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Original Article

Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL

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ABSTRACT

Although nickel-based aerospace superalloys such as alloy 625 have superior properties including high-tensile and fatigue strength, corrosion resistance and good weldability, etc., its machinability is a difficult task which can be solved with alternative cooling/lubrication strategies. It is also important that these solution methods are sustainable. In order to facilitate the machinability of alloy 625 with sustainable techniques, we investigated the effect of minimum quantity lubrication (MQL), cryogenic cooling with liquid nitrogen (LN_2) and hybrid-CryoMQL methods on tool wear behavior, cutting temperature, surface roughness/topography and chip morphology in a turning operation. The experiments were performed at three cutting speeds (50, 75 and 100 m/min), fixed cutting depth (0.5 mm) and feed rate (0.12 mm/rev). As a result, CryoMQL improved surface roughness (1.42 μm) by 24.82% compared to cryogenic cooling. The medium level of cutting speed (75 m/min) can be preferred for the lowest roughness value and lowest peak-to-valley height when turning of alloy 625. Further, tool wear is decreased by 50.67% and 79.60% by the use of MQL and CryoMQL compared with cryogenic machining. An interesting result that MQL is more effective than cryogenic machining in reducing cutting tool wear.

1. Introduction

Nickel-based superalloys are preferred in critical tasks because of their superior properties at very high and very low temperatures. Inconel 625 is one of these alloys and has been used for many years. It is used in oil and gas production components, marine vehicles, various surfaces in contact with acids, biomedical applications, automotive industry, aerospace industry and nuclear reactors, etc. However, the behaviors of the material such as good mechanical characteristics under stress, poor heat conductivity, high strain hardening and high chemical closeness to tool material cause

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Nomenclature

MQL	Minimum quantity lubrication
Cryo	Cryogenic cooling
CryoMQL	Hybrid cooling/lubrication (MQL + Cryogenic)
Vc	Cutting speed (m/min)
f	feed rate (mm/rev)
ap	depth of cut (mm)
LN_2	Liquid nitrogen
Ni	Nickel
SEM	Scanning electron microscopy
EDX	Energy dispersive x-ray analysis
CR	Cooling regime
PVD	Physical vapor deposition
AMS	Aerospace Material Specification
Ra	Average surface roughness
ISO	International organization for standardization
V_{Bmaxq}	Flank wear
BUE	Built up edge
BUL	Built up layer
ν	Kinematic viscosity (mm^2/s)
VI	Viscosity index

some concerns which are high temperature in cutting zone, quick tool wear and poor surface integrity in the machining of these alloys [1,2]. One of the methods used to contribute to the machinability characteristics of these materials is the employment of cutting fluid.

Cutting fluids have an important place in chip removal operations. They perform basic tasks such as reducing the friction and power consumption, chip evacuation as well as cooling/lubrication of the cutting zone that directly affect the efficiency of chip removal operations. Moreover, there are also benefits such as protecting the cutting tool and machine tool from oxidation [3]. Due to all these positive effects, the use of cutting fluids is vital especially in turning of nickel based alloy-Inconel 625. However, there are some damages to the environment and worker health when using conventional (flood) cutting fluids [4]. In addition to these, it is known that the use of conventional cutting fluid increases the production costs [5]. As a result, the amount of coolant used in metal removal operations should be reduced. Currently, there are various alternative techniques available. For example, minimum quantity lubrication (MQL) and cryogenic cooling are some of them which are quite popular [6]. In the MQL system, the cutting fluid at an average flow rate of 10−100 ml/h is mixed with air and sent to the tool-work region as an aerosol [7]. In this system, the lubrication function is carried out by means of cutting oil, while the cooling function is achieved by using compressed air at high pressure. Thanks to the MQL system, very small amount of cutting fluid is used and so the negative impact of conventional technique on environment, worker health and production costs is minimized [8–10]. Some researches in the literature available [11–16] have indicated that the MQL technique can be an option to the conventional techniques. Another alternative cooling method is cryogenic cooling. Cryogenic cooling is used especially in heavy machining conditions, such as nickel alloys [17], titanium alloys [18] and stainless steels [19], which produce high heat during chip removal. The main advantage of this method is to reduce the temperature by providing effective cooling in the cutting zone. Due to these properties, cryogenic cooling has been employed in diverse operations namely turning [19], milling [20] and drilling [21]. In this method, helium, hydrogen, neon, nitrogen, oxygen and carbon dioxide are injected into the cutting zone with the help of compressed air. Nitrogen and carbon dioxide are the most preferred among these gases. However, the use of carbon dioxide gas causes a number of difficulties due to the fact that it is dry ice at solid-state, difficult to control and heavier than air [22]. Therefore, the use of liquid nitrogen (LN_2) is the most preferred gas in cryogenic cooling. The effect of LN_2 on machinability was investigated in several studies [23–25]. In these studies, the positive contribution of cryogenic cooling with LN_2 to machinability has been reported by researches.

In the above studies, it is seen that both the MQL and the cryogenic cooling can be an alternative to wet machining (conventional cooling). However, although these methods are efficient in light and medium cutting conditions, they are ineffective under heavy machining conditions. In heavy machining conditions, the MQL system shows deficiencies with regard to the cooling, while cryogenic cooling also exhibits deficiencies related to lubrication [26]. Therefore, in order to benefit from further cooling and lubrication, several studies have been conducted especially under heavy machining conditions, where cryogenic cooling is used together with the MQL [27].

According to the literature review, it is seen that studies have been made by researches to explore the influence of different cooling/lubrication methods on machinability indicators. In addition, some experimental studies focused on the hybrid cooling method such as CryoMQL [25]. As a result of the authors' research, no studies were found on the effect of the hybrid cooling/lubrication method as well as MQL and cryogenic cooling on investigating the surface roughness/topography, cutting insert wear, wear mechanisms, cutting temperatures and chip morphology in machining Ni-based alloy Inconel 625. In present work, to fill this gap, we aimed to investigate the effectiveness of MQL, cryogenic cooling and CryoMQL cooling/lubrication regimes in turning Ni-based alloy 625. In addition, the performance of these regimes under different variations of the cutting speed was also studied.

2. Material and methods

2.1. *Material-alloy 625, machine and cutting tool*

Inconel 625 (alternatively known as alloy 625) was chosen as workpiece material with the specification of AMS 5666. This material is a nickel-based alloy with excellent thermo-mechanical properties. Thanks to these properties, they find numerous applications in critical sectors such as aerospace, nuclear chemistry and petrochemical industry. The workpiece material properties are listed in Tables 1 and 2. ACCUWAY JT-150-8 CNC lathe (maximum spindle speed: 4000 rpm) manufactured by Taiwan was employed during the experiments. In the turning experiments, a type of PVD-TiAlN/TiN coated

Table 1 – Chemical composition of alloy 625 (% weight).

Ni	Cr	Fe	Mo	Nb	C	Mn	Si	Al	Ti	Co
58	20–23	5	8–10	3.15–4.15	<0.1	≤0.5	≤0.5	≤0.4	≤0.4	≤1

Table 2 – Mechanical and physical properties of alloy 625.

Ultimate tensile strength [MPa]	Modulus of elasticity [MPa]	Density [g/cm^3]	Melting range [°C]	Thermal conductivity [W/mK]	Elongation (%)
880	209	8.47	1290–1350	9.8	35

Table 3 – Cutting fluid properties.

Kinematic viscosity, ν at 20 °C (mm^2/s)	Kinematic viscosity, ν at 40 °C (mm^2/s)	Viscosity index, VI	Density (kg/m^3)	Flash point (°C)	Thermal conductivity (W/mK)
18	10	192.02	860	205	0.1684

Table 4 – Turning parameters.

Cutting parameters	Unit	Level 1	Level 2	Level 3
Cooling regime, CR	–	MQL	Cryogenic (LN_2)	CryoMQL (MQL + LN_2)
Cutting speed, *Vc*	m/min	50	75	100
Feed rate, *f*	mm/rev	0.12	–	–
Cutting depth, *ap*	mm	0.5	–	–

carbide tool (ISO designation: CNGG 120404 (S05-S25)) manufactured by Taegutec, Korea (manufacturer's insert code: TT5080) was utilized with specifications of rake angle: −6°, clearance angle: 0°, major edge cutting angle: 75° and nose radius: 0.4 mm because the PVD AlTiN coated quality on the ultra-thin substrate gives an excellent surface finish for turning of high temperature alloys. The cutting insert was rigidly mounted to a tool holder having ISO designation: PCLNR 2020M12-TB.

2.2. *Cooling/lubrication conditions and cutting parameters*

In the experiments, three different cooling/lubrication strategies were used. These are MQL, cryogenic cooling and CryoMQL (MQL + LN_2). For MQL experiments, Vario model MQL device manufactured by SKF was operated. Water-soluble cutting oil formulated with vegetable esters and special additives was employed during the experiments. The physical properties of cutting fluid are given in Table 3. The MQL system was configured for 8 bar pressure and 50 ml/h flow rate. The cutting oil was sprayed at a distance of 15 mm with nozzle diameter of 2 mm and spray angle of 30°. The spraying process was done on the rake face. In order to determine MQL parameters, it was utilized from preliminary experiments and literature [7,27]. The operating parameters used in this study are illustrated in Table 4. Here, in order to see the impact cooling/lubrication regimes at different cutting speeds, the feed and cutting depth were kept constant.

The liquid nitrogen (LN_2) at −196 °C was employed for cryogenic cooling in experiments. The LN_2 was stored in Taylor Wharton XL-45 HP model tank. It was delivered to the cutting area with the help of a flexible vacuum insulated hose. In this way, heat losses have been tried to be minimized. The nozzle with a 3 mm outlet diameter was used to be similar to the MQL system during the spraying of the LN_2. The liquid nitrogen was passed to the cutting point over the rake face at a distance of 15 mm with a spray angle of 30°. A schematic overview of the experimental setup is seen in Fig. 1.

2.3. *Measurements*

In order to collect the data of the cutting temperatures, Infrared Optris PI 450 camera with optical resolution of 382 × 288 pixels, framerate of 80 Hz and real-time thermographic monitoring was employed. A software was used to evaluate the temperature data determined from the camera. In this measurement, the emissivity value is very important in determining the temperature correctly depending on the material. In this study, the emissivity value for Inconel 625 was chosen as 0.5. For surface roughness measurement, Mahr Marsurf PS 10 device manufactured by Germany was employed. In measurements, Ra (average surface roughness value) was considered. This measurement was conducted based on ISO 4287 standard [28]. Measuring device has been set to 0.8 mm, 4 mm and 4.8 mm for sampling length, evaluation length and travel length, respectively. The workpiece was rotated in the cutting direction and the main data of the Ra was calculated by measuring at different regions. Moreover, a Phase View optical profilometer device was employed for 3D surface topography image. In tool wear experiments, AM 4113ZT (Dino-Lite) polarized digital microscope was used to determine the amount of wear. Wear types were determined according to ISO 3685 standard. After the wear value was determined, to analyze the wear mechanism on cutting insert and chip morphology, a scanning electron microscope (SEM; Zeiss LEO 440) was used.

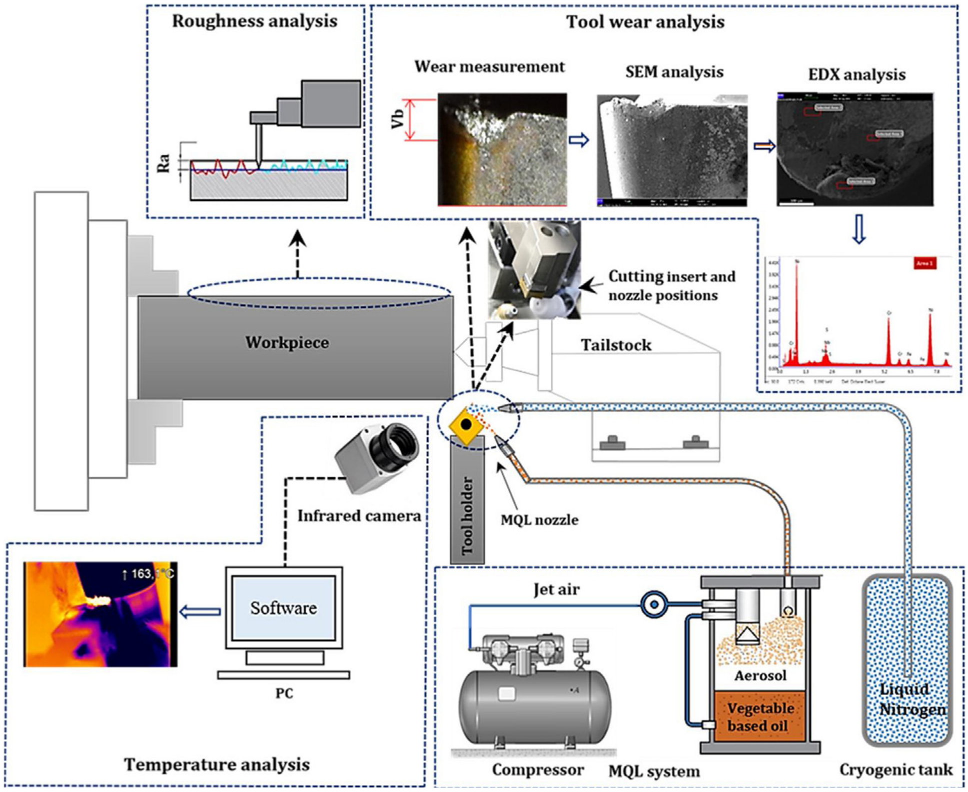

Fig. 1 – Experimental setup and workflow.

Moreover, it has previously been reported that superalloys tend to adhere to the cutting tool [29]. Thus, work material adhered to the cutting tool was investigated by means of Energy-dispersive X-ray spectroscopy (EDX) and so built-up-edge (BUE), built-up-layer (BUL) and their damage were analyzed.

3. Results and discussion

3.1. Cutting temperature

The majority of the mechanical energy used during the cutting process is converted to heat energy. The resulting temperature has a direct impact on factors such as dimensional accuracy, geometric accuracy, and surface integrity and particularly tool wear/life that are of great importance for machinability [30]. Therefore, controlling the cutting temperature is important for machining efficiency. In this part of the study, it is aimed to find the optimum parameter group for minimizing the cutting temperatures. When Fig. 2 is examined, it is seen that the most effective cooling/lubrication environment on the cutting temperature is CryoMQL. However, it should be noted that the results obtained from cryogenic cooling and CryoMQL cooling are close to each other. The highest cutting temperature was obtained from MQL. The cutting temperatures that occurred in LN_2 and CryoMQL were reduced by 21.7% and 24.9%, respectively compared to the MQL. The use of LN_2 provided a further reduction in cutting temperatures compared to MQL. It is clearly possible to say that cooling performance with LN_2

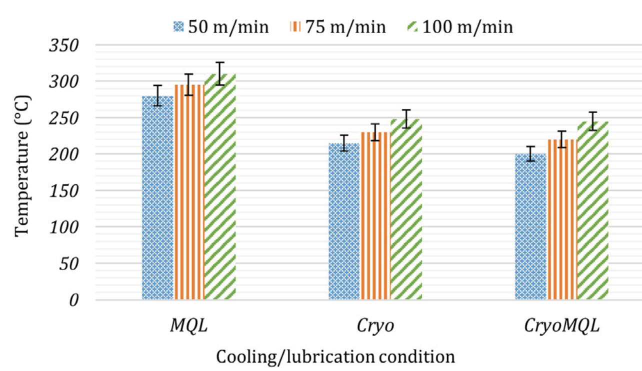

Fig. 2 – The effect of cooling regimes on temperature.

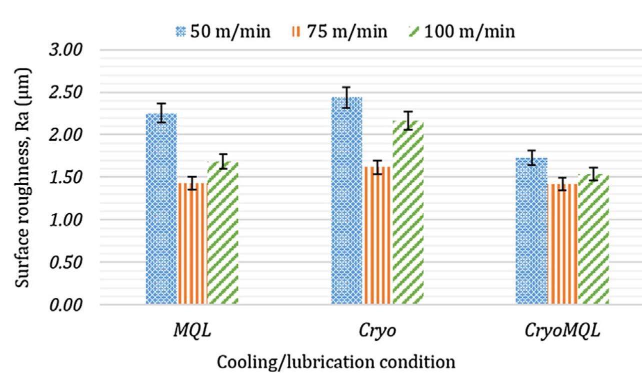

Fig. 3 – The effect of cooling regimes on surface roughness.

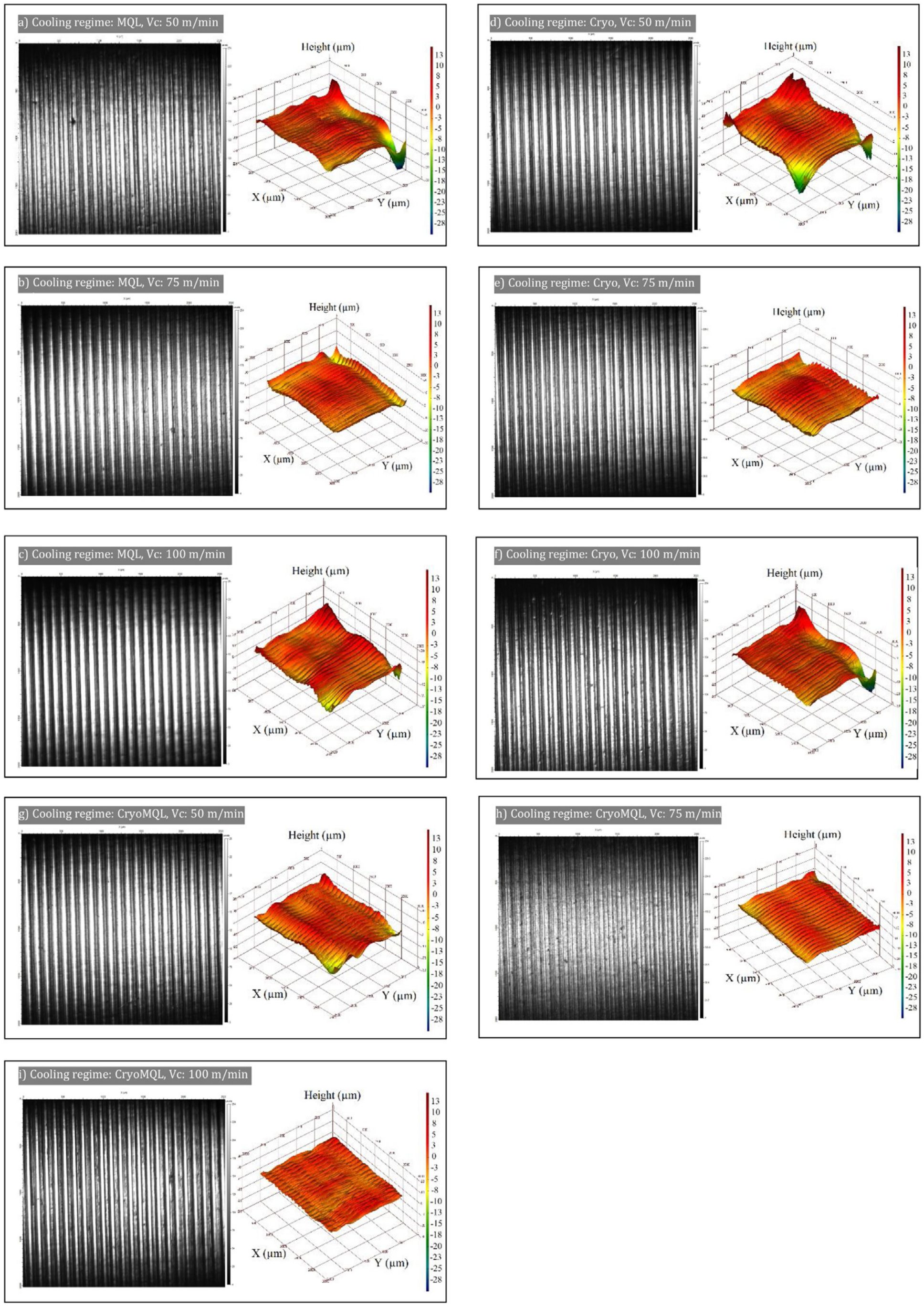

Fig. 4 – Images of machined surfaces and their 3D topographies under different cutting regimes a) MQL, Vc = 50 m/min b) MQL, Vc = 75 m/min c) MQL, Vc = 100 m/min d) Cryogenic, Vc = 50 m/min e) Cryogenic, Vc = 75 m/min f) Cryogenic, Vc = 100 m/min g) CryoMQL, Vc = 50 m/min h) CryoMQL, Vc = 75 m/min i) CryoMQL, Vc = 100 m/min.

usage is more effective than MQL. As it is known from previous studies, the cryogenic cooling environment exhibits better cooling performance under heavy machining conditions [31]. However, it is not possible to say that it has the same performance in terms of lubrication. In other words, in the cryogenic cooling process, the lubrication process is particularly weak for heavy machining conditions and therefore its efficiency decreases. Therefore, both the lubrication and cooling features were effectively used in the CryoMQL system. In terms of cutting speed, there was a linear relationship between cutting speed and temperatures (Fig. 2). In the experiments carried out at cutting speeds of 75 m/min and 100 m/min, the cutting temperature increased by 7.2% and 15.5% respectively, compared to the cutting speed of 50 m/min. Furthermore, with the cutting speed rising to 100 m/min, the rate of increase in the cutting temperature was much higher. This is associated with reduced cutting ability as well as friction. As a matter of fact, the results confirming this situation are given in section 3.3.

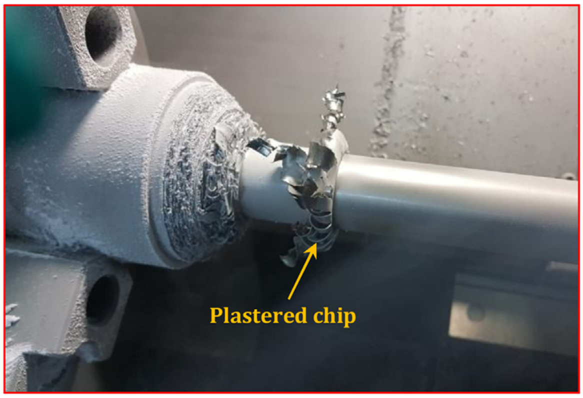

Fig. 5 – An image from the machining with cryogenic cooling.

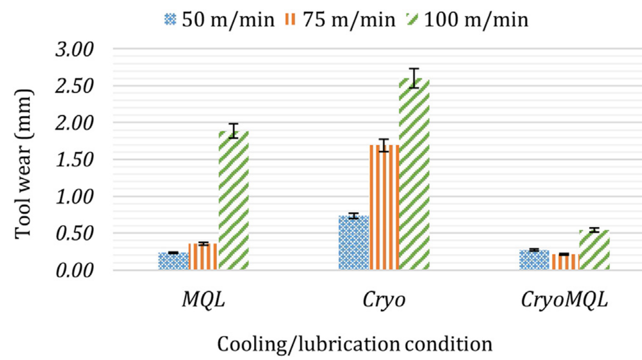

Fig. 7 – Variation in tool wear depending on cooling/lubrication regime and cutting speed.

3.2. *Surface roughness*

Surface roughness *Ra* on materials is commonly expressed to identify the changing in the height of the surface relative to a basic line. The roughness of solid surfaces is very important for surface interaction since the surface features impress the actual contact area, friction, wear, lubrication, fatigue strength, etc. Furthermore, surface roughness is also prominent in some conditions including optical, electrical and thermal ability, coloring and visual, etc. [32]. Therefore, it is very important to determine and minimize surface roughness. There are many parameters affecting the surface roughness, such as cutting speed, feed rate, cutting depth, cutting tool material and tool coating, cooling/lubricating environment, etc. In this study, other parameters were kept constant in order to more clearly analyze the effect of the cooling/lubrication regime together with the cutting speed.

Fig. 3 represents the average surface roughness. Here, it is seen that CryoMQL gives the lowest surface roughness (Ra = 1.42 μm) under CryoMQL cooling environment at 75 m/min of cutting speed; on the other hand, the highest surface roughness (Ra = 2.438 μm) was obtained under cryogenic cooling at 50 mm/min of cutting speed. Compared to cryogenic machining, Ra values obtained by MQL and CryoMQL decreased by 13.8% and 24.82%, respectively. From this result, it is said that both cooling and lubrication with CryoMQL have a positive effect on the surface quality. When CryoMQL is used, it is more effective because of combined with the cooling process that reduces the cutting temperature and the lubrication that reduces friction and therefore the roughness value on the machined surface is lower. On the other hand, when the effect of cryogenic cooling with LN_2 is compared to the effect of lubrication with the MQL process, it can be said that vegetable-based cutting oil in MQL has a good lubricating ability due to the principle structure of vegetable-based lubricant molecules and element component [33]. Vegetable-based cutting oil molecules can create a film layer on the workpiece surface, and the fatty acid in vegetable oil can interact with the work surface, creating a monofilm of metallic soap. They can reduce friction and wear and thus can improve surface quality [34]. In addition, the tool life is increased by using the appropriate cooling method. This is directly related to surface quality. Because homogeneity of tool flank wear directly affects surface quality [17]. To reach the lowest surface roughness value, it is determined that the medium cutting speed selection is suitable. This has been associated with a slight increment in speed to soften the cutting zone and make cutting easier. However, with the continued increment in speed, the cutting tool entered the wear process and started to lose its effective cutting ability. Thus, the surface quality deteriorated. It can be clearly stated here that when the cutting speed 100 m/min is used, the cutting tool enters the wear process earlier in all three cooling environments.

In addition to the evaluation of the average surface roughness, the texture and topography of the machined surface are also important for final products because a better surface topography can make many positive contributions to the product by improving the tribological properties of a surface [35]. In this part of the paper, the influence of cutting speeds and cutting regimes on surface topography is examined and the results are given in Fig. 4. When evaluated in terms of cutting speed, it was observed that the peak-to-valley height was higher at 50 m/min cutting speed, but this distance decreased with increasing speed. In other words, the surface topogra-

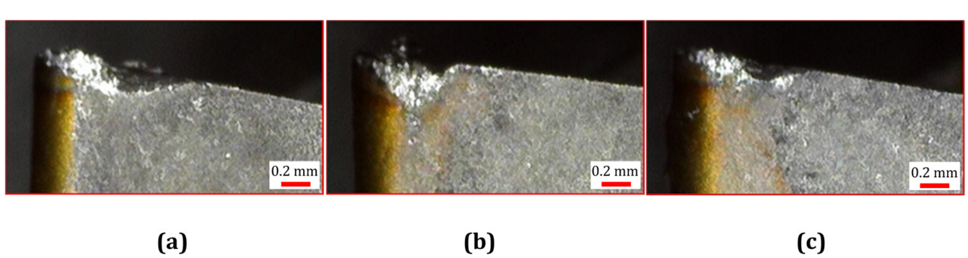

Fig. 6 – Overall condition of the worn cutting tool under a) MQL b) Cryogenic c) Cryo-MQL.

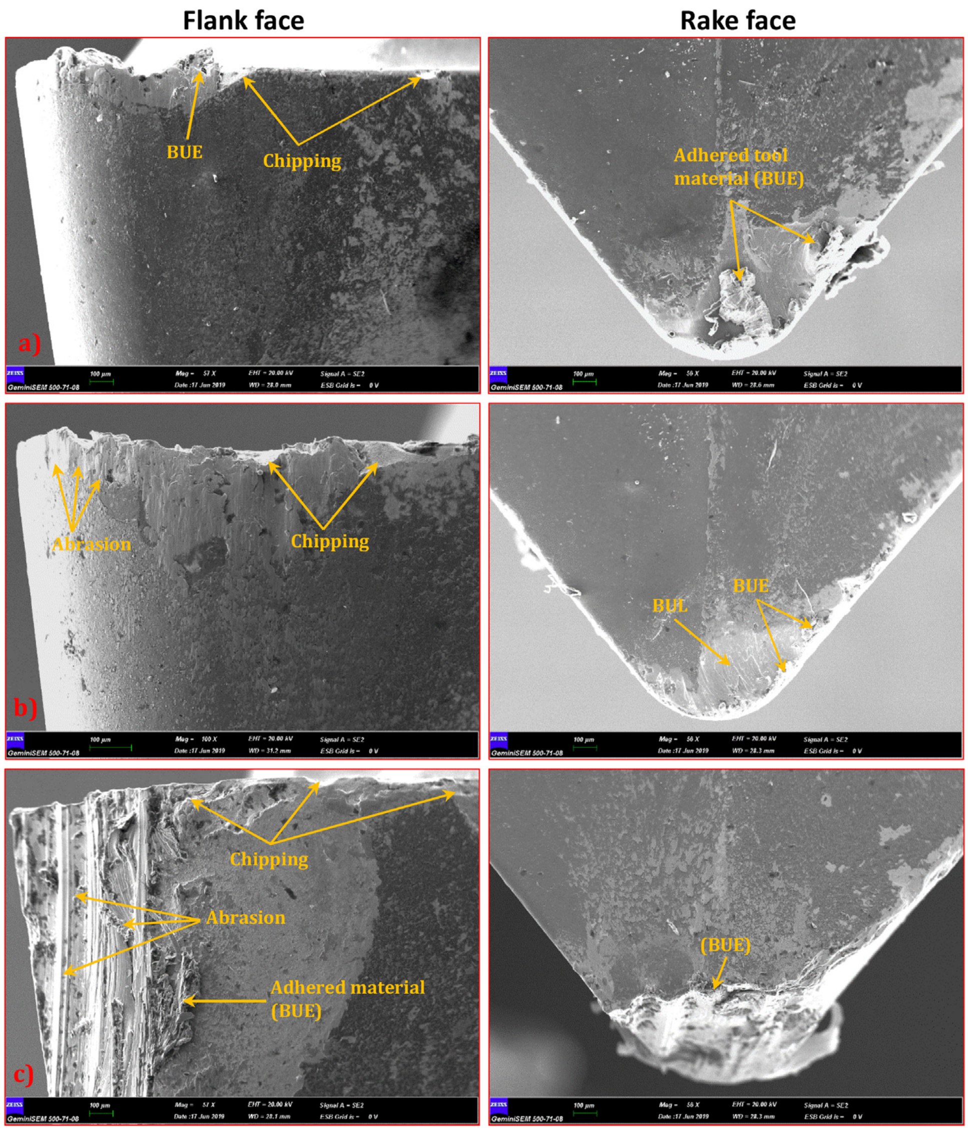

Fig. 8 – SEM images of the worn cutting insert under MQL cutting condition a) Vc = 50 m/min, b) Vc = 75 m/min, c) Vc = 100 m/min.

phy improved an increment in speed to 75 m/min. However, as the cutting speed continued to increase, it was observed that there has been some climbing in the distance between the peaks and the valleys. The high cutting speed causes high heat generation, which accelerates the wear and adversely affects the surface roughness. Furthermore, the workpiece rotates faster around the cutting tool as the cutting speed increases. This contributes to surface deterioration and the formation of irregular surface texture [36]. Another factor affecting the surface topography is the tribological interactions at the tool-chip interface. When Fig. 4 is analyzed from this view, it is seen that the lowest peak-to-valley height is obtained by CryoMQL. The highest peak-to-valley height is formed in the cryogenic cooling results. An image from the experiment with cryogenic cooling is given in Fig. 5, the chip was not regularly broken and therefore could not be evacuated from the cutting area. As a result of the ongoing cutting operation, it was observed that chip was plastered onto the workpiece. Although the cooling ability of cryogenic cooling is superior, the lack of lubrication during cryogenic machining makes chip removal difficult and therefore adversely affects the surface quality. The peak-to-valley height was lower than the other two methods when cryogenic cooling and the MQL system were used together. Moreover, irregular feed lines and debris have been reduced with the CryoMQL system. This can be explained by the efficient operation of both lubrication and cooling [37].

3.3. *Tool wear and wear mechanisms*

Machinability criteria such as surface roughness, cutting temperature, surface integrity, etc. are often dependent on tool wear and are directly influenced by it. It is under the effect of many parameters such as tool material, coating application, cutting speed, feed, cutting depth and cooling condition, etc. [38]. In this section of the study, to evaluate the impact of diverse cooling/lubrication regimes and cutting speed on tool

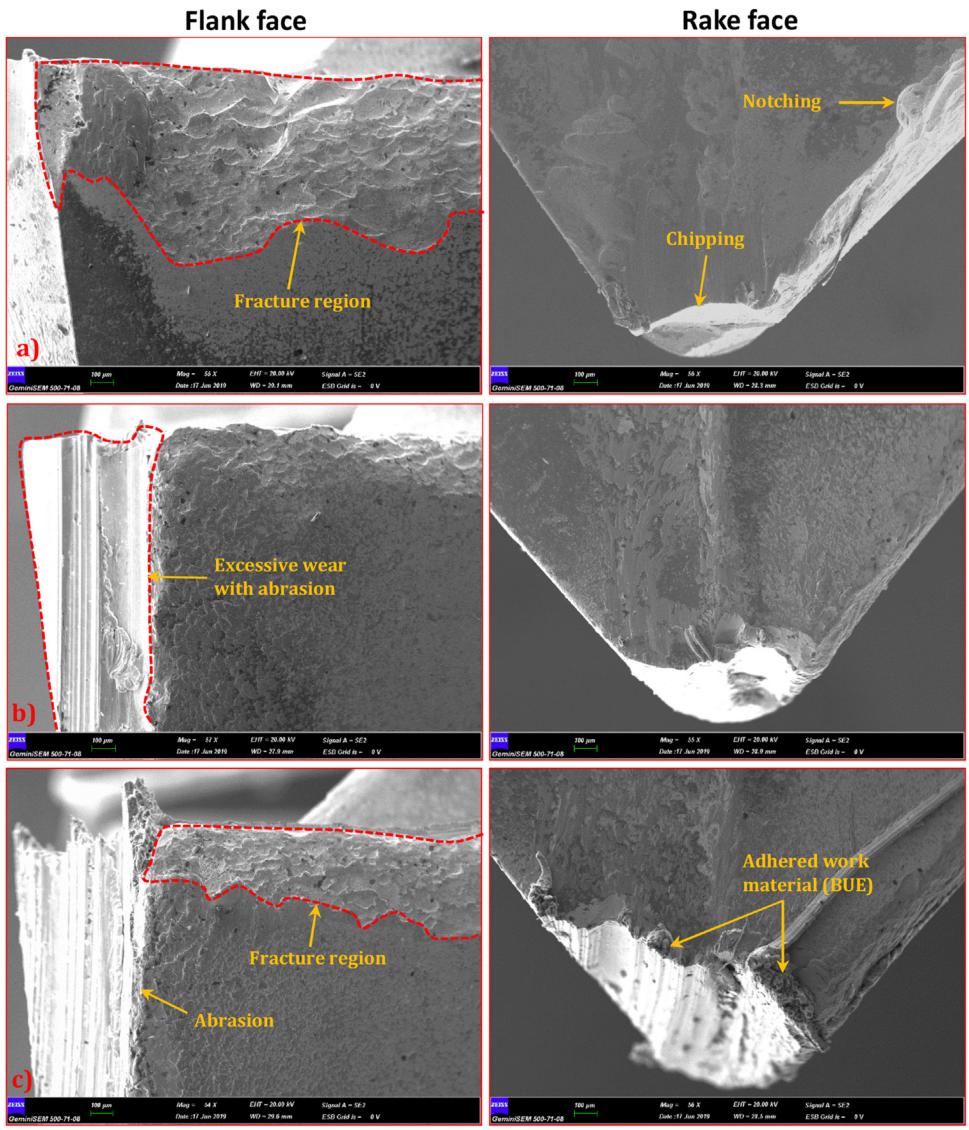

Fig. 9 – SEM images of the worn cutting insert under cryogenic cutting condition a) Vc = 50 m/min, b) Vc = 75 m/min, c) Vc = 100 m/min.

wear, the feed and cutting depth were fixed as 0.12 mm/rev and 0.5 mm. In each experiment, a fixed volume of the chip (40,000 mm^3) was taken from the workpiece and the state of the wear was observed. As a result of the preliminary tests, it is seen that the effective wear kind on cutting insert was notch wear as seen in Fig. 6.

Therefore, it can be said that notch wear is primarily responsible for completing the life of the cutting tools. It has also been reported in previous studies that notch wear is mostly observed in the machining of Ni-based alloys [27,29]. In many studies of machining of Ni-based alloys, although notch wear has been observed, there is no common consensus about the cause of it. In addition, the cause of the notch has been associated with more than one factor. They can be counted as high temperature, stress, work-hardening and abrasive chips [39].

Fig. 7 indicates the variation in tool wear depending on cooling/lubrication regimes and cutting speed. It was found that while the maximum tool wear (2.602 mm) occurred under cryogenic cooling, the minimum tool wear (0.211 mm) was reached from the CryoMQL cutting environment in turning of Ni-based Inconel 625. According to this, tool wear is reduced by 50.67% and 79.60% with the use of MQL and CryoMQL compared with cryogenic machining. An interesting finding that MQL is more effective than cryogenic machining in reducing tool wear. The cryogenic cooling helps reduce the temperature in the cutting zone only through forced convection, while the MQL method contributes more than one. Firstly, the lubrication in MQL wraps the cutting region with a layer of oil and this helps to reduce friction. Secondly, MQL contributes to the heat transfer due to the evaporation of droplets. Moreover, the improvement in tool wear was more obvious with the use of CryoMQL. Similar results on the effective performance of the CryoMQL have been reported by Bagherzadeh and Budak [40] and Gupta [6]. Bagherzadeh and Budak [40] claimed that more than one mechanism on this performance

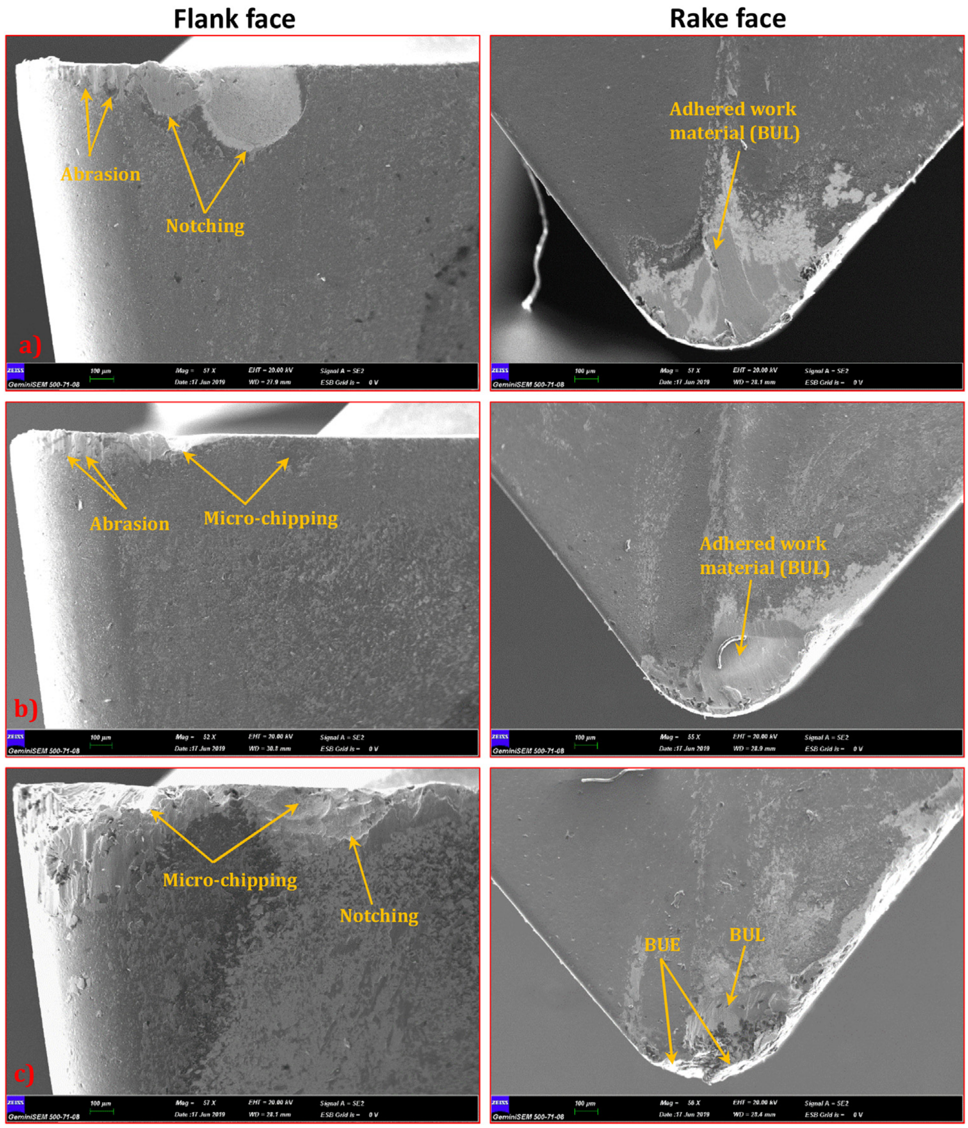

Fig. 10 – SEM images of the worn cutting insert under Cryo-MQL cutting condition a) Vc = 50 m/min, b) Vc = 75 m/min, c) Vc = 100 m/min.

could be effective with the simultaneous application of MQL and cryogenic cooling. These are higher penetration of oil into the chip tool interface, higher heat transfer because of very low-temperature oil, spraying the oil into the pre-cooled zone and reducing oil burning with cryogenic cooling and increasing the efficiency of MQL. As seen in Figs. 8, 9 and 10, SEM images indicate the characterization of wear mechanism of the cutting tool under different cooling/lubrication regimes (MQL, cryogenic cooling and CryoMQL and at cutting speeds of 50, 75, and 100 m/min). It is observed from these figures that the active wear mechanism was found to be adhesion in all cutting inserts. The presence of the adhesion mechanism has been proven with the built-up edge (BUE) and layer (BUL) forms occur on the cutting tool. Moreover, as seen in Fig. 11, EDX analysis made on the rake surface of cutting tools clearly demonstrates that adhesion is effective in all cooling/lubricating regimes since the element composition of the work material is obtained in these analyses. Habeeb et al. [41] stated that these phenomena (BUE and BUL) are very common during cutting Ni-based superalloys. It has been reported by Ezugwu et al. [42] that welding/adhesion of Ni-based superalloys onto the cutting insert often observe in cutting process, which causes serious damage to the cutter. It can be said that once the temperature of the tool-chip interface reaches a critical level, the tendency of workpiece to weld increases due to the chemical closeness between the cutting tool material and the work material. When Figs. 8, 9 and 10 were analyzed, it was seen that the cooling/lubrication methods used in this study were insufficient to eliminate the BUE and BUL forms. Moreover, another common type of damage that occurred in all conditions was chipping. Cantero et al. [43] emphasized that tool wear mechanisms are not treated as separate subjects, but are all interrelated. BUE and BUL resulting from the adhesion mechanism tend to encourage tool chipping which is formed by the separation of tool materials together with the workpiece material adhered on tool, because

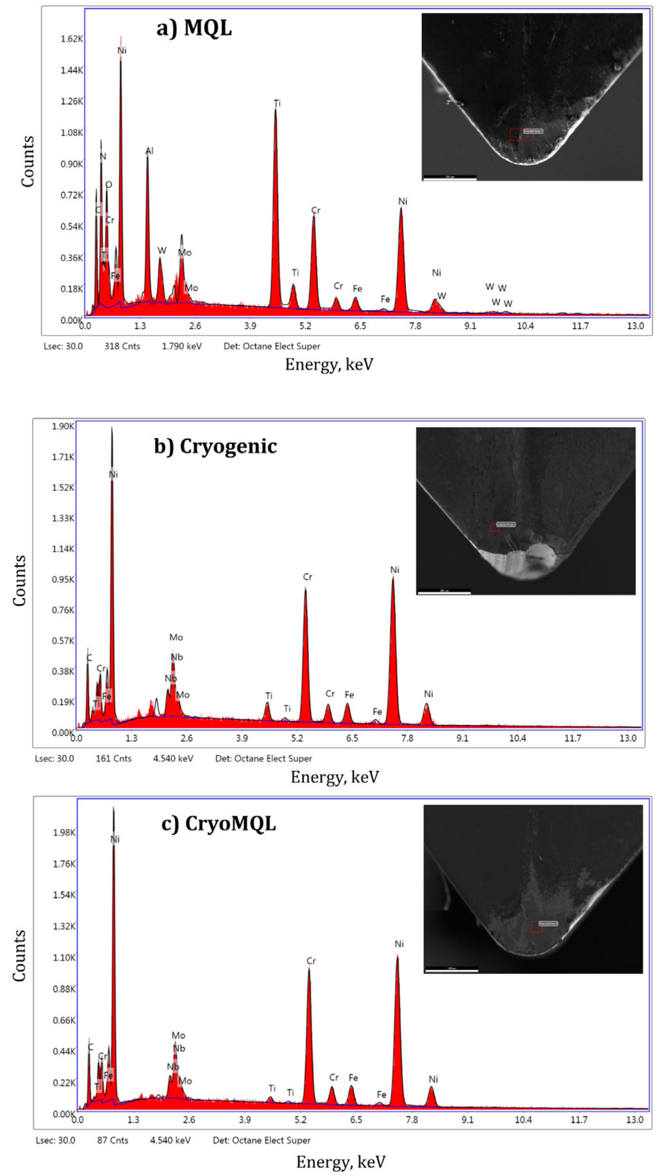

Fig. 11 – EDX analysis for worn cutting insert under a) MQL, b) Cryogenic, c) CryoMQL.

the BUE and BUL are not completely stable on the cutting insert.

In Figs. 8, 9 and 10, it can be seen that another effective wear mechanism on cutting tool was abrasive wear when turning of Ni-based alloy 625. Grooves parallel to direction of the chip flow in the flank-surface proved the presence of abrasive wear. As stated in previous researches, abrasive wear is common during the cutting of nickel-based alloys [39]. Hard-abrasive carbides in workpiece material enter the tool-workpiece interface, which produces a similar effect to the grinding process, which causes abrasive wear. Fig. 9 shows that abrasive wear in machining under cryogenic cooling conditions is quite noticeable compared to other cooling/lubrication conditions. Moreover, an increase in cutting speed accelerated this situation. The reason for this is thought to be the poor performance of cryogenic cooling in lubricating, as the friction between the tool and the workpiece increases in unit time. When SEM photographs are examined, another finding is notching. However, as mentioned above, there is no general consensus in the category of factors causing notching. When an evaluation was made according to cooling/lubrication conditions and cutting parameters, notching was observed in almost all cutting speeds and cutting conditions. However, it cannot be said that there is a significant change in parallel with the change in cooling conditions and cutting parameters.

3.4. *Chip morphology*

Chip morphology provides important clues about the cutting mechanics and is closely related to surface integrity of the finished product (surface roughness, surface topography, etc.) and machining efficiency. There are many variables such as cutting tool and workpiece material properties, operating parameters (feed, cutting speed, cutting depth, etc.) and

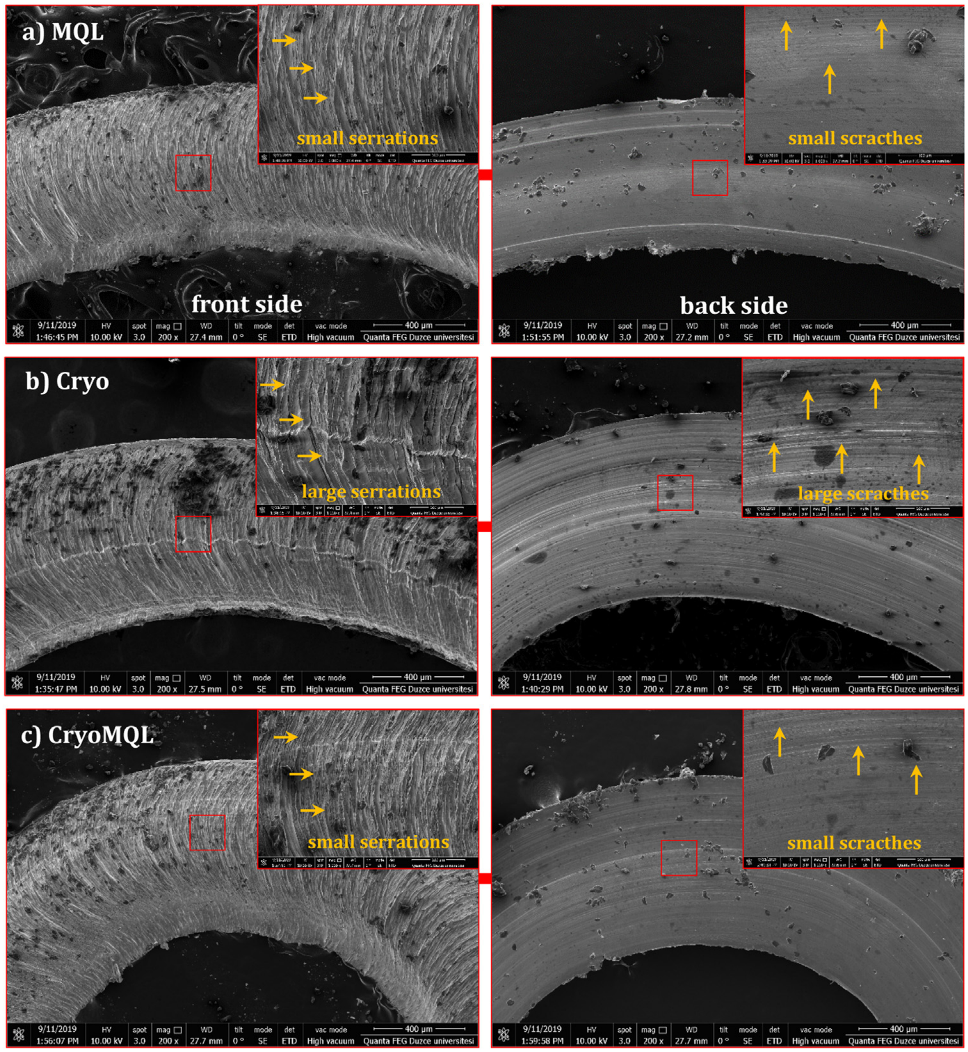

Fig. 12 – Chip morphologies of front and back side under cutting speed 75 m/min and feed rate 0.1 mm/rev when using a) MQL, b) Cryo and c) CryoMQL.

cooling/lubrication conditions affecting chip morphology and its shape [44]. In present work, the impact of diverse cooling/lubrication strategies on chip formation morphology has been analyzed while keeping other variables constant. For this purpose, SEM photographs of the chips produced under cryogenic cooling, MQL, CryoMQL cooling regimes at 75 m/min of speed and 0.1 mm/rev of feed were considered. Fig. 12 shows the micrographs of the front and back surfaces of the chips produced under different cutting conditions. When the backside of the chip is examined, it is seen that large scratches occur owing to the severe friction between the tool rake surface and the chip, especially in cryogenic cooling condition. This is an indication that the lubricity of the cryogenic cooling at the tool-chip interface is insufficient. The fact that the highest Ra value and poor surface topography (see section 3.2) obtained under cryogenic cooling condition confirms this situation. MQL and CryoMQL cooling regimes were found to significantly reduce scratches on the back face of the chip (Fig. 12(a) and (c)). Here, it can be said that the MQL has a decisive role in reducing the friction at the tool-chip interface thanks to its superior lubricity. By combining the superior cooling performance of cryogenic cooling and the superior lubrication properties of MQL, the reduction of scratches on the back face of the chip, better Ra values and higher tool life has been achieved. Looking at the chip front surfaces, serrated chip formation is clearly seen for all cutting conditions (Fig. 12).

When the front surfaces of the chips are examined, serrated chip formation is clearly visible for all cutting conditions (Fig. 12). Large serration occurred in the cryogenic cutting condition while small serration occurred in the MQL and CryoMQL cutting conditions. In addition, chip cross-section photographs given in Fig. 13 shows that the formation of serration under cryogenic cooling condition has sharp and linear lines compared to MQL and CryoMQL. Here, it can be said that there is a relationship between the formation of serration on the front face of the chip and the scratches on the back surface of the chip. Therefore, it can be stated that high deformation due to friction may be effective in clarifying serration formation.

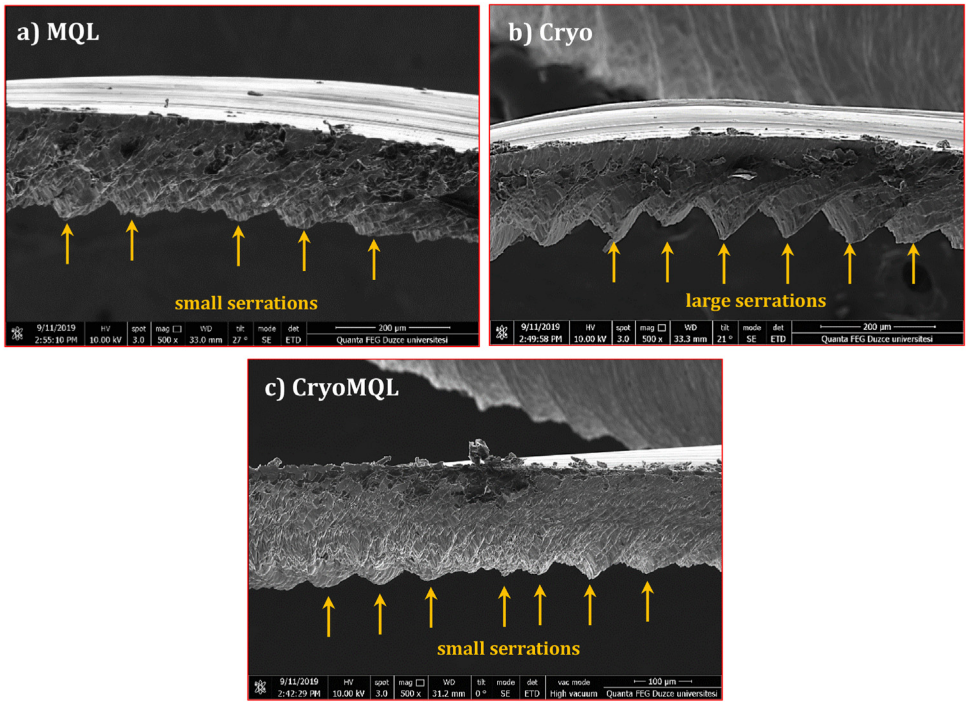

Fig. 13 – SEM images of chip cross section produced under a) MQL, b) Cryo and c) CryoMQL.

4. Conclusions

In this experimental work, Ni-based superalloy-Inconel 625 was handled in order to determine the consequences of the various cooling/lubricating cutting conditions and cutting speed on tool wear and mechanisms, cutting temperatures, surface roughness, surface topography and chip morphology in turning process. The findings from this work were summarized as follows:

1) Hybrid cooling/lubrication strategy (CryoMQL) has revealed better surface roughness *Ra* (1.42 μm) and surface topography (the lowest peak-to-valley height), on the other hand, the highest surface roughness (2.438 μm) value is obtained under cryogenic cooling. According to the calculations, CryoMQL improved the Ra by 24.82% compared to cryogenic cooling. The medium level of cutting speed (75 m/min) can be preferred for the lowest roughness value and lowest peak-to-valley height in the machining of Inconel 625. Further, MQL also contributed to the improvement of surface roughness with %13.8.
2) The cutting temperature was highest (310 °C) in MQL cooling/lubrication regime at 100 m/min of cutting speed while minimum cutting temperature (200 °C) obtained from CryoMQL at 50 m/min of cutting speed. Thanks to cryogenic cooling and CryoMQL, the cutting temperatures were reduced by 21.7% and 24.9%, respectively compared to the MQL. In the experiments carried out at cutting speeds of 75 m/min and 100 m/min, the cutting temperature increased by 7.2% and 15.5%. With the cutting speed rising to 100 m/min, the rate of increase in the cutting temperatures was much higher. This was explained with the reduced cutting ability of the cutting tool as well as friction.
3) It was obtained that the notch wear is primarily responsible for completing the life of the cutting tools as seen clearly in all cutting conditions. It was found that maximum tool wear (VB = 2.602 mm) is emerged from cryogenic cooling at 100 m/min of cutting speed, while minimum tool wear (VB = 0.211 mm) is in CryoMQL at 75 m/min of cutting speed. Moreover, tool wear is decreased by 50.67% and 79.60% by the use of MQL and CryoMQL compared with cryogenic machining. An interesting result that MQL is more effective than cryogenic machining in reducing tool wear when turning Ni-based alloy 625.
4) From SEM photographs, it was found that the effective mechanism for wear is adhesion in all cooling/lubrication regimes followed by abrasive wear mechanism. These wear mechanisms have caused damage to the cutting tool such as chipping, BUE and BUL formations, fracture, flank wear and notch wear. As a result of the adhesion mechanism, the BUE and BUL forms are very active on the cutting tool. Moreover, the presence of the adhesion mechanism has been proven with EDX analysis. It is said that the cooling/lubrication methods such as MQL, cryogenic and CryoMQL are insufficient to eliminate the BUE and BUL forms and their damages such as chipping.
5) SEM photographs of the backside of chips produced under different cooling regimes indicated that large scratches form due to the severe friction between the tool rake surface and the chip, especially in cryogenic cooling condition. It was found that MQL and CryoMQL cooling regimes reduce significantly the scratches on the back surface of the chip. Furthermore, serrated chip formation at the front surfaces of the chips is existed for all cutting conditions. Large ser-

ration occurred in the cryogenic cutting condition while small serration occurred in the MQL and CryoMQL cutting conditions. The formation of serration under cryogenic cooling condition has sharp and linear lines compared to MQL and CryoMQL.

Conflict of interest

The authors declare no conflicts of interest.

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