmented chip formation, and excessive chatter, the machining of such alloys is more difficult [2]. Due to the negative environmental impact of cutting fluids, the metal cutting sector is experiencing a lot of pressure to adopt different environmentally friendly machining strategies [3]. These machining strategies either deal with this by completely replacing the hazardous cutting fluid or proposing to minimize their usage. For the green and sustainable machining of difficult-to-machine materials, minimum quantity lubrication (MQL) is qualified as a potential solution method that can be a substitute for traditional flood-assisted cooling [4]. Green solutions based on vegetable oil also have a high potential to improve machinability [5]. MQL is a lubrication-based method that controls heat generation in machining by reducing the friction at the cutting interface with oil-based mist, convection of compressed air, and evaporation of the oil mist. The literature points out at the limitations associated with MQL because of its low cooling properties [6]. Better temperature control during the machining process improves tool life by reducing the rate of tool wear [7].

Nowadays, there are several advanced MQL approaches such as minimum quantity cooling lubrication (MQCL) [8], hybrid MQL+ CO_2 lubrication [9], solid-lubricant-assisted MQL [10], MQL with nano-fluids [11], oil on water droplet MQL [12], and electrostatic minimum quantity lubrication (EMQL) [13]. MQCL has gained popularity in the metal cutting industry, but the performance is very sensitive to the MQL-specific parameters such as droplet size, air flow, and the distance of the nozzle from the cutting zone [14]. Pervaiz et al. [8] investigated the performance of minimum quantity cooling lubrication using uncoated cutting tools. The study revealed that there is a strong link between the lubrication capacity and penetration ability as a function of sub-zero temperature air. Pereira et al. [9] proposed a solution to address the disadvantage of poor cooling in the conventional MQL strategy by combining a cryogenic cooling system with it. Sartori et al. [10] investigated solid lubrication (SL)-assisted minimum quantity lubrication (MQL) and minimum quantity cooling (MQC) for machining Ti6Al4V ELI titanium alloys. The study revealed that SL-assisted MQC provided the best performance.

Hegab et al. [11] studied the machinability of difficult-to-cut materials using MQL with nano-cutting fluids. The main advantage of using nano-cutting fluids is linked with the improved thermal and frictional behaviour at the cutting interface. The study utilised multi-walled carbon nanotubes and aluminium oxide gamma nanoparticles as additives with the MQL strategy to machine Inconel 718. In the case of higher concentrations of nano-additives, an evident increase in nano-additives-induced wear was observed that can affect tool life significantly. Yuan et al. [12] utilised a novel MQL-based approach, where super-critical carbon dioxide and oil-on-water droplet systems were combined for the high speed machining of stainless steel 316L. The study revealed that a combined super critical carbon dioxide and oil-on-water droplet system approach provided low cutting forces and improved surface finish as compared to other stand-alone approaches. Lv et al. [13] utilised an electrostatic minimum quantity lubrication (EMQL) approach using graphene nano-lubricants. The study was focused on measuring the penetration ability and deposition property of the system, and the machining performance was investigated with a conventional MQL strategy. The study revealed that the proposed EMQL approach lowered the coefficient of friction and worn-scar diameter.

Several studies have also revealed the encouraging potential of advanced cutting tools with novel tool materials as a feasible option when machining these difficult-to-cut materials. Fernandes et al. [15] investigated the influence of Cr addition to the Ti(Al)N/Cr(Al)N multi-layered cutting tools. The study utilised these multi-layer coated tools in the drilling operation and the performance was compared with monolayer Ti0.47Al0.46N. The studied revealed that Cr-rich film performed better at higher cutting speeds when the cutting temperature was above 650 °C. The good performance is linked with lubricious properties due to formation of a Cr-O tribolayer at the cutting interface. Rabinovich et al. [16] inspected the performance of TiAlCrSiYN/TiAlCrN-coated tools. The study utilised scanning electron microscopy (SEM) to investigate the tool wear failure modes and mechanisms. The study pointed out that better wear performance is linked with the formation of tribo-oxide films.

Pervaiz et al. [17] conducted a study using PVD-coated tools to machine Ti6Al4V using an MQCL arrangement. In this study, an MQCL strategy was employed using external settings and internal settings with specially designed cutting tools having internal passages to facilitate the approach at the rake and flank faces. The study revealed that an internal MQCL arrangement was more efficient for a higher cutting speed of 150 m/min. In another study [8], the machinability of Ti6Al4V was inspected using uncoated carbide tools by using an MQCL setup with internal channels. The study utilised different oil flow rates for the development of the internal MQCL strategy. It has been revealed that oil flow rates of 60–70 mL/h provided the best performance. A superior tool life was observed in the case where the oil flow rate was 70 mL/h. This revealed the concept of an optimized flow rate in an MQCL setting. The optimized oil flow rate provides desirable oil penetration and lubricity.

Khanna et al. [18] incorporated a life-cycle analysis (LCA) to investigate the sustainability components during machining if Ti6Al4V using liquid CO_2 -cryogenic cooling, flood cooling, and minimum quantity lubrication. The study revealed that, due to high tool wear, MQL was not as sustainable when compared with the cryogenic cooling method. This is because in MQL, a cooling part is missing. Pereira et al. [19] in another study provided a more detailed analysis of the system where both cryogenic and MQL methods were combined using a specially designed adapter. The study performed theoretical calculations in combination with CFD (computational fluid dynamics) simulations and experimental runs. The proposed solution was found to be a good balance between machining and sustainable performance. Yang et al. [20] performed a numerical study on the proposed model for the minimum chip thickness under different lubrication schemes. The study incorporated the influence of different lubrication schemes by using different frictional angles. The study revealed a trend that by increasing the friction angle, the minimum chip thickness decreases. Yang et al. [21] in another study investigated the minimum chip thickness for zirconia ceramics using different lubrication schemes. Yin et al. [22] investigated the physiochemical properties of different vegetable-based oils in a minimum quantity lubrication arrangement. The study was composed of the following oils: cottonseed, palm, castor, soybean, and peanut. The study revealed that the lowest cutting force, friction coefficient, and surface roughness was obtained using palm oil.

It is important to recognize the efforts being made in the area of artificial intelligence applications in the metal cutting sector. Several experimental, numerical, and analytical methods are available in the literature [23] to study the residual stresses in metal cutting. El Sheikh et al. [24] conducted a study to compare the performance of a traditional artificial neural network (ANN), an artificial neural network (ANN) combined with a Pigeon Optimization Algorithm (POA), and an artificial neural network (ANN) combined with particle swarm optimization (PSO) when predicting residual stresses. The study revealed that machine-learning-based ANN models outperformed the traditional ANN and provided accurate results. In another study, El Sheikh et al. [25] developed a temperature-field-reconstruction (TFR)-based model to study the thermal dynamics of a continuous cutting turning process. The approach was found to be compatible with providing online sensing and real-time monitoring of the cutting process. Khoshaim et al. [26] studied the performance of an ANN in combination with particle swarm optimization (PSO) and flower pollination algorithm (FPA) optimization methods. The study revealed that machine-learning-based ANN models outperformed the traditional ANN and provided accurate results. Padhan et al. [27] investigated the MQL performance when machining Nitronic 60 steel using ceramic cutting tools. The results revealed that MQL improved life by 11% when compared with a flood cooling method.

Another important trend in MQL-assisted machining is the usage of nano-fluids in the MQL arrangement. El Sheikh et al. [28] utilised biodegradable rice bran vegetable oil mixed with CuO and Al_2O_3 nano-particles. The study compared the performance of different models such as an experimental data model, a random vector functional link (RVFL) model, a random vector functional link with a political optimizer (RVFL-PO), and a random vector functional link with a particle swarm optimizer (RVFL-PSO). The study showed that RVFL-PO outperformed the others. Nouzil et al. [29] reviewed the nano-MQL technology with respect to their toxicity-related issues. The study revealed that transition metal dichalcogenides (MoS2 and WS2) provided low toxicity as compared to other nanoparticles and also provided lower surface roughness and forces. Ibrahim et al. [30] utilised MQL machining using rice bran vegetable oil (RBO) mixed with Zinc Oxide (ZnO) nanoparticles to machine AISI D3 Steel. It was found that the machining performance was better in case of RBO-ZnO compared to only RBO oil.

It is very rarely found in the literature where the performance of TiAlN-coated tools was investigated for the machining of Ti6Al4V using MQCL under internal delivery arrangements. In this proposed current study, the use of TiAlN-PVD-coated tools to machine Ti6Al4V was investigated under an internal MQCL strategy. In addition to the coated tools, numerous oil flow rates, altering from 70mL/h–100 mL/h, were employed during the study.

2. Minimum Quantity Cooling Lubrication Mechanisms

MQCL consists of a traditional MQL method mixed with sub-zero temperature air. Benjamin et al. [30] points out at the benefits of MQCL by considering two major parts. The first benefit is linked with the effect of enhancement in the lubrication at the cutting interface due to the increase in the viscosity of the lubricant because of the sub-zero-cooled air interaction with the oil droplets [8,30]. The second benefit was linked with the improved convective heat transfer at the cutting interface due to sub-zero temperature air [30]. Figure 1 represents the schematic illustration of the MQCL mechanisms.

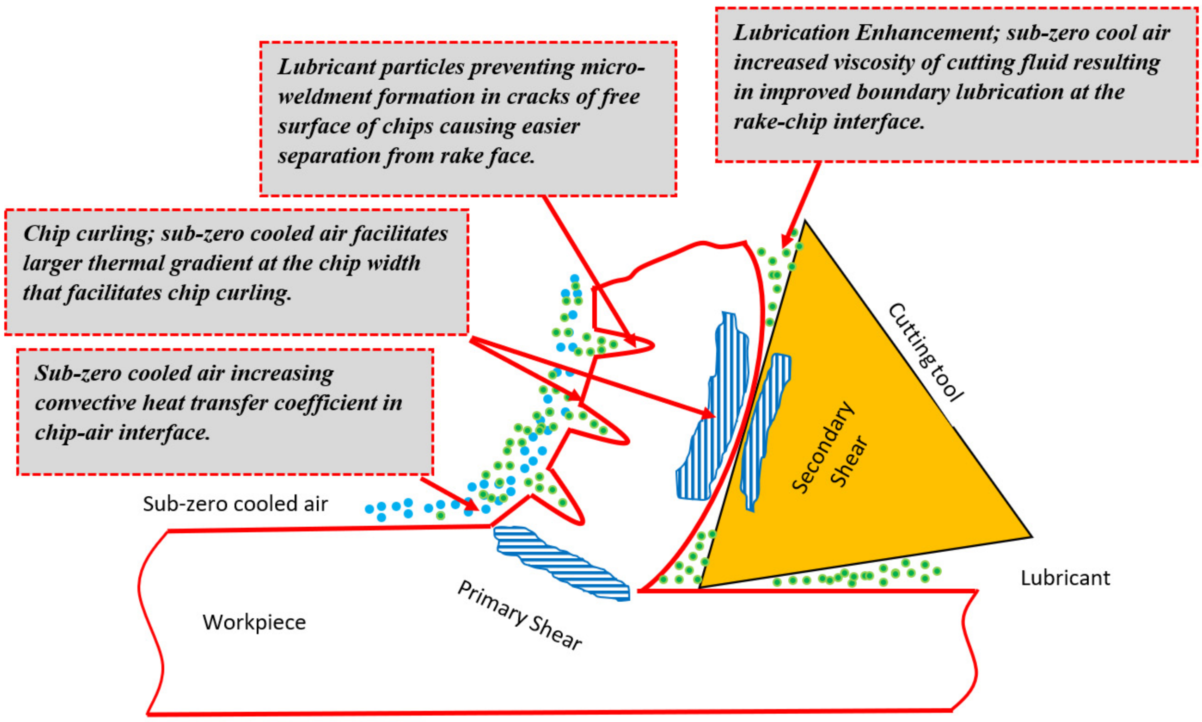


Figure 1. Schematic illustration of the MQCL mechanisms (redrawn with kind permission from [31]).

The literature [31,32] associates that effective cooling on the free surface of the chip can improve the chip up-curling and separation at the chip–tool interface due to the Rehbinder effect. As per the Rehbinder effect, active substances can diffuse in to the micro-cracks at the newly machined surface and prevent re-welding [33]. Smith et al. [34] investigated using cutting fluid as a liquid, viscous vapour and free-molecular-flow vapour in the cutting zone where imaginary fissures/micro-cracks were created during the machining process. It is also understood that lubrication during metal cutting is very complex in nature due to the associated physical properties and the related chemical interactions. Physical properties can be associated with the viscosity, Marangoni effect, and capillary flow etc., whereas chemical interactions can be linked with the chemical reactions and adsorption involved during the process [33]. As per the Marangoni effect, the lubricant will try to move away from the regions of higher cutting temperatures resulting in reduced efficiency and wettability.

3. Experimental Investigations

3.1. Material Preparation

This study utilised titanium alloy (Ti6Al4V) as a workpiece material for the current research work. Ti6Al4V is very popular in the aerospace sector due to its superior properties. The raw workpiece material was obtained as per American Society of Testing Materials (ASTM B381). The dimensions of the cylindrical shape of the raw material were 100 mm and 300 mm in diameter and length, respectively.

3.2. Machine and Cutting Tool

Turning experiments were conducted on a rigid CNC turning center (Excel BNC-21437, Santa Clara, CA, USA; Controller: Fagor800T, Elk Grove Village, IL, USA). The study utilised TiAlN-PVD-coated inserts with an ISO designation code of CCMT120404MM1105. The cutting insert has corner radius of 0.4 mm and the rake angle was positive. Usually, TiAlN-coated inserts are recommended for machining titanium alloys due to their high wear resistance that results in improving tool life and the overall machining performance. The study also utilised a specialized version of the cutting tool holder with internal flood delivery channels focusing at the rake and flank faces. The cutting tool holder was manufactured by Mircona under the designation SCLCR2525M12-EB. A new cutting edge was employed for every machining trial. Each machining trial was conducted for a flank-tool-wear value of 0.3 mm. A schematic illustration of the experimental setup is shown in Figure 2. The strength-based properties are reported in Table 1.

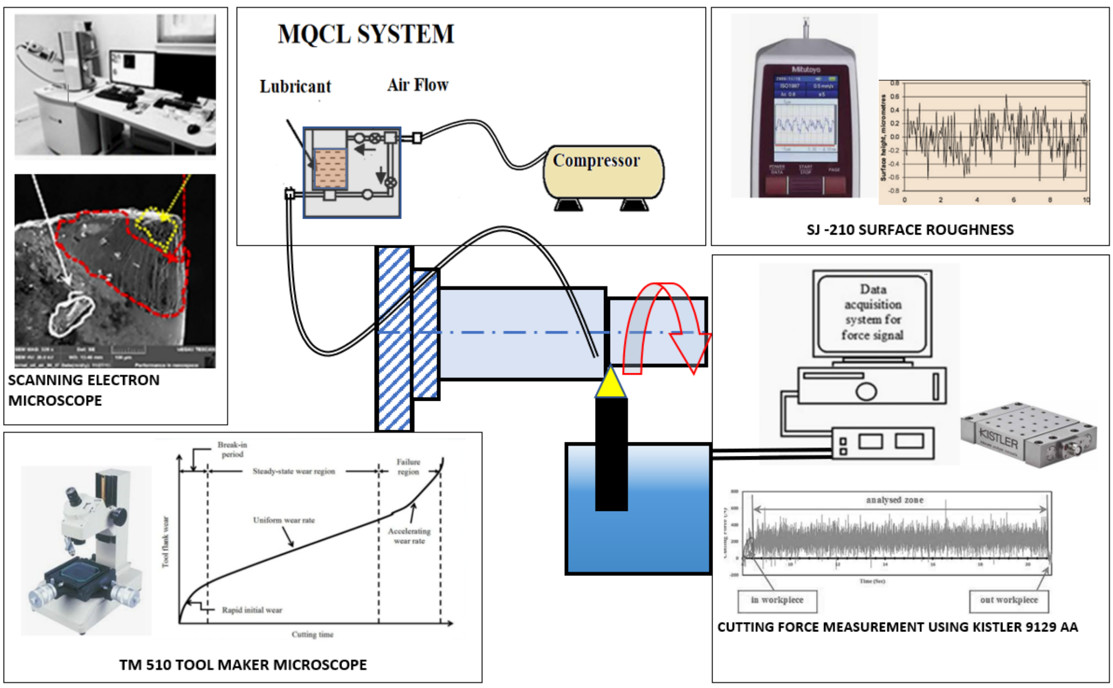
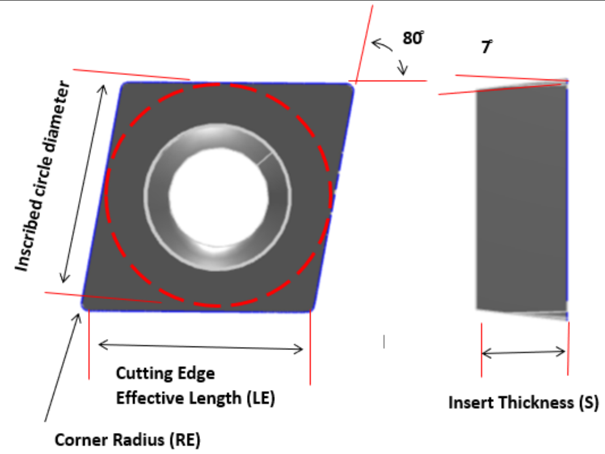


Figure 2. Experimental setup used in the current study.

Table 1. Mechanical properties of Ti6Al4V at room temperature [8].

Type of Property	Value
Tensile strength	993 MPa
Yield strength	830 MPa
Elongation	14
Poisson's ratio	0.342
Modulus of elasticity	114 GPa
Hardness (HRC)	36

Cutting Tool Information



CCMT CoroTurn®107 Turning Inserts feature an 80° rhombic shape ideal for external and internal machining.

- Cutting edge count: 2
- Inscribed circle diameter (IC):12.7 mm
- Insert shape code (SC): C
- Cutting edge effective length: 12.496 mm
- Corner radius (RE): 0.397 mm
- Grade (GRADE): 1105
- Substrate (SUBSTRATE): HC
- Coating (COATING): PVD TiAlN
- Insert thickness(S): 4.762 mm
- Major clearance angle (AN): 7 degrees

3.3. Responses and Measurement

To compare the machinability of the different cutting environments such as dry, flooded, and MQCL with the various oil flow rates, output parameters such as surface finish, tool life, cutting forces, and associated tool wear mechanisms were measured and analysed. The surface finish was measured by the SJ-210 surface roughness tester (Mitutoyo, Kawasaki, Japan) with a cut-off length of 2.5 mm. The cutting forces were measured using Kistler 9129 AA dynamometer (Kistler, Winterthur, Switzerland). To monitor tool life using flank wear, a TM 510 optical microscope (Mitutoyo, Kawasaki, Japan) was employed. To investigate the related wear mechanisms, a Tesla SEM scanning electron microscope (Tesla, Brno, Czech Republic) was utilised.

3.4. MQCL System Details

The study employed an MQL system where low sub-zero temperature compressed air was mixed with an oil mist. The MQCL system was capable of spraying a mixture of oil and air at the cutting interface. The MQCL system had pumps that were controlled using a Programable Logic Controller PLC [35]. A booster system was utilised to achieve sub-zero (−4 C) temperatures in the MQL system. In this study, machining experiments on the MQCL system were performed with different levels of oil flow rates (70, 90, and 100 mL/h) and their performance was compared with the conventional dry cutting and flood cooling settings. The study utilised vegetable-based rapeseed oil (Eculubric E200L). Table 2 represents the different specifications of the vegetable oil utilised in this study.

Table 2. Specifications of Eculubric E200L [35].

Chemical Description	Ignition Point	Flash Point	Density	Dynamic Viscosity
A fraction of natural triglycerides, easily biodegradable substances	365 °C	325 °C	At 0 °C = 0.9273 g/cm³ At −4 °C = 0.9297 g/cm³	At 0 °C = 2.881 Ns/m² At −4 °C = 3.652 Ns/m²

3.5. Design of Experiment

The design of the experiments in this work utilised a full-factorial design. The study utilised different levels of associated machining and lubrication-based parameters such as cutting speed (v_c), feed rate (f_r), and oil flow rates for the MQCL-based lubrication. The study utilised a constant depth of cut (DoC). The selection of these cutting parameters was in accordance with the metal cutting literature and as per the recommendations of the cutting tool manufacturer. Table 3 represents the cutting conditions and parameters utilised in this work. Figure 2 represents the schematic configuration of the equipment employed in this work.

Table 3. Machining/lubrication parameters and their levels.

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
Cooling/Lubrication method	MQCL-70 mL/h	MQCL-90 mL/h	MQCL-100 mL/h	Dry	Flood
Cutting Speed, v_c (m/min)	90	120	150	--	--
Feed, f (mm/rev)	0.1	0.2	0.3	--	--
Depth of cut, DoC (mm)	0.8 mm	--	--	--	--

4. Results and Discussion

4.1. Cutting Force and Surface Roughness

This section describes the cutting forces and surface roughness for the experiments conducted at numerous values of cutting speed and feed using dry, flood, and the various oil flowrates under the MQCL arrangements. Figure 3a–f represents the cutting force and surface roughness for the three different values of cutting speeds, i.e., 90, 120, and 150 m/min. A generic trend was observed for all the cutting environments in that increasing the feed rate increased the surface roughness and cutting force simultaneously. In the metal cutting literature, it is a well-known phenomenon that a higher feed rate increases the surface roughness. A likely reason is that higher cutting forces with increasing the feed rate can be linked with the aggressive nature of the shearing operation. The higher relative movement did not allow the MQCL strategy to reduce the friction at cutting interface. At the cutting speed of 90 m/min and low feed rate of 0.1 mm/rev, the lowest cutting force was observed for the MQCL (70 mL/h) as compared to the other lubrication methods. At a feed value of 0.1 mm/rev, the surface roughness was found to be very similar in all the methods, but a lower value was associated with the MQCL (90 mL/h). This revealed the better performance of the MQCL (90 mL/h) towards the surface integrity of the workpiece at a cutting speed of 90 m/min and a low feed rate 0.1 mm/rev. The fluctuation of the MQCL performance with respect to the various oil flow rates at different cutting conditions was linked with the ability of the mist to penetrate and reach the cutting zone.

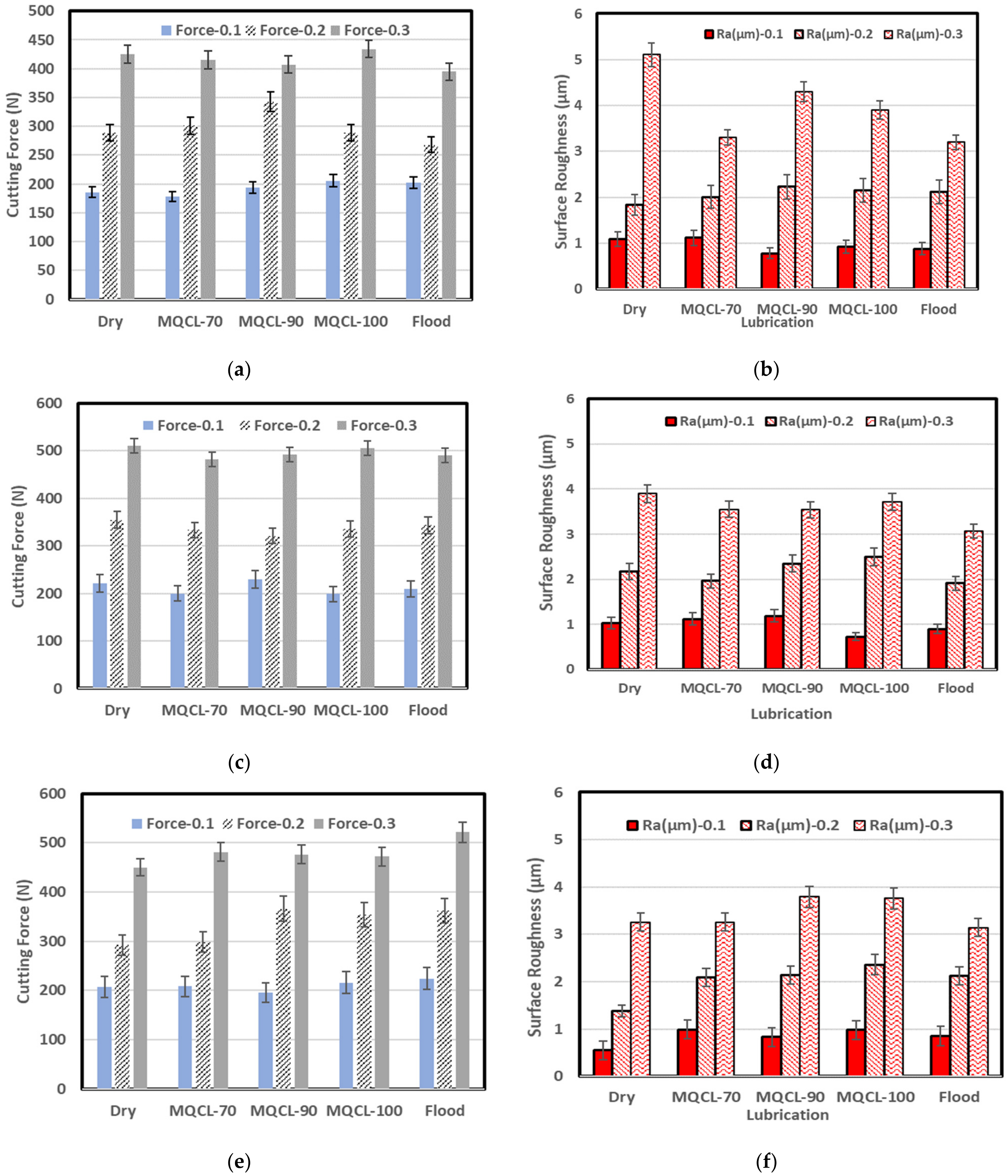


Figure 3. (**a**) Cutting forces at 90 m/min, (**b**) surface roughness at 90 m/min, (**c**) cutting forces at 120 m/min, (**d**) surface roughness at 120 m/min, (**e**) cutting forces at 150 m/min, and (**f**) surface roughness at 150 m/min

The presence of a high cutting temperature at the cutting interface evaporates mist and dissipates heat from the cutting interface. At a cutting speed of 120 m/min, the MQCL-100 and MQCL-70 provided a better performance compared to the flood cooling method at feed rates of 0.1 and 0.2 mm/rev, respectively, as reported in Figure 3c,d. When the cutting forces were compared between 120 and 150 m/min, at 150 m/min the cutting force for all the lubrication methods was found to be lower than at 120 m/min. At this point, there was a trend that a higher cutting speed resulted in elevated cutting temperatures, activating the thermal softening phenomenon. Higher forces in the flood cooling and MQCL arrangements point out a better heat dissipation that lowered thermal softening. The MQCL-70 arrangement provided comparatively better machining performance compared with the other cooling/lubrication methods. The variation in the MQCL performance was associated with the ability of the oil to penetrate and the resulting capacity to provide lubrication. The penetration ability and the associated lubrication capacity is a complex function based on cutting conditions and MQCL-associated parameters. Keeping in view the complexity of surface roughness and cutting-force-based data observed in Figure 3a–f, it was plotted again, as shown in Figures 4 and 5, to identify the influence of the MQCL strategy with an increasing oil flow rate. The trendlines observed for surface roughness at a low feed rate of 0.1 mm/rev showed the common trend of decreasing surface roughness at all cutting speeds of 90, 120, and 150 m/min when the oil flow rate was increased from 70 mL/h to 100 mL/h. It revealed that a higher oil flow rate in the MQCL at a low feed rate provided effective lubrication. A possible reason can be linked with the effective penetration of lubricant particles that facilitated chip up-curling and provided improved separation of chips with the workpiece, whereas the surface roughness trend was found to increase with an increasing oil flow rate at higher feed levels of 0.2–0.3 mm/rev for all cutting speeds of 90, 120, and 150 m/min. As shown in Figure 5, at a cutting speed of 90 m/min and low feed level of 0.1 mm/rev, the cutting forces increased when the oil flow rate in the MQCL strategy was increased. This is linked with the effective cooling and activation of the related material hardening mechanism. For the same feed of 0.1 mm/rev, higher cutting speeds provided no significant influence on the cutting forces with a trend of a slight decrease in the forces, which could be due to the thermal softening of the material.

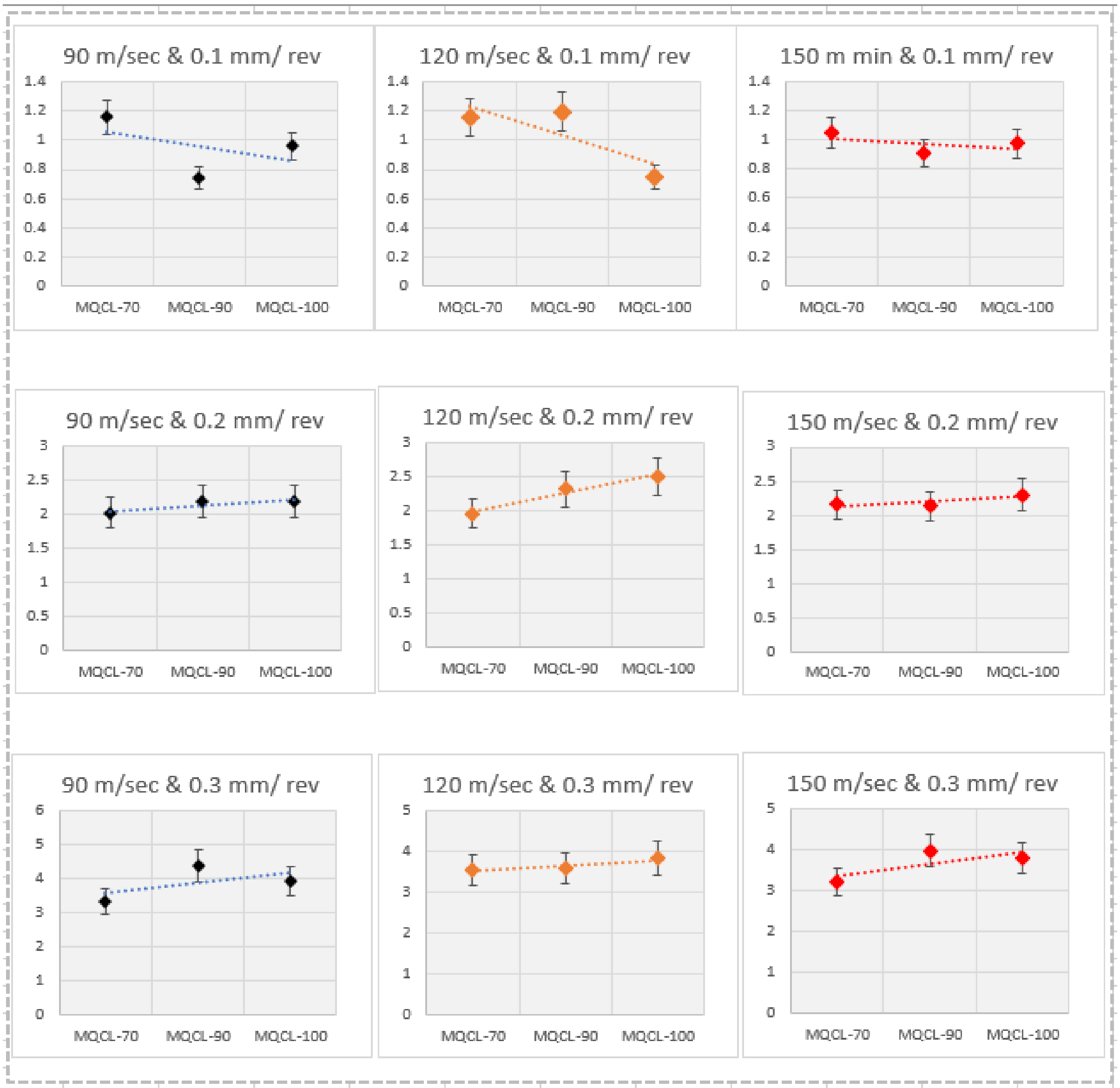


Figure 4. Comparison of surface roughness (μm) trends for the different cutting speeds, feed rates, and oil flow rates in MQCL strategy.

Analysis of variance was employed to assess the significance of a parametric effect. A confidence interval of 95% was defined to rate a parametric effect as significant for a particular response attribute. Analysis of Variance (ANOVA) was performed for both the responses, namely the surface roughness and cutting forces. Based on ANOVA, a significance of control variables for surface finish and cutting forces is mentioned in Tables 4 and 5, respectively. Figure 6a,b shows the mean effect plots for surface roughness and cutting force.

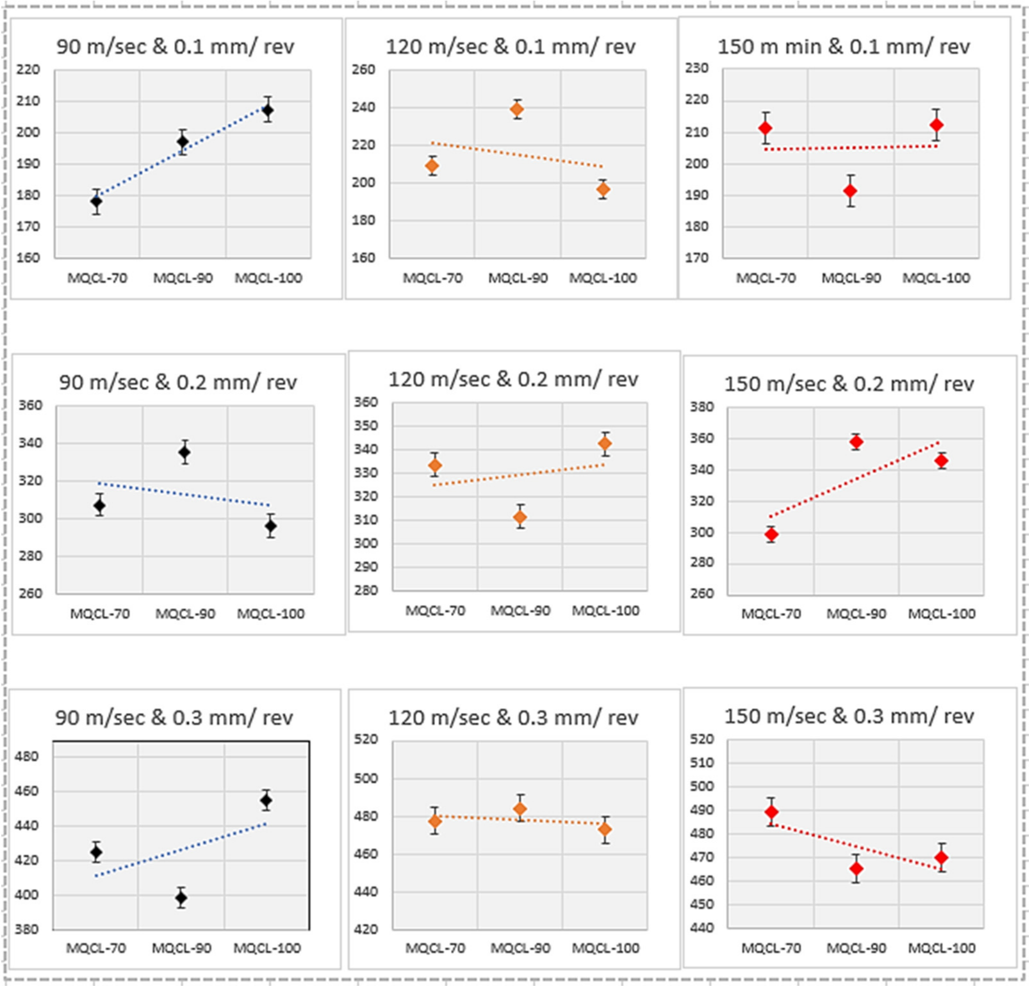
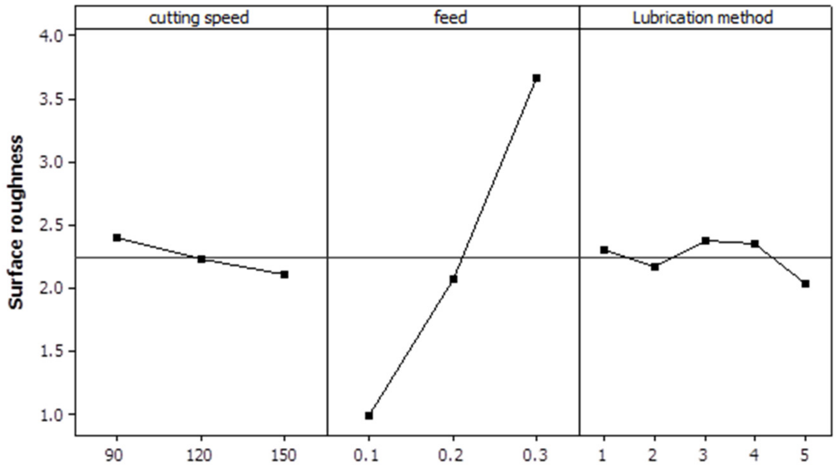


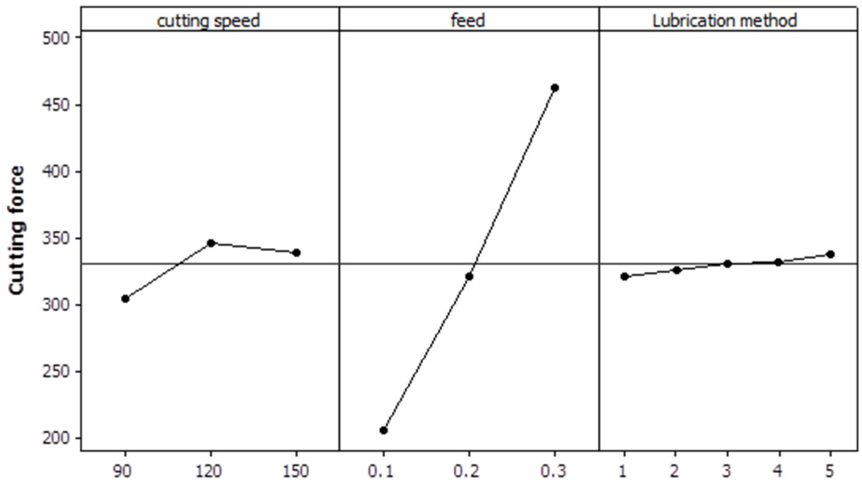
Figure 5. Comparison of cutting force (N) trends for the different cutting speeds, feed rates, and oil flow rates in MQCL strategy.

Table 4. ANOVA for surface roughness.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage Contribution
Cutting Speed, v_c (m/min)	2	0.642	0.642	0.321	2.11	0.136	1.0
Feed, f (mm/rev)	2	54.08	54.08	27.04	177.6	0.000	88.8
Cooling/Lubrication method	4	0.727	0.727	0.182	1.19	0.330	1.2
Error	36	5.483	5.483	0.152			9
Total	44	60.93					
S = 0.390246			R-Sq = 91.00%			R-Sq (adj) = 89.00%	



(**a**)



(**b**)

Figure 6. (**a**) Main effect plots for surface roughness (μm), (**b**) main effect plots for cutting force. (N)—Lubrication methods. 1—MQCL 70 mL/h, 2—1 MQCL 90 mL/h, 3—MQCL 100 mL/h, 4—dry and 5—flood.

Table 5. ANOVA for cutting force.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Percentage Contribution**
Cutting Speed, v_c (m/min)	2	14918	14918	7459	13.66	0.000	2.8
Feed, f (mm/rev)	2	496610	496610	248305	454.6	0.000	93.2
Cooling/Lubrication method	4	1423	1423	356	0.65	0.630	0.2
Error	36	19663	19663	546			3.8
Total	44	532614					
S = 23.3710			R-Sq = 96.31%			R-Sq (adj) = 95.49%	

ANOVA showed that the feed had a p-value lesser than the predefined alpha value (0.05) in the case of surface roughness, as shown in Table 4. In other words, the feed was the only significant control parameter for surface roughness during the MQCL-based cutting of titanium alloy (Ti6Al4V). Moreover, the feed also held a leadingly high percentage contribution of 88.8% for the surface finish of the cut specimen. In the case of the cutting force, two control variables, namely cutting speed and feed, had a *p*-value lower than the predefined alpha value. Thus, both the cutting speed and feed were the significant input parameters with respect to the cutting forces produced the during cutting of titanium alloy using the MQCL-based machining strategy. However, the feed proved to be the major contributing parameter (percentage contribution of 93.2%) towards the cutting force in comparison to the cutting speed (percentage contribution of 2.8%). This result was expected because the cutting parameters such as feed rate, cutting speed, and depth of cut are more dominant parameters compared to the cutting environment. A possible reason of this high dependency of cutting parameters with the cutting force can be directly linked with the chip load.

4.2. Tool Wear and Observed Tool Wear Mechanisms

Cutting tool life is directly linked with the cutting temperature and chip formation, as they can initiate different tool wear mechanisms, namely adhesion (sticking/sliding of workpiece materials resulting in BUE), abrasion (rubbing of hard particles), and diffusion (atomic mass transfer between workpiece and cutting tool), etc., at higher rates. The cutting tool life at the various cutting speed levels of 90, 120, and 150 m/min at a feed rate of 0.1 mm/rev is reported in Figure 7. At a cutting speed 90 m/min and a feed rate of 0.1 mm/rev, the flood environment provided the best tool life, whereas the second best was MQCL at 90 mL/h. The cutting forces and surface roughness were also found to be in agreement for MQCL at 90 mL/h. For 120 m/min, the flood environment provided the best tool life, whereas the second-best tool life was MQCL at 100 mL/h. At a cutting speed 150 m/min, almost all the cooling methods provided a very short tool life with minor variations. Dry cutting emerged as a good option with the highest tool life and was verified with lower cutting forces and better roughness. A possible explanation for this could be that the higher temperatures triggered thermal softening that reduced the cutting forces and extended the tool life. Figure 8a,b represents the scanning electron micrographs (SEM) of dry cutting and flood cooling at a cutting speed and feed rate of 90 m/min and 0.1 mm/rev, respectively.

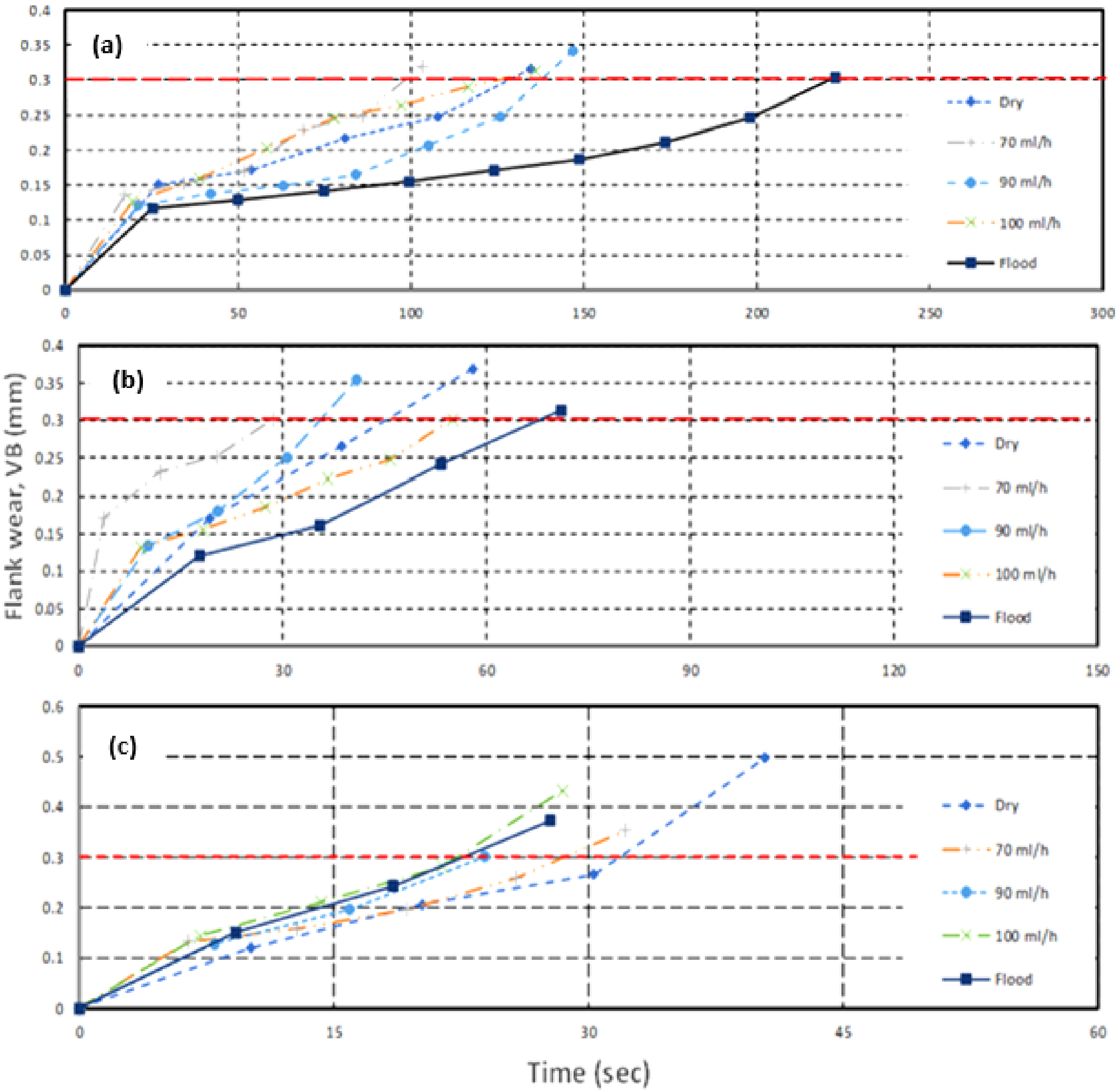
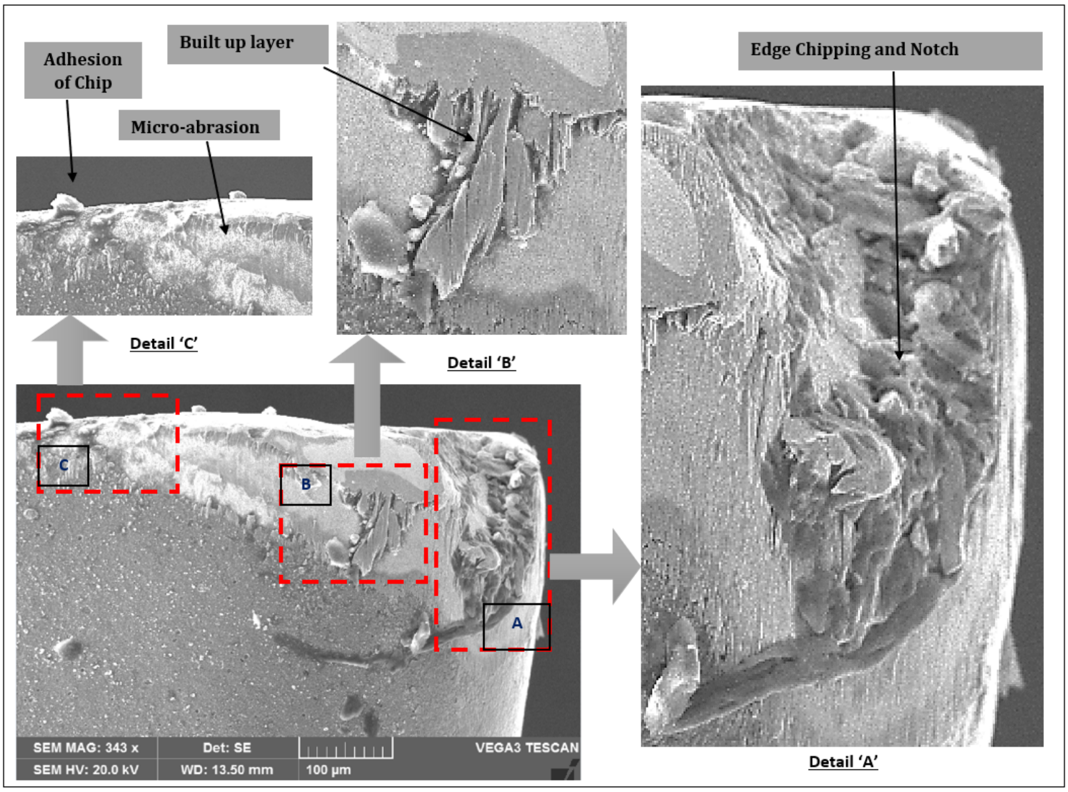
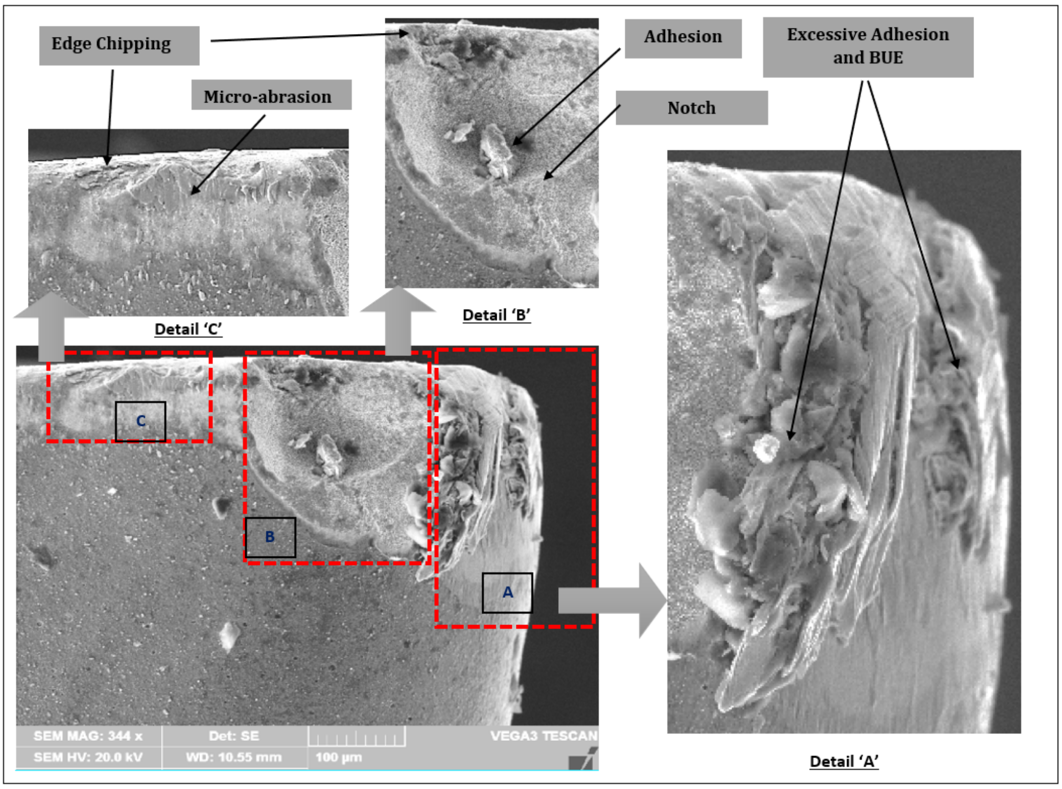


Figure 7. Progression of flank tool wear for the feed rate of 0.1 mm/rev and depth of cut of 0.8 mm, (**a**) cutting speed of 90 m/min, (**b**) cutting speed of 120 m/min, and (**c**) cutting speed of 150 m/min.

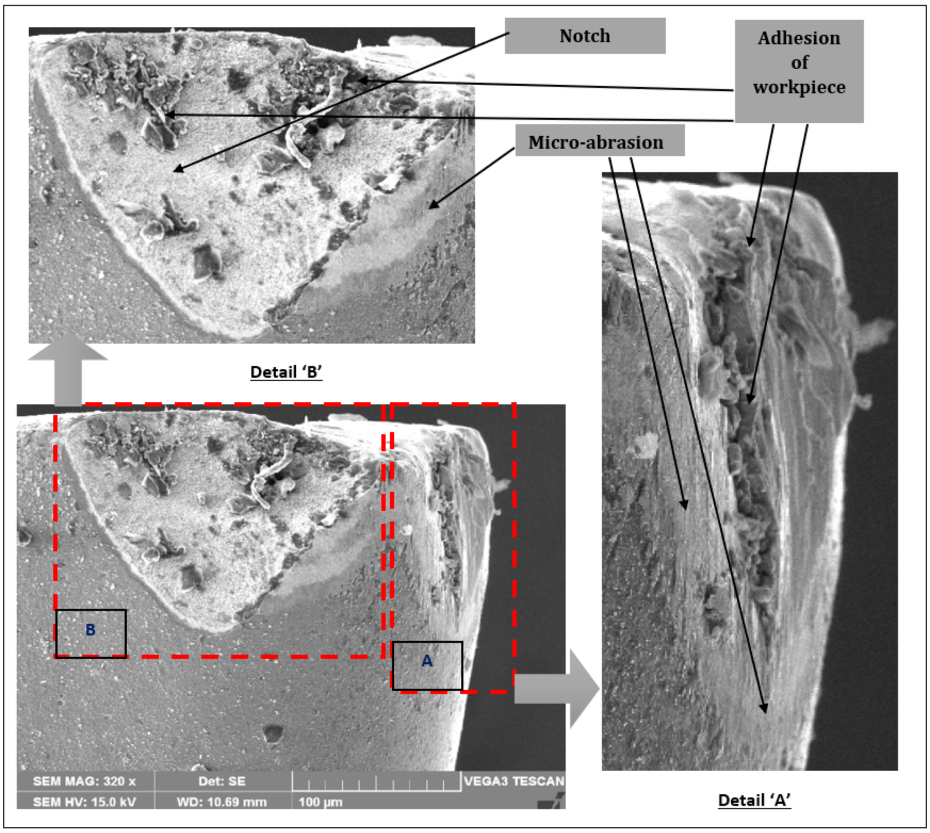
As reported in Figure 8a, detail A, it was noticed that, in the case of dry cutting, extreme edge chipping was observed at the flank face and closer to the nose radius of the cutting tool. The occurrence of elevated cutting temperatures also resulted in the adhesion or sticking of the workpiece material at the edge and the formation of a built-up-layer (BUL), as shown in Figure 8a, details B and C. Micro-abrasion was also observed on the flank face. As reported in Figure 8c, detail B, flank wear at the flank face was mainly composed of edge chipping with a notch. The excessive adhesion of the workpiece material and built-up edge (BUE) development was noticed at the cutting edge close to the nose radius region, as reported in Figure 8a, detail A. Micro-abrasion was also observed at the cutting edge. Micro-abrasion occurs because of the rubbing of hard-phase particles on the tool surface.


Adhesion of Chip
Built up layer
Micro-abrasion
Edge Chipping and Notch
Detail 'C'
Detail 'B'
C
B
A
SEM MAG: 343 x
Det: SE
VEGA3 TESCAN
SEM HV: 20.0 kV
WD: 13.50 mm
100 μm
Detail 'A'

(**a**)


Edge Chipping
Adhesion
Excessive Adhesion and BUE
Micro-abrasion
Notch
Detail 'C'
Detail 'B'
C
B
A
SEM MAG: 344 x
Det: SE
VEGA3 TESCAN
SEM HV: 20.0 kV
WD: 10.55 mm
100 μm
Detail 'A'

(**b**)



(**c**)

Figure 8. SEM of flank tool wear at *V*c of 90 m/min, f of 0.1 mm/rev and DoC of 0.8 mm. (**a**) Dry cutting, (**b**) flood cutting, and (**c**) MQCL 70 mL/h.

Figure 8c represents the scanning electron micrograph of MQCL at 70 mL/h, observed at a cutting speed and feed of 90 m/min and 0.1 mm/rev, respectively. It was observed that the pattern of tool wear was very similar to the flood cooling in Figure 8b, with the presence of a big visible notch representing edge chipping or flaking. In Figure 8c, the notch at MQCL-70 was larger than the one observed in flood cooling. The region closer to the nose radius had traces of workpiece material adhesion and BUE. However, the extent of BUE here was comparatively lower than the flood cooling.

Figures 9 and 10 report the tool life at the various cutting speed levels of 90, 120, and 150 m/min against the feed levels of 0.2 and 0.3 mm/rev. As shown in Figures 9 and 10, flood cooling outperformed other the cooling/lubrication methods. In Figure 9, as expected, dry cutting mostly performed the worst, pointing out that tool life was affected by the presence of high cutting temperatures and the associated tool life. As shown in Figure 9 (90 m/min speed), MCQL at 100 mL/h performed comparatively closer to flood cooling. As shown in Figure 9 (120 and 150 m/min), MQCL at 70 mL/h performed second best, comparatively closer to flood cooling. Figure 11a reports the scanning electron micrograph of the MQCL at 70 mL/h cooling strategy for the cutting speed and feed of 150 m/min and 0.2 mm/rev, respectively. It was clearly observed that the cutting insert was free from edge chipping or the presence of a resulting notch. There were small traces of workpiece material adhesion at the flank face, indicating the presence of the cutting temperature. The major tool wear mechanism observed in the SEM was abrasion. This is because of the intensive rubbing of hard particles between the workpiece and the cutting tool materials, as shown in Figure 11a, detail A. At a similar speed of 150 m/min and feed level of 0.2 mm/rev, another cooling strategy of MQCL at 90 mL/h was analysed, as shown in Figure 11b. Figure 11b clearly shows a higher wear formation at the flank face. The dominant tool wear mechanism was found to be adhesion. The excessive adhesion represented that the cutting temperature was not efficiently dissipated during the cutting test. The inefficient control of cutting temperature provided the development of built-up layers (BUE) and built-up edges (BUE), as reported in Figure 11b, detail A. Minor edge chipping was detected at the nose radius of the cutting insert.

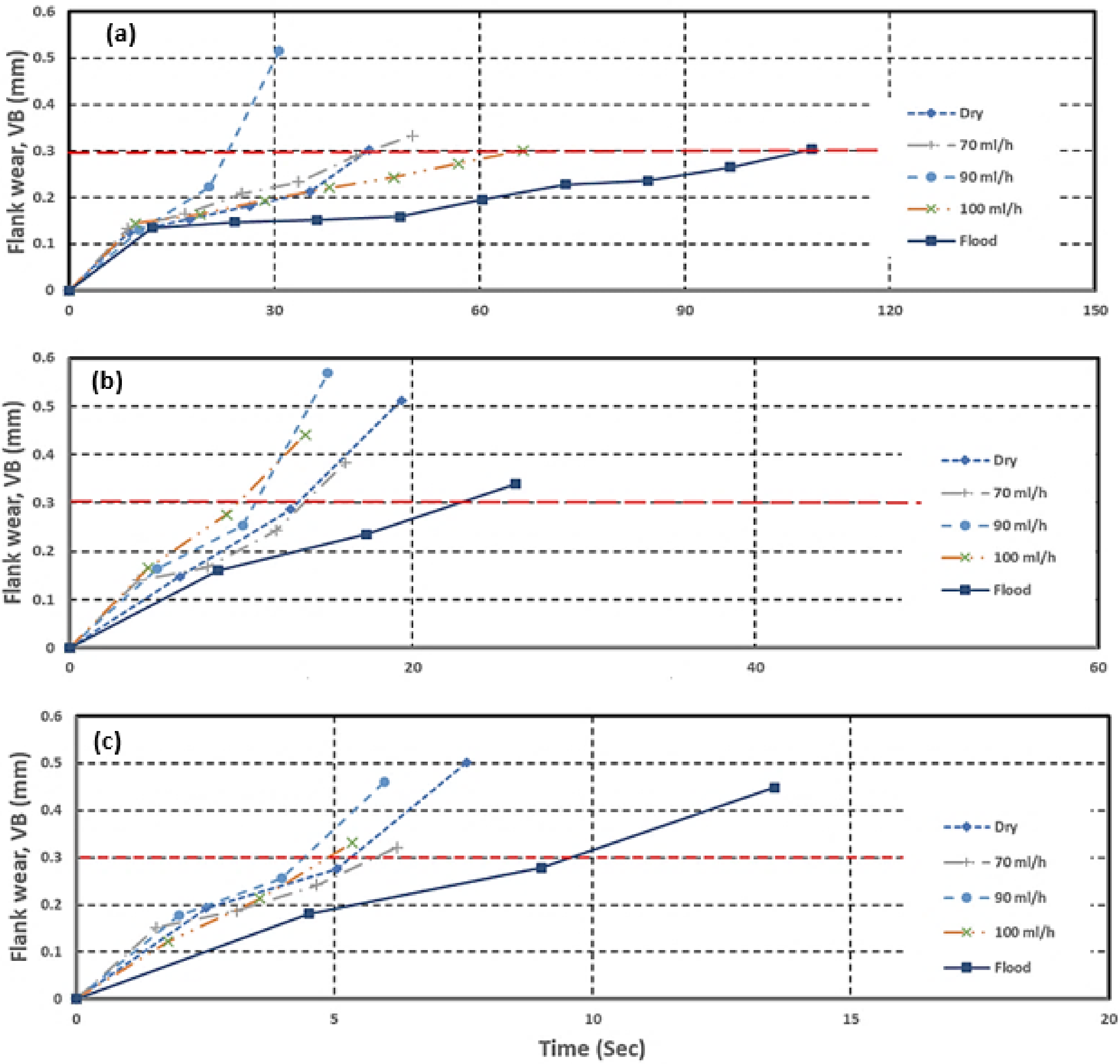


Figure 9. Progression of flank tool wear for the feed of 0.2 mm/rev and depth of cut of 0.8 mm, (**a**) cutting speed of 90 m/min, (**b**) cutting speed of 120 m/min, and (**c**) cutting speed of 150 m/min.

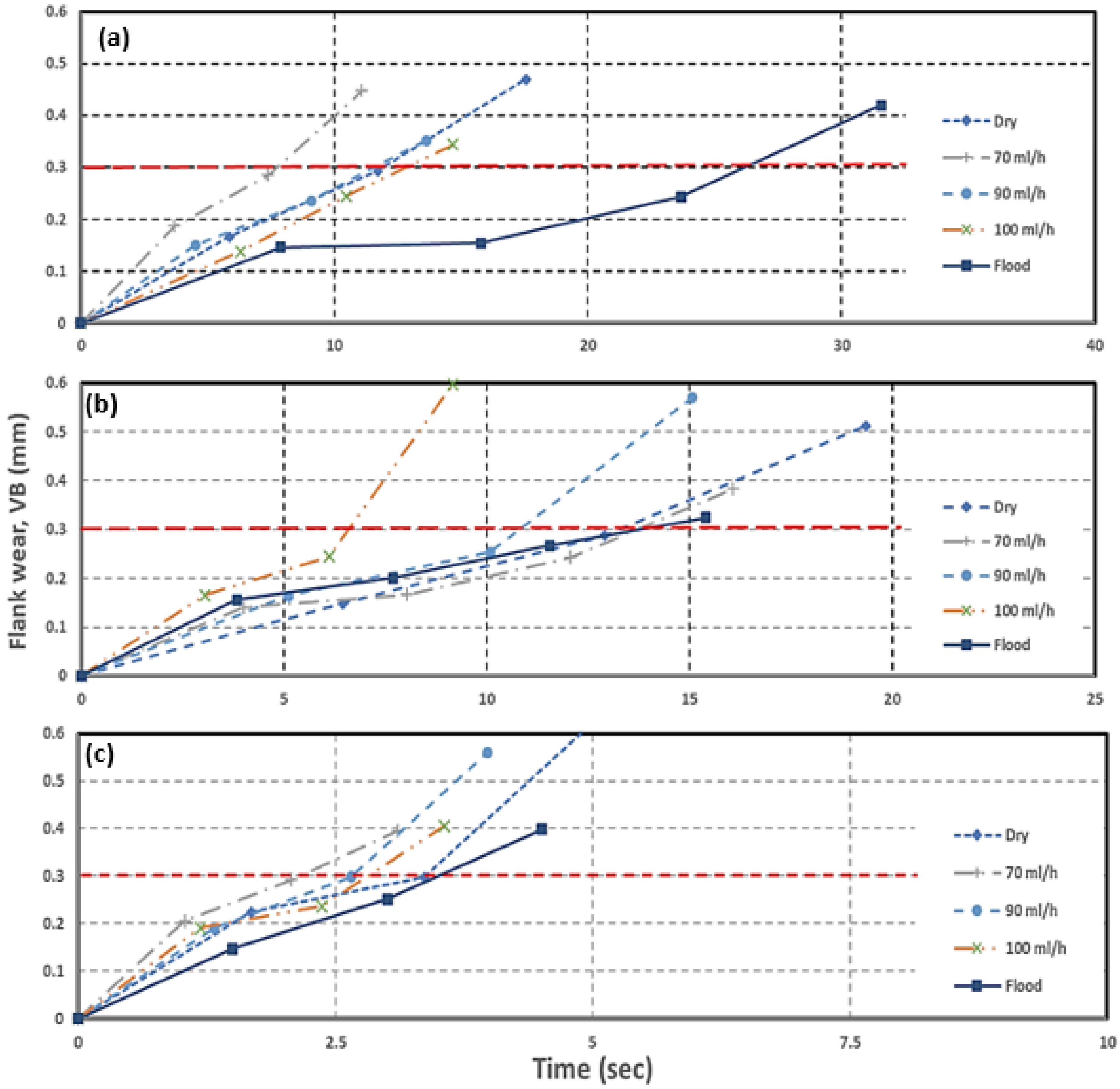
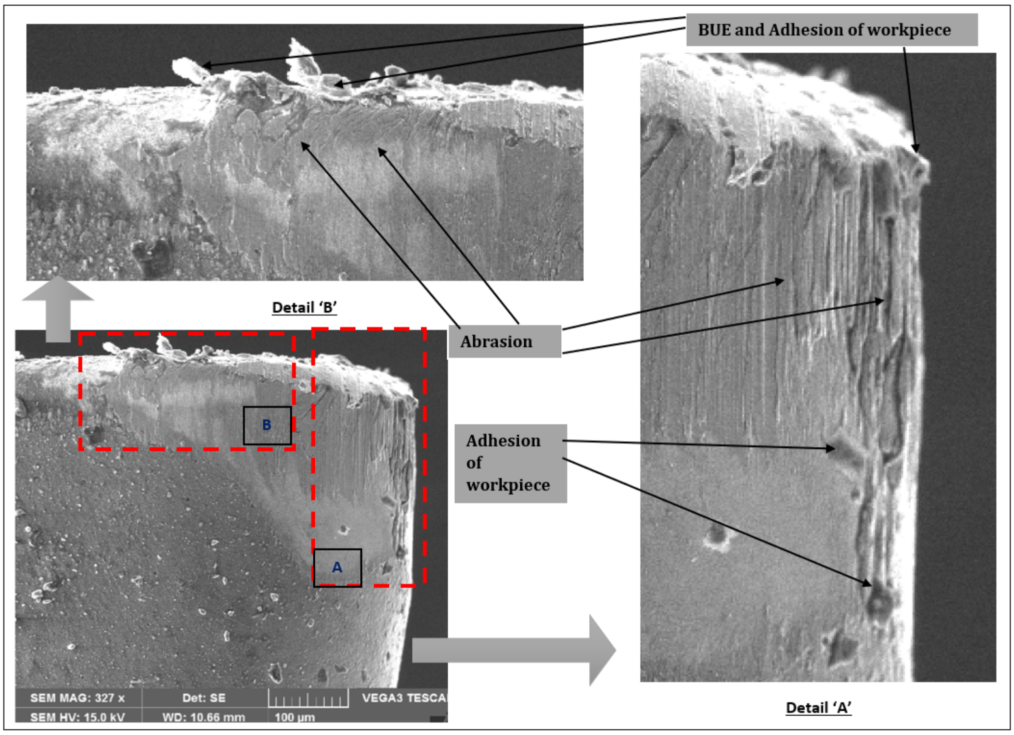


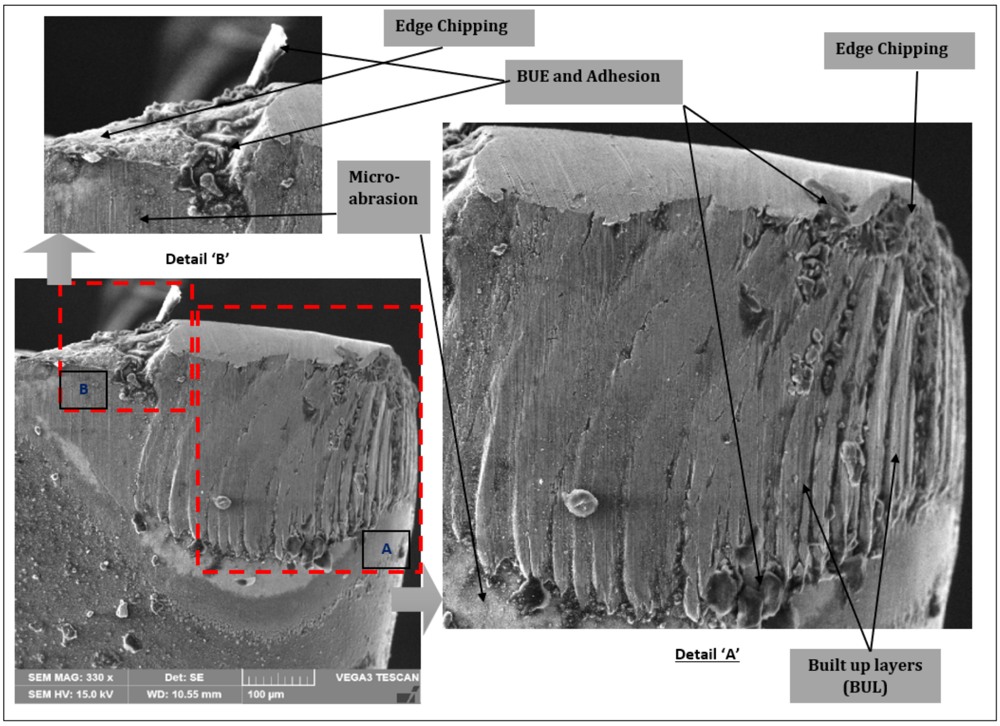
Figure 10. Progression of flank tool wear for the feed rate of 0.3 mm/rev and depth of cut of 0.8 mm, (**a**) cutting speed of 90 m/min, (**b**) cutting speed of 120 m/min and (**c**) cutting speed of 150 m/min.

The flood environment provided the best tool life for the 90, 120, and 150 m/min cutting speeds. The MQCL strategy with various oil flow rates performed without any remarkable performance, clearly pointing out that MQCL was not suitable at higher speeds and higher feeds. A possible explanation for this could be the inefficient control of heat dissipation with the MQCL methodology, or the higher cutting forces for the MQCL methodology. Surprisingly, the dry environment was not the worst among the cooling/lubrication methods. This could be explained by the thermal softening behaviour that provided low cutting forces, as shown in Figure 3.

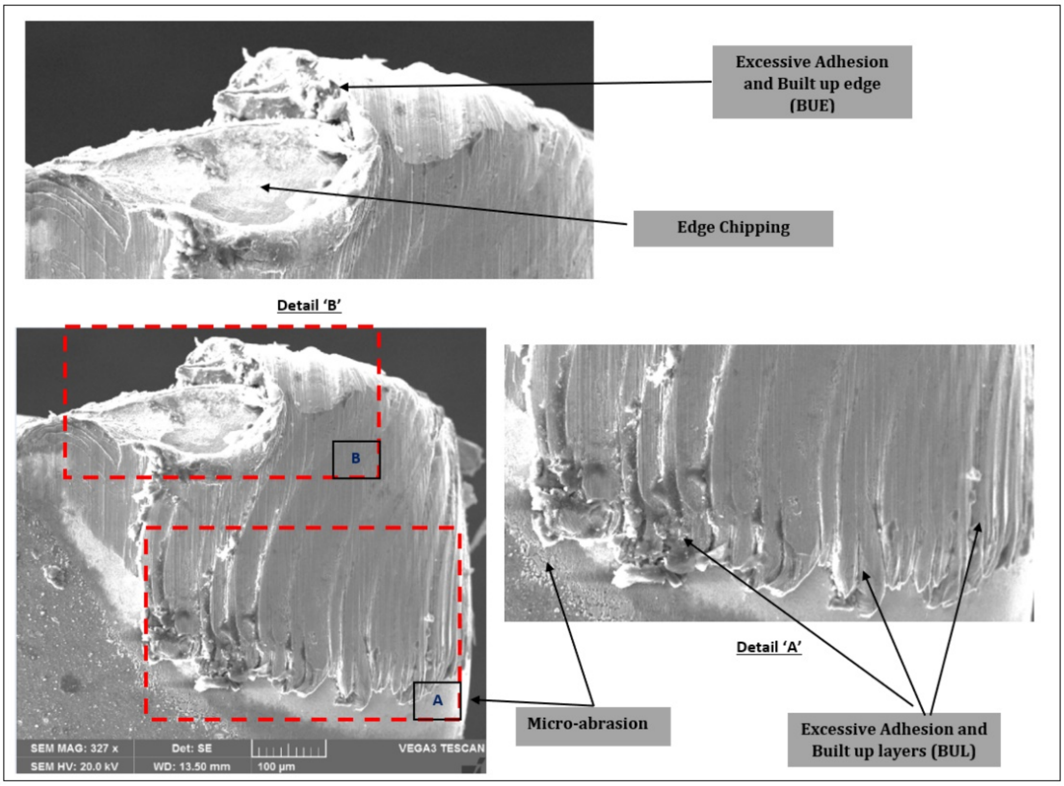
Figure 11c represents the scanning electron micrograph of dry cutting at the speed 150 m/min and feed rate of 0.3 mm/rev. It clearly shows the presence of excessive adhesion and built-up edges (BUE) at the cutting edge, as shown in Figure 11c, detail B. Similarly, on the flank face, the presence of several built-up layers (BUL) was clearly visible in Figure 11c, detail A. Edge chipping or flaking was also detected on the cutting edge. In addition to these dominant tool wear mechanisms, micro-abrasion was also found at the flank face of the tool. At the cutting speed of 150 m/min and feed rate of 0.3 mm/rev, the MQCL-assisted method did not provide a better tool life, as shown in Figure 11d. In order to investigate the underlying wear mechanisms, a scanning electron micrograph for MQCL at 100 mL/h was examined. The major observation at the flank face was linked with the existence of a big notch and associated edge chipping or flaking. This was the main reason associated with the lower life of MQCL-100. Besides that, there were hints of adhesion at the cutting edge and flank face. Micro-abrasion was also found at the flank face. As compared to dry cutting in Figure 11c, the cutting edge was found to be more deteriorated in the case of MQCL at 100 mL/h.



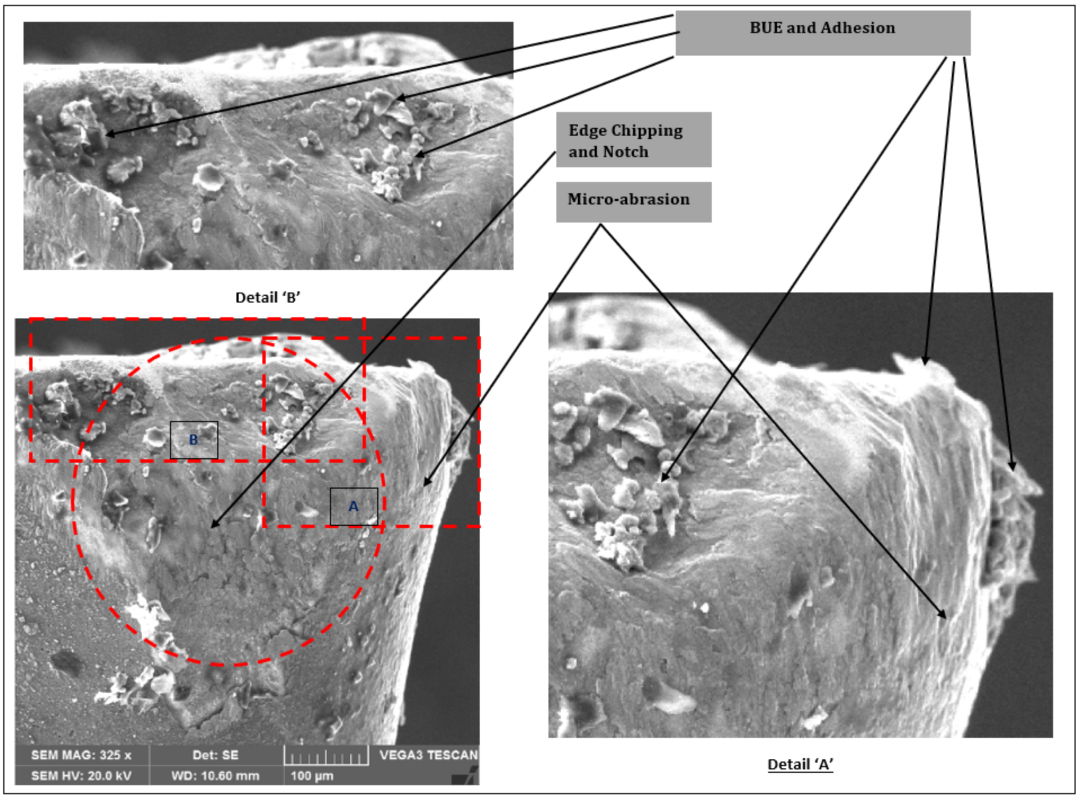
(**a**)



(**b**)



(**c**)



(**d**)

Figure 11. SEM of flank tool wear. (**a**) MQCL 70 mL/h at *V*c of 150 m/min, f of 0.2 mm/rev (**b**) MQCL 90 mL/h at *V*c of 150 m/min, f of 0.2 mm/rev, (**c**) dry cutting at *V*c of 150 m/min, f of 0.3 mm/rev, (**d**) MQCL 100 mL/h at *V*c of 150 m/min, f of 0.3 mm/rev.

5. Conclusions

This study evaluated the machining performance of Ti6Al4V using various oil flow rates under MQCL for TiAlN-coated cutting inserts. The following conclusions were drawn from this study:

- Lubrication during the metal cutting process is a very complex phenomenon due to the physical characteristics and chemical interactions. The MQCL approach showed encouraging performance due to its ability to improve lubrication by increasing the viscosity and dissipate heat by effective convective heat transfer, but its optimal performance at different oil flow rates highly fluctuated. this is because of the fact that when the machining interactive aspects (cutting conditions) varied, it became crucial for the lubricant to access the relevant locations of interactions.
- At the cutting interface, the penetration ability of the MQCL-based strategy was linked with the lubrication-specific parameters such as oil flow rates and air pressure, whilst at the same time was a function of the relative tool–workpiece movement (cutting conditions) and chip formation. This points out the complex selection involved in the MQCL-assisted strategy to attain optimal machining performance.
- At the cutting speed of 90 m/min and feed rate 0.1 mm/rev, MQCL at 90 mL/h provided the optimum performance. For the cutting speed of 120 m/min and feed rate 0.2 mm/rev, MQCL at 90 mL/h provided better performance. In both cases, said MQCL strategies were the second best behind flood cooling. A likely reason here can be linked with achieving an appropriate wettability using the MQCL method to dissipate heat efficiently from the cutting zone.
- At the higher cutting speed of 150 m/min, dry cutting emerged as a good option with the highest tool life and was verified with lower cutting forces and better roughness. A possible explanation could be that the higher temperature triggered thermal softening, which reduced the cutting forces and extended the tool life.
- At a higher speed and feed of 150 m/min and 0.3 mm/rev, MQCL with various oil flow rates did not provide reasonable tool life. SEM-assisted examination of MQCL at 100 mL/h showed excessive edge chipping and the presence of a notch at the cutting edge.
- A generic trend was observed in the oil flow rate under the MQCL strategy. Increasing the oil flow rate from 70mL/h to 100 mL/h improved surface finish and reduced thermal softening at a low feed rate of 0.1 mm/rev. For the feed rates, the effect of increasing the oil flow rate was not evident. this means that, at low feed rates, the possibility of lubricant particles reaching the cutting interface/chip fissures was higher, resulting in better chip up-curling and reduction in the contact length. However, more dedicated studies for chip formation and morphology are required to investigate this phenomenon.
- When machining Ti6Al4V with TiAlN-coated cutting inserts, tool wear comprised different combinations of wear mechanisms such as edge chipping or flaking, adhesion, BUE, and BUL can be found to be the dominant tool wear mechanisms. However, adhesion, BUE, and BUL were found in most of the cases.

6. Future Recommendations

- BUE formation is very complex in nature and can be affected by the experimental setup involved. In order to understand the BUE formation mechanism, there is a need to perform orthogonal machining on Ti6Al4v using a quick-stop device (QSD) setup.
- Residual stress formation is an important parameter that can significantly control the functionality of the parts being machined. It is important to study the influence of residual stresses during MQCL-based machining.
- MQCL-based machining simulation is an important tool, and the role of several MQCL-based parameters should be investigated further by developing a computational fluid dynamics (CFD)-assisted simulation model of MQCL.

Author Contributions: Conceptualization, S.P. and I.D.; methodology, S.P. and N.A.; validation, K.I., S.K. (Sarmad Khan) and S.K. (Sathish Kannan); formal analysis, S.P., N.A. and S.K. (Sarmad Khan); investigation, S.P., N.A. and S.K. (Sarmad Khan); resources, I.D. and S.K. (Sathish Kannan); data curation, S.P., K.I. and S.K. (Sathish Kannan); writing—original draft preparation, S.P.; writing—review and editing, I.D. and S.K. (Sathish Kannan); supervision, I.D.; project administration, S.P.; funding acquisition, I.D. and S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received financial support by Dubai Silicon Oasis Authority (DSOA), and Rochester Institute of Technology—Dubai (RIT-D).

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: The authors sincerely acknowledge the financial support provided by the Dubai Silicon Oasis Authority (DSOA), and Rochester Institute of Technology—Dubai (RIT-D).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Machado, A.R.; Wallbank, J. Machining of Titanium and its Alloys—a Review. *Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf.* **1990**, *204*, 53–60. https://doi.org/10.1243/pime_proc_1990_204_047_02.
2. Ezugwu, E.O.; Wang, Z.M.; Machado, A.R. The machinability of nickel-based alloys: A review. *J. Mater. Process. Technol.* **1999**, *86*, 1–16. https://doi.org/10.1016/s0924-0136(98)00314-8.
3. Sharma, V.S.; Singh, G.; Sørby, K. A Review on Minimum Quantity Lubrication for Machining Processes. *Mater. Manuf. Process.* **2014**, *30*, 935–953. https://doi.org/10.1080/10426914.2014.994759.
4. Sharma, A.K.; Tiwari, A.K.; Dixit, A.R. Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review. *J. Clean. Prod.* **2016**, *127*, 1–18. https://doi.org/10.1016/j.jclepro.2016.03.146.
5. Chetan; Ghosh, S.; Rao, P.V. Application of sustainable techniques in metal cutting for enhanced machinability: A review. *J. Clean. Prod.* **2015**, *100*, 17–34. https://doi.org/10.1016/j.jclepro.2015.03.039.
6. Su, Y.; He, N.; Li, L.; Iqbal, A.; Xiao, M.; Xu, S.; Qiu, B. Refrigerated cooling air cutting of difficult-to-cut materials. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 927–933. https://doi.org/10.1016/j.ijmachtools.2006.07.005.
7. Pervaiz, S.; Deiab, I.; Darras, B. Power consumption and tool wear assessment when machining titanium alloys. *Int. J. Precis. Eng. Manuf.* **2013**, *14*, 925–936. https://doi.org/10.1007/s12541-013-0122-y.
8. Pervaiz, S.; Rashid, A.; Deiab, I.; Nicolescu, C.M. An experimental investigation on effect of minimum quantity cooling lubrication (MQCL) in machining titanium alloy (Ti6Al4V). *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 1371–1386. https://doi.org/10.1007/s00170-016-8969-6.
9. Pereira, O.; Català, P.; Rodríguez, A.; Ostra, T.; Vivancos, J.; Rivero, A.; López-de-Lacalle, L.N. The Use of Hybrid CO_2+MQL in Machining Operations. *Procedia Eng.* **2015**, *132*, 492–499. https://doi.org/10.1016/j.proeng.2015.12.524.
10. Sartori, S.; Ghiotti, A.; Bruschi, S. Solid Lubricant-assisted Minimum Quantity Lubrication and Cooling strategies to improve Ti6Al4V machinability in finishing turning. *Tribol. Int.* **2017**, *118*, 287–294. https://doi.org/10.1016/j.triboint.2017.10.010.
11. Hegab, H.; Darras, B.; Kishawy, H. Sustainability Assessment of Machining with Nano-Cutting Fluids. *Procedia Manuf.* **2018**, *26*, 245–254. https://doi.org/10.1016/j.promfg.2018.07.033.
12. Yuan, Y.; Wang, C.; Yang, J.; Zheng, L.; Weiqiang, X. Performance of supercritical carbon dioxide (scCO2) mixed with oil-on-water (OoW) cooling in high-speed milling of 316L stainless steel. *Procedia CIRP* **2018**, *77*, 391–396. https://doi.org/10.1016/j.procir.2018.08.301.
13. Lv, T.; Huang, S.; Liu, E.; Ma, Y.; Xu, X. Tribological and machining characteristics of an electrostatic minimum quantity lubrication (EMQL) technology using graphene nano-lubricants as cutting fluids. *J. Manuf. Process.* **2018**, *34*, 225–237. https://doi.org/10.1016/j.jmapro.2018.06.016.
14. Maruda, R.W.; Krolczyk, G.M.; Feldshtein, E.; Pusavec, F.; Szydlowski, M.; Legutko, S.; Sobczak-Kupiec, A. A study on droplets sizes, their distribution and heat exchange for minimum quantity cooling lubrication (MQCL). *Int. J. Mach. Tools Manuf.* **2016**, *100*, 81–92. https://doi.org/10.1016/j.ijmachtools.2015.10.008.
15. Fernandes, F.; Danek, M.; Polcar, T.; Cavaleiro, A. Tribological and cutting performance of TiAlCrN films with different Cr contents deposited with multilayered structure. *Tribol. Int.* **2018**, *119*, 345–353. https://doi.org/10.1016/j.triboint.2017.11.008.
16. Fox-Rabinovich, G.; Yamamoto, K.; Beake, B.; Kovalev, A.; Aguirre, M.; Veldhuis, S.; Dosbaeva, G.; Wainstein, D.; Biksa, A.; Rashkovskiy, A. Emergent behavior of nano-multilayered coatings during dry high-speed machining of hardened tool steels. *Surf. Coatings Technol.* **2010**, *204*, 3425–3435. https://doi.org/10.1016/j.surfcoat.2010.04.002.
17. Pervaiz, S.; Deiab, I.; Rashid, A.; Nicolescu, M. Minimal quantity cooling lubrication in turning of Ti6Al4V: Influence on surface roughness, cutting force and tool wear. *J. Eng. Manuf.* **2015**, *231*, 345–353. https://doi.org/10.1177/0954405415599946.

18. Khanna, N.; Shah, P.; de Lacalle, L.N.L.; Rodríguez, A.; Pereira, O. In pursuit of sustainable cutting fluid strategy for machining Ti-6Al-4V using life cycle analysis. *Sustain. Mater. Technol.* **2021**, *29*, e00301. https://doi.org/10.1016/j.susmat.2021.e00301.
19. Pereira, O.; Rodríguez, A.; Barreiro, J.; Fernández-Abia, A.I.; De Lacalle, L.N.L. Nozzle design for combined use of MQL and cryogenic gas in machining. *Int. J. Precis. Eng. Manuf. Technol.* **2017**, *4*, 87–95. https://doi.org/10.1007/s40684-017-0012-3.
20. Yang, M.; Li, C.; Zhang, Y.; Jia, D.; Li, R.; Hou, Y.; Cao, H.; Wang, J. Predictive model for minimum chip thickness and size effect in single diamond grain grinding of zirconia ceramics under different lubricating conditions. *Ceram. Int.* **2019**, *45*, 14908–14920. https://doi.org/10.1016/j.ceramint.2019.04.226.
21. Yang, M.; Li, C.; Zhang, Y.; Jia, D.; Zhang, X.; Hou, Y.; Li, R.; Wang, J. Maximum undeformed equivalent chip thickness for ductile-brittle transition of zirconia ceramics under different lubrication conditions. *Int. J. Mach. Tools Manuf.* **2017**, *122*, 55–65. https://doi.org/10.1016/j.ijmachtools.2017.06.003.
22. Yin, Q.; Li, C.; Dong, L.; Bai, X.; Zhang, Y.; Yang, M.; Jia, D.; Li, R.; Liu, Z. Effects of Physicochemical Properties of Different Base Oils on Friction Coefficient and Surface Roughness in MQL Milling AISI 1045. *Int. J. Precis. Eng. Manuf. Technol.* **2021**, *8*, 1629–1647. https://doi.org/10.1007/s40684-021-00318-7.
23. Elsheikh, A.H.; Shanmugan, S.; Muthuramalingam, T.; Thakur, A.K.; Essa, F.A.; Ibrahim, A.M.M.; Mosleh, A.O. A comprehensive review on residual stresses in turning. *Adv. Manuf.* **2021**, *10*, 287–312. https://doi.org/10.1007/s40436-021-00371-0.
24. Elsheikh, A.H.; Muthuramalingam, T.; Shanmugan, S.; Ibrahim, A.M.M.; Ramesh, B.; Khoshaim, A.B.; Moustafa, E.B.; Bedairi, B.; Panchal, H.; Sathyamurthy, R. Fine-tuned artificial intelligence model using pigeon optimizer for prediction of residual stresses during turning of Inconel 718. *J. Mater. Res. Technol.* **2021**, *15*, 3622–3634. https://doi.org/10.1016/j.jmrt.2021.09.119.
25. Elsheikh, A.; Guo, J.; Huang, Y.; Ji, J.; Lee, K.-M. Temperature field sensing of a thin-wall component during machining: Numerical and experimental investigations. *Int. J. Heat Mass Transf.* **2018**, *126*, 935–945. https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.006.
26. Khoshaim, A.B.; Elsheikh, A.H.; Moustafa, E.B.; Basha, M.; Mosleh, A.O. Prediction of residual stresses in turning of pure iron using artificial intelligence-based methods. *J. Mater. Res. Technol.* **2021**, *11*, 2181–2194. https://doi.org/10.1016/j.jmrt.2021.02.042.
27. Padhan, S.; Das, S.R.; Das, A.; Alsoufi, M.S.; Ibrahim, A.M.M.; Elsheikh, A. Machinability Investigation of Nitronic 60 Steel Turning Using SiAlON Ceramic Tools under Different Cooling/Lubrication Conditions. *Materials* **2022**, *15*, 2368. https://doi.org/10.3390/ma15072368.
28. Elsheikh, A.H.; Elaziz, M.A.; Das, S.R.; Muthuramalingam, T.; Lu, S. A new optimized predictive model based on political optimizer for eco-friendly MQL-turning of AISI 4340 alloy with nano-lubricants. *J. Manuf. Process.* **2020**, *67*, 562–578. https://doi.org/10.1016/j.jmapro.2021.05.014.
29. Nouzil, I.; Eltaggaz, A.; Pervaiz, S.; Deiab, I. Toxicity Analysis of Nano-Minimum Quantity Lubrication Machining—A Review. *Lubricants* **2022**, *10*, 176. https://doi.org/10.3390/lubricants10080176.
30. Benjamin, D.M.; Sabarish, V.N.; Hariharan, M.; Raj, D.S. On the benefits of sub-zero air supplemented minimum quantity lubrication systems: An experimental and mechanistic investigation on end milling of Ti-6-Al-4-V alloy. *Tribol. Int.* **2018**, *119*, 464–473. https://doi.org/10.1016/j.triboint.2017.11.021.
31. Gnanadurai, R.R.; Varadarajan, A.S. Investigation on the effect of an auxiliary pulsing jet of water at the top side of chip during hard turning of AISI 4340 steel with minimal fluid application. *Int. J. Precis. Eng. Manuf.* **2014**, *15*, 1435–1441. https://doi.org/10.1007/s12541-014-0488-5.
32. Savenko, V.; Shchukin, E. New applications of the Rehbinder effect in tribology. A review. *Wear* **1996**, *194*, 86–94. https://doi.org/10.1016/0043-1648(95)06789-2.
33. Brinksmeier, E.; Meyer, D.; Huesmann-Cordes, A.; Herrmann, C. Metalworking fluids—Mechanisms and performance. *CIRP Ann.* **2015**, *64*, 605–628. https://doi.org/10.1016/j.cirp.2015.05.003.
34. Smith, T.; Naerheim, Y.; Lan, M. Theoretical analysis of cutting fluid interaction in machining. *Tribol. Int.* **1988**, *21*, 239–247. https://doi.org/10.1016/0301-679x(88)90001-1.
35. Accu-Svenska AB. ECOLUBRIC E200L, Material Safety Data Sheet. Available online: http://www.accu-svenska.se/ecolubric-vegetablebased-lubricant (accessed on 01/05/2022).

.

.