EXPERIMENTAL INVESTIGATION OF ALTERNATIVE COOLING METHODS IN MACHINING OPERATIONS

by

AMIN BAGHERZADEH

Submitted to the Graduate School of Engineering and Natural Sciences

in partial fulfillment of the requirements for the degree of

Master of Science

Sabanci University

December, 2018

EXPERIMENTAL INVESTIGATION OF ALTERNATIVE COOLING METHODS IN MACHINING OPERATIONS

APPROVED BY:

Prof. Dr. Erhan Budak
(Thesis Supervisor)

Prof. Dr. Yusuf Menceloğlu

Assoc. Prof. Dr. Yusuf Kaynak

DATE OF APPROVAL: 30.11.2018

In memory of my father and my brother

To my mother
With love and eternal appreciation

EXPERIMENTAL INVESTIGATION OF ALTERNATIVE COOLING METHODS IN MACHINING OPERATIONS

Amin Bagherzadeh

Manufacturing Engineering, MSc. Thesis, 2018

Thesis Supervisor: Prof. Dr. Erhan Budak

ABSTRACT

The most crucial demand in manufacturing industry is to improve productivity and efficiency of the processes. Cooling strategies play a significant role in determining the quality and cost of manufactured parts in machining operations. The present study examines machinability under new and alternative cooling methods in turning, milling and orthogonal turn-milling operations. It begins with an investigation of tool wear, surface finish, cutting forces and chip formation in turning of Ti6Al4V and Inconel 718 using a new cryogenic cooling approach, followed by a new assessment to enhance efficiency of cryogenic cooling in turn-milling of Inconel 718 and steel 1050. Finally, thermal analyses of steel 1050 slot milling and elemental analyses of the generated surface for different cooling methods have been presented.

Keywords: Cryogenic, Tool wear, Surface finish, Hard-to-cut materials, Thermal and Elemental Analyses

MAKİNE İŞLETMELERİNDE ALTERNATİF SOĞUTMA YÖNTEMLERİNİN DENEYSEL İNCELENMESİ

Amin Bagherzadeh
Üretim Mühendisliği, yüksek lisans Tezi, 2018
Tez danışmanı: Prof. Dr. Erhan Budak

Özet

İmalat sanayinde en önemli talep, proseslerin verimliliğini arttırmaktır. Soğutma stratejileri, işleme operasyonlarında üretilen parçaların kalitesini ve maliyetini belirlemede önemli bir rol oynamaktadır. Bu çalışma tornalama, frezeleme ve ortogonal frezeleme işlemlerinde yeni ve alternatif soğutma yöntemleri altında işlenebilirliği incelemektedir. Bu çalışma, yeni bir kriyojenik soğutma yaklaşımı kullanarak, Ti6Al4V ve Inconel 718'in tornalanmasında takım aşınması, yüzey kalitesi, kesme kuvvetleri ve talaş oluşumunun araştırılmasıyla başlıyor, Inconel 718 ve çelik 1050'nin frezeyle tornalama operasuyonu, kriyojenik soğutma verimliliğini artırmak için yeni bir değerlendirme ile devam ediyor. Son olarak, çelik 1050 slot frezelemede termal analizler ve farklı soğutma yöntemleri için üretilen yüzeyin elementel ve temel analizleri sunulmuştur.

Anahtar Kelimeler: Kriyojenik, Takım aşınması, Yüzey kalitesi, Kesilmesi zor malzemeler, Isıl ve Element Analizi

Table of Contents

CHAPTER1 INTRODUCTION ... 1

1.1. Historical perspective and review of cooling in machining ... 1

1.2. Sustainable machining ... 1

1.3. Literature Survey and Problem Definition of Cryogenic Machining ... 2

1.3.1. Cryogenic Turning ... 2

1.3.2. Cryogenic Milling ... 3

1.4. Organization of the Thesis ... 4

CHAPTER 2 INVESTIGATION OF MACHINABILITY IN TURNING OF DIFFICULT-TO-CUT MATERIALS USING A NEW CRYOGENIC COOLING APPROACH ... 5

2.1. Experimental setup ... 6

2.1.1. Experimental procedure and process strategy ... 6

2.1.2. Tool wear measurement and analysis method ... 7

2.1.3. Surface roughness measurement ... 8

2.1.4. Chip morphology analysis ... 8

2.2. Cooling methods ... 8

2.2.1. Cryogenic CO_2 system ... 8

2.2.2. Combination of MQL and CO_2 ... 9

2.2.3. Modification of CO_2 supply ... 10

2.3. Experimental results and discussion ... 12

2.3.1. Tool wear ... 12

2.3.2. Cutting forces ... 16

2.3.3. Surface finish ... 17

2.3.4. Chip morphology ... 21

... 23

2.4. Summary ... 24

CHAPTER 3 NEW ASSESMENT TO ENHANCE EFFICIENCY OF CRYOGENIC TURN-MILLING ... 25

3.1. Orthogonal Turn-Milling ... 26

3.2. Experimental setup ... 27

3.3. Result and discussion ... 29

3.4. Summary ... 31

CHAPTER 4 THERMAL ANALYSES AND ELEMENTAL ANALYSES OF THE GENERATED SURFACE OF STEEL 1050 MILLING FOR THE DIFFERENT COOLING METHODS 32

4.1. Experimental setup 33

4.2. Result and discussion 34

4.3. Elemental Analysis of the Specimens 38

4.4. Summary 44

CHAPTER 5 CONCLUSION 45

References 47

CHAPTER1 INTRODUCTION

1.1. Historical perspective and review of cooling in machining

From 16th century, cooling has been applied for the machining operations using water [1]. However, water-based cutting fluid and oil entered machining processes in the early 20th century. Cutting fluids can dissipate heat from the cutting zone and thus decrease chemical and thermal wear whereas enhancing part quality [2, 3, 4, 5, 6]. Nonetheless, recent studies [7, 8] indicate that metal cutting fluids are suspected of increasing different types of cancers, larynx, scrotum, rectum pancreas and bladder [9, 10]. Jawahir et. al [11] reviews progress of metal working fluids in detail.

In the 1990s, Minimum Quantity Lubrication (MQL) has emerged whilst improving power consumption, surface finish, tool life, etc. in machining. The effectiveness of minimum quantity lubrication (MQL) was limited because of low temperature reduction. Furthermore, environmental and health hazardous effects of mist oil is not completely understood [12, 13, 14], and thus, many promising areas of research is being conducted.

1.2. Sustainable machining

In recent years, sustainable manufacturing has emerged as a new trend in production. Cryogenic coolants have been reported to be a sustainable alternative to MQL and conventional metalworking fluids. Liquid Nitrogen (LN2) and Carbon dioxide (CO2) due to low temperature are used as a coolant in machining whereas different effects and application have been reported in literature. Since gas-based metal cutting fluids have lower specific heat capacity and lower molecular density in average, it is expected to have lower heat removal energy than for minimum quantity lubrication (MQL) spray. Nevertheless, higher heat removal energy is observed for high pressure LN2 and CO2 in comparison to MQL. This observation can be refer to the Joule–Thomson effect in which result in a drop in its internal energy and temperature when a gas experience adiabatic expansion. Furthermore, lower temperature during penetration is an essential influence of CO2 compared to liquid nitrogen (LN2) due to Joule–Thomson effect (Lemmon et al, 2011) [15]. Subsequently, Jerold and Kumar (2012) observed high deduction in tool wear and cutting forces as well as better surface finish for application of CO2 compared to LN2, while LN2 resulted in better cutting temperature reduction than CO2 supply [16]. As a result, this study examines alternative cooling based on CO2 whilst it offers advantages of sustainability in combination with better surface finish and higher heat removal efficiency compared to LN2.

1.3. Literature Survey and Problem Definition of Cryogenic Machining

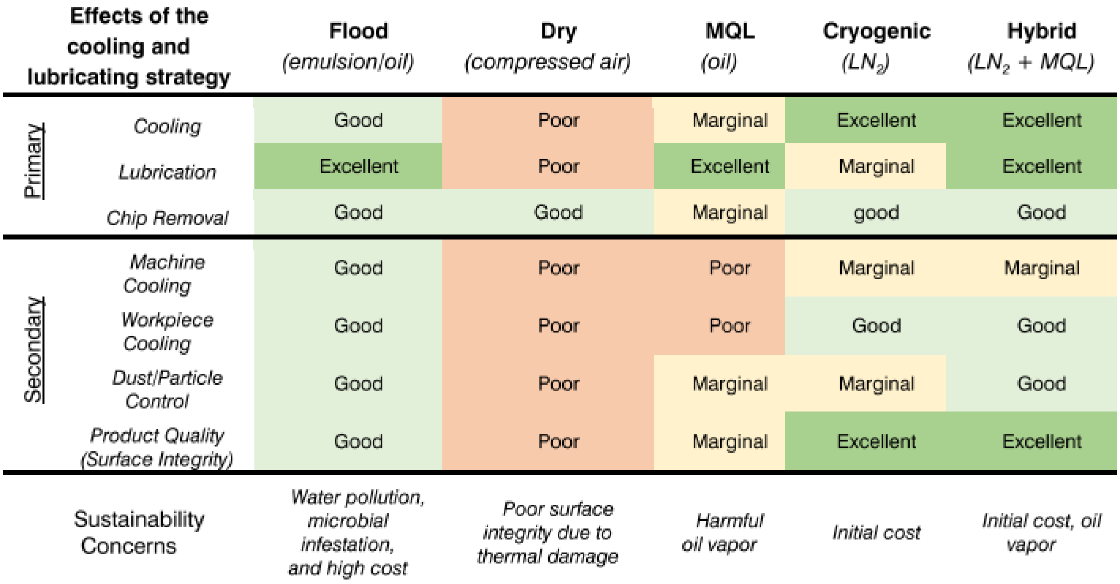
1.3.1. Cryogenic Turning

Wang and Rajurkar (2000) showed low tool life in turning of Ti6Al4V and Inconel 718 and thus designed a cryogenic cooling system for the cutting tool which resulted in improvement in tool life. They claimed that keeping tool's temperature at lower ranges lead to maintain the strength and hardness of the cutting tool material [17]. Hong and Ding (2001) investigated various types of cryogenic cooling method and reported that the target location of cryogenic cooling plays substantial role in dissipating tool's temperature [18]. Venugopal et al (2007) showed promotion of distinct types of tool wear and low tool life during turning of Ti6Al4V and investigated effectiveness of cryogenic turning [19]. The experimental results demonstrated that cryogenic cooling slowed down the tool wear progress but the effectiveness of cryogenic cooling decreased at high cutting speed of 100 and 117m/min, and therefore, claimed that reason could be improper penetration of cryogenic cooling. Bermingham et al (2011) reported lower cutting forces and lower tool wear when cryogenic coolant was used [20]. Nevertheless, he noted that not only the coefficient of friction in tool-chip interfaces did not reduce under cryogenic turning, but also in some cases increased in comparison with dry Ti6Al4V cutting. More recently, Rotella et al. (2014) noted there is no impact on the friction coefficient under cryogenic lubrication when machining Ti6Al4V [21]. To the authors' opinion, providing lubrication agent to cryogenic coolants could make a strong alternative in metalworking operations. In this case, not only the cooling characteristic of the cryogenics improve machining operation, but also marginal lubricant effect of the cryogenics could be supplemented by improving lubricant effectiveness of the supply. An extensive review on cryogenic machining have been published by Kaynak et al (2014) [22]. As can be seen from the review, cryogenic machining result in desirable surface integrity characteristics.

The combination of cooling and lubricant fluid was recently performed in different works. Supekar et al. (2012) used supercritical carbon dioxide ($SCCO_2$) based MQL and have shown that $SCCO_2$ with dissolved lubricant has a higher heat removal potential and heat removal efficiency than $SCCO_2$ with no dissolved lubricant[23]. Furthermore, he reported that $SCCO_2$ with dissolved lubricant can be both better coolants and lubricants than conventional metalworking fluids as reported by Clarens et al. (2006)[24]. In this system, liquid CO_2 pressurized above 7.38 MPa using a pump, and heated to its critical point (31.2 °C) as shown by Hyatt (1984)[25]. Pusavec et al. (2014) proposed special position for cooling and lubricant where LN2 delivered to the flank face while the oil mist was delivered to the rake face[26]. Overall, this method provided lowest cutting forces and lowest tool wear in comparison to dry, MQL and cryogenic cooling, but in some of the tests, highest cutting force component and the highest tool-wear on both faces resulted for his trend. Biermann et al. (2015) reported a better cooling method of cutting edge using combined cooling of CO_2-snow-cooling and minimum quantity lubrication through a modified tool holder where CO_2 was supplied from the rake face while MQL was supplied from flank face [27].

1.3.2. Cryogenic Milling

Effect of cryogenic cooling in milling operation is not well understood. For instance, Cordes et al (2014) showed that CO2 reduce tool wear 62% in comparison to MQL when milling [28]. On the other hand, Tayler and Schmits reported 89% longer tool life using MQL cooling in comparison to CO2 cooling when milling Hatelloy X [29]. However, Pereira et al reported lower tool life for CO2 compared to MQL, but, they developed a nozzle to combine MQL and CO2, and thus, the effectiveness of cooling has been enhanced 9.3% than for MQL in milling Inconel 718 while more study needed to demonstrate improvement of cooling [30]. Various cooling methods with a comparison of effectiveness and sustainability concerns are displayed in table 1.



	Effects of the cooling and lubricating strategy	Flood (emulsion/oil)	Dry (compressed air)	MQL (oil)	Cryogenic (LN_2)	Hybrid (LN_2 + MQL)
Primary	*Cooling*	Good	Poor	Marginal	Excellent	Excellent
	Lubrication	Excellent	Poor	Excellent	Marginal	Excellent
	Chip Removal	Good	Good	Marginal	good	Good
Secondary	*Machine Cooling*	Good	Poor	Poor	Marginal	Marginal
	Workpiece Cooling	Good	Poor	Poor	Good	Good
	Dust/Particle Control	Good	Poor	Marginal	Marginal	Good
	Product Quality (Surface Integrity)	Good	Poor	Marginal	Excellent	Excellent
	Sustainability Concerns	*Water pollution, microbial infestation, and high cost*	*Poor surface integrity due to thermal damage*	*Harmful oil vapor*	*Initial cost*	*Initial cost, oil vapor*

Table 1: Effectiveness of lubricating and cooling methods [11].

In spite of the fact that cryogenic machining yielded substantial advantages in comparison to other cooling methods, it has still not found a wide use in industry. High improvements in terms of machining economics, productivity, and above all part quality could convince the industry to use cryogenic cooling. In order to help this, new methods needed to provide lubricant agent to cryogenic coolants, whereas they intend to enhance productivity and the benefit of cryogenic cooling specially in high speed machining.

1.4. Organization of the Thesis

This thesis includes 4 chapters as is listed below:

- After this introductory chapter 1, Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach is presented in chapter 2.
- Chapter 3 is deducted to new assessment to enhance efficiency of cryogenic cooling in turn-milling of Inconel 718 and steel 1050.
- In chapter 4, thermal analysis of the various cooling and elemental analysis of the generated surfaces under new cooling strategy is studied.
- In chapter 5, conclusions achieved from this study are presented. The summary of the results are reported and future work is outlined.

CHAPTER 2 INVESTIGATION OF MACHINABILITY IN TURNING OF DIFFICULT-TO-CUT MATERIALS USING A NEW CRYOGENIC COOLING APPROACH

In this study, external application of liquid CO_2 and minimum quantity oil as a lubricant (CMQL) have been examined as an alternative method for supercritical CO_2 and other available types of single or lubricant-combined cryogenic techniques in the literature. Among recent cryogenic techniques, super critical carbon dioxide such a lubricant-combined method will be problematic in industry. This is mainly due to the fact that higher energy is needed to provide and support critical pressure and temperature of adequate CO_2 in the production line in addition to the high cost of this equipment. Moreover, Hong and Ding (2001) reported efficiency of the coolants/lubricants in tool-chip interface is much more than workpiece cooling or tool flank face cooling in terms of both heat removing and lubricating. As a result, it is hypothesized that CMQL on the tool's rake face without any extra pressurizing and heating to reach supercritical phase of CO_2 and dissolved lubricant can be more economical and effective. In addition, it produces better lubrication and cooling condition rather than various available combined method of cryogenics and MQL supply on the cutting tools and the workpiece. Consequently, this study investigated three scenarios with the same consumption of CO_2 (CO_2/CO_2+MQL/CMQL) in addition to modified CO_2 nozzle technique with higher consumption of CO_2 with respect to best performance of CO_2 nozzles in the literature. Since, cryogenic coolants have less impact on machinability at high speeds than low speeds as reported by Venugopal et al (2007), high cutting speed of 150 m/min and 100 m/min were selected for Ti6Al4V and Inconel 718 cutting respectively. In order to experimentally verify these hypotheses, tool wear, surface finish, chip formation and cutting force measurements were conducted to compare machinability under each cooling scenario. As a result, the CMQL technique offers a new and alternative solution to enhance the efficiency of high speed cryogenic machining leading to higher tool life and better surface finish.

2.1. Experimental setup

2.1.1. Experimental procedure and process strategy

The turning operation was carried out on Mori Seiki NL 1500 CNC-Turning lathe. Uncoated carbide inserts with designation of TPGN160308 and nose radius of 0.8mm were clamped on tool holder to provide a lead angle of 0° and a rake angle of -5°, which was held by Kistler Piezo-dynamometer to measure forces. The workpiece material of the Ti6Al4V and Inconel 718 have been used. Data logging was done by Lab View Signal Express software. Since, high cutting speed results in higher rate of wear, cutting speed of 150m/min and 100m/min were selected in the tests of modified and new method of cooling. Other cutting parameters used in the tests were f=0.2mm/rev and a_p=1mm as displayed in Table 2. The experiment repeated five times for each cutting method and then, the average of each measurement reported for the behavior of tool wear, surface roughness and cutting forces.

Cutting speed (m/min)	**Feedrate (mm/rev)**	**Depth of cut (mm)**	**Cooling methods (varies for each listed techniques below)**
		Ti6Al4V	
150	0.2	1	CO_2 (rake)
150	0.2	1	CO_2 (rake)+MQL(flank)
150	0.2	1	CMQL(rake)
150	0.2	1	Cryogenic CO_2 (modified nozzle)
		Inconel718	
100	0.2	1	CO_2 (rake)
100	0.2	1	CO_2 (rake)+MQL(flank)
100	0.2	1	CMQL(rake)
100	0.2	1	Cryogenic CO_2 (modified nozzle)

Table 2: Cutting Data

2.1.2. Tool wear measurement and analysis method

The progress of tool wear was measured by Dino-Lite digital microscope which was attached to the machine tool using a magnetic clamp to measure the tool wear without removing insert from tool holder as is displayed in Figure 1-a. This method of measurement enables measurement to be done for the fixed position of the insert eliminating potential error sources due to successive clamping and un-clamping of the insert during the tests. Wear measurements in every repeated trial and for every types of wear were done three times and the average was taken as the result. After reaching average flank or nose wear of 300μm cutting tests were aborted according to ISO 3685. Besides, the criteria for maximum flank wear and notching at the depth of cutline was 600μm for Inconel 718. Nonetheless, the limit of 400μm was selected for maximum and notch wear of Ti6Al4V due to lower progress of these wear in comparison to Inconel 718.

2.1.3. Surface roughness measurement

The surface roughness measurement was carried out with mobile roughness instrument Mahr PRN10, which was attached to machine tool by a magnetic clamp as is displayed in Figure 1-b.

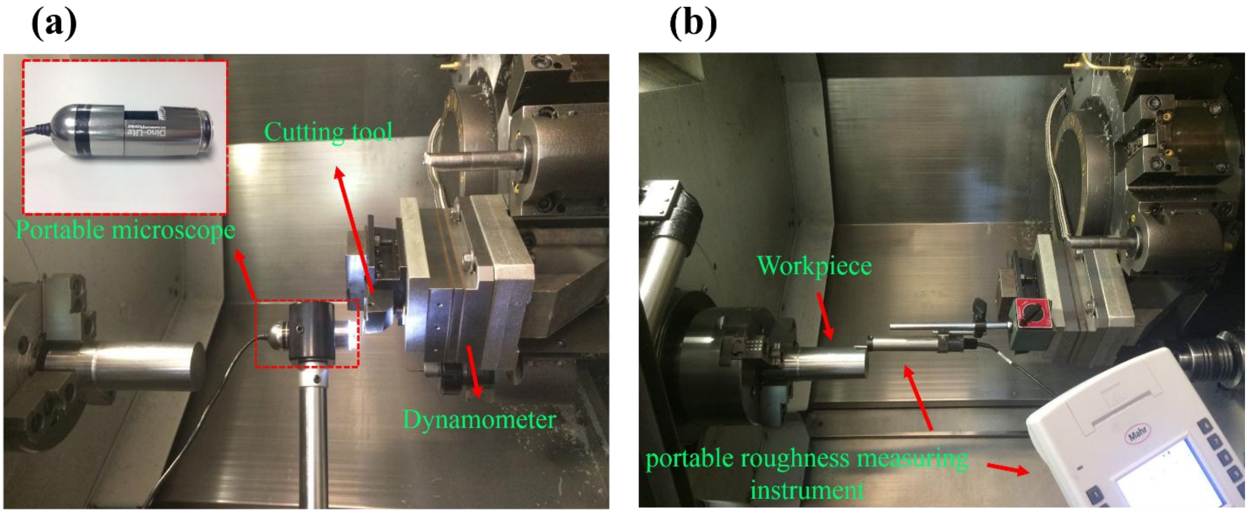


Figure 1: a) Tool wear measurement method using portable digital microscope without removing inserts from tool holder and machine tool. b) Surface roughness measurement strategy using portable roughness measuring instrument without detaching workpiece from spindle.

2.1.4. Chip morphology analysis

In order to compare different types of cooling methods, the produced chips ranging from 7 to 11 meter cutting length were characterized under SEM to investigate behavior of chip breakage and their microstructures.

2.2. Cooling methods

2.2.1. Cryogenic CO_2 system

In order to investigate the effects of various cryogenic coolants, various cooling types were applied during turning operation, where the base of applied coolants were cryogenic CO_2 due to its environmental friendliness. A carbon dioxide cylinder containing combination of gaseous and liquid CO_2 was used in the tests. The pressure in the cylinder was approximately 57 bar at 20^0C. If liquid CO_2 is abruptly depressurized during injection, its temperature considerably drops producing a mixture of CO_2 gas and CO_2 snow. The CO_2 tubes were renewed when the pressure of the CO2 were decreased down to 54bar. The temperature of CO_2 snow theoretically is -79.05^0C. The cylinder was connected to the digital pressure gage to monitor the pressure drop. The pressure was dropped for a while after activating CO_2 until reaching stable outlet pressure condition. For that reason, cooling was activated before cutting. All connection parts were made of stainless steel and resistant to high pressure to supply CO_2 through the nozzle.

2.2.2. Combination of MQL and CO_2

The new method of cooling was carried out using combination of MQL and CO_2, where both coolants supplied from the rake face (CMQL). In this method, the injected liquids meet each other before reaching the cutting zone as frozen oil particles, thereby making a different attempt in comparison to separately cooling/lubricating each faces of cutting tool and workpiece or using the supercritical CO_2 in turning of the hard to cut materials. The nozzle of CO_2 with diameter of 0.5mm and distance of 1.25mm was fixed from the center of the cutting edge. The nozzle was supplied to cutting zone with the angle of 15° from both the planes of xz and zy as shown in Figure 2-a. The nozzle of MQL was supplied to the outlet of CO_2 nozzle with the angle of 90°C as displayed in Figure 2-c. As CO_2 was injected at the pressure of 57bar and average flow rate of about 3g/s, oil was conveyed by means of the high pressure CO_2 to the cutting zone. Vegetable oil with boiling point of 200^0C and melting point of -39°C was used in micro lubrication system to spray at the pressure of 6 bar and flow rate of 100cc/min for a period of 0.1 second with 0.4 second interruptions. Moreover, while the mentioned position for CO_2 was kept constant, the position of the MQL nozzle located 6 mm from the center of the cutting edge with fixed position was changed from the rake face to flank face in order to limit the number of variables, as shown in figure2-b. As the last type of coolant the MQL system was stopped while only the CO_2 with thin nozzle was supplied to the cutting zone.

The authors believe that CMQL is sensitive and hard to create correctly for the first time. There is a limited space on the rake face to supply 2 coolants simultaneously. In addition, the higher pressure of CO_2 may prevent the oil entering the cutting edge. Using low flow rate of CO_2 makes application of CMQL possible in practice. An underlying key point to the control of CMQL technique is making sure that the oil enters the cutting zone. The solidification of the oil with CO2 resulted in higher adhesion of the oil. Thereby, where applied vegetable oil had red color, solidified light red material due to frozen oil should be created clearly on whole cutting edge line. This clue can be observed from down view of flank face when delivery was done correctly. Furthermore, when the workpiece obstruct the CMQL supply before cutting, the frozen oil particles emerge on workpiece absolutely as is shown in figure3.

2.2.3. Modification of CO_2 supply

The performance of the cryogenic cooling can be enhanced further by optimizing the position of the nozzle as discussed by Hong et al(2001). The modification of CO2 nozzle is regarded in terms of easy to assemble, occupying less space, having suitable distance and angle from cutting zone as well as less pressure drop. The cryogenic cooling nozzle was designed to supply CO2 from the rake and the flank faces, simultaneously. In this regard, one head open tube with diameter of 2.5mm was connected to the CO_2 cylinder, while it bended through the cutting edge. Two holes with diameter of 1mm were drilled on the steel tube where the angle of holes from rake and flank planes were about 15°. Creation of these angles was possible to the reason of tube wall thickness. Moreover, distance of 1.25mm was maintained from the center of the cutting zone by moving and fixing the tube on the insert. The above mentioned design not only helps covering rake and flank faces using less space, but it also contributes to approach nozzle to high efficiency positions. Other advantages of the proposed nozzle is to facilitate using different holders and insert designs in machine shops without damaging tool holders as is displayed in figure 2-d and figure 4.

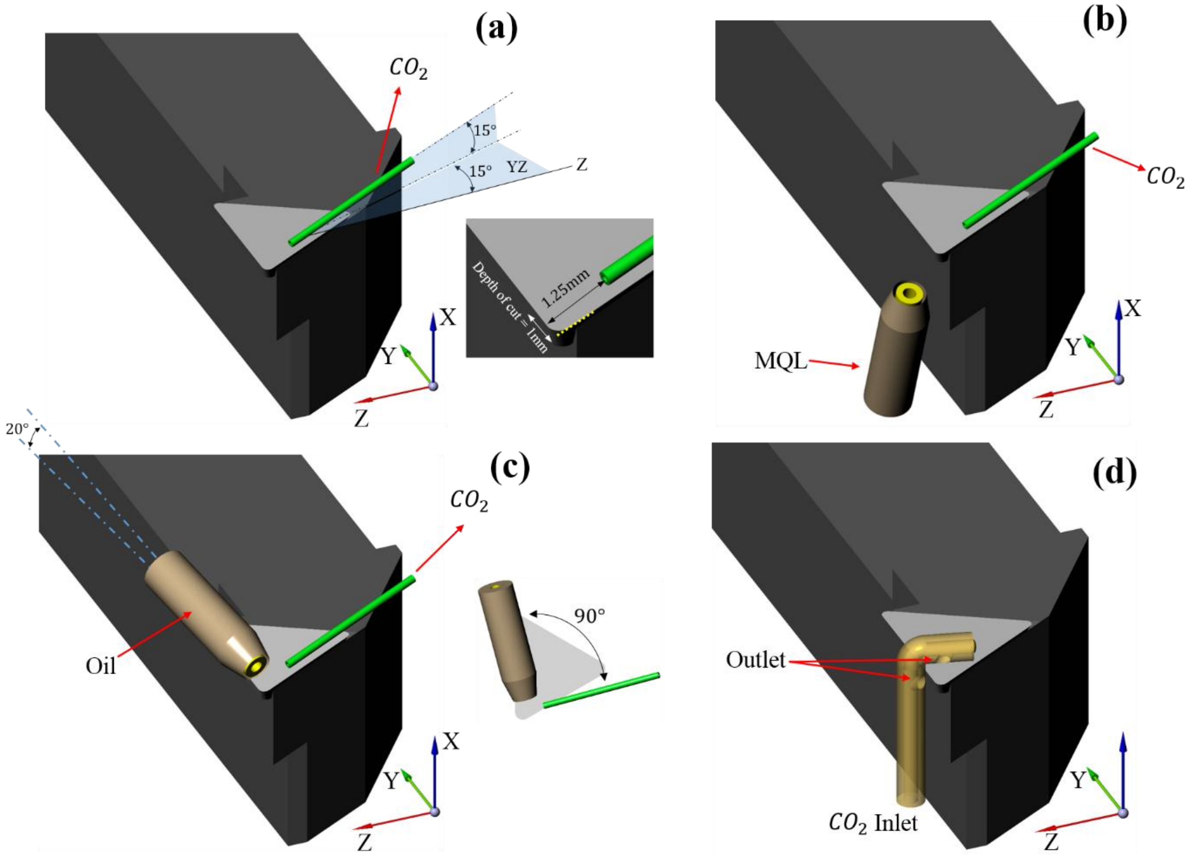


Figure 2: Schematics of the applied cryogenic cooling methods in turning. a) CO_2 delivery on the rake face. b) CO_2+MQL supply where CO_2 delivered from rake face and MQL supplied from flank face c) directing CMQL technique on the rake face d) modified CO_2 delivery

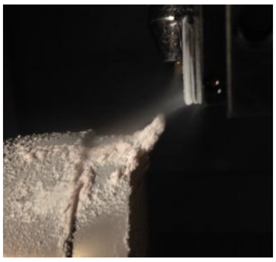


Figure3: CMQL supply is obstructed by workpiece

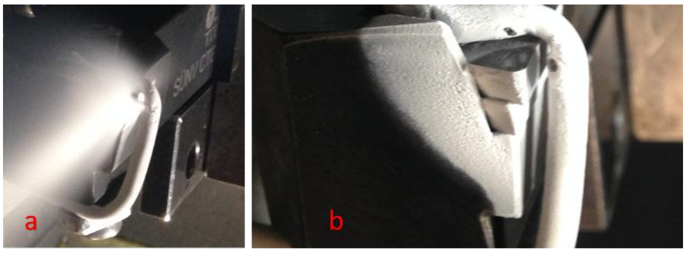


Figure 4: Modified externally CO_2 delivery;
a) During supply b) After supply

2.3. Experimental results and discussion

2.3.1. Tool wear

Cryogenic liquid CO_2 is able to reduce tool wear due to lower temperature, which is a function of the cooling method as well. The progresses of the maximum and average primary flank wear as well as nose wear and notching at the depth of cut line for each scenario are illustrated respectively in Figure 5 for Ti6Al4V and in Figure 6 for Inconel 718. As summarized in Tables 2 and 3, the effectiveness of each method is different. The effectiveness of CO_2 cooling can be increased substantially with a lubricant. The technique of CMQL enhanced tool life about 60% when compared to CO_2+MQL in Ti6Al4V machining, where, this improvement was about 30% in Inconel 718 cutting. However, CO_2+MQL did not improve tool life in cutting of Inconel 718. The notable reason for improvements under CMQL could be, first, higher penetration of the oil to the chip-tool interface leading to more reduction of heat transfer in addition to lubricant efficiency. Second, higher heat removal efficiency due to the frozen or low temperature oil. In comparison of the only cryogenic coolant with the combination of oil and super critical temperature of CO_2, higher heat removal potential and heat removal efficiency was reported by Supekar et al., further investigation on generated surface and chip morphologies help to prove this claim precisely. The third reason can be claimed as, the creation of pre-cooling condition via CMQL in addition to direct cooling/lubricating[26]. The direction of CMQL spray lead to put low temperature oil on workpiece as well, whereas this issue can behave as workpiece pre-cooling. Forth, less oil smell and vapor during CMQL machining indicate that heat extraction with CO_2 results in reduction of oil burning and evaporation. The flank cooling or lubricating lead to heat removal from the flank face which is the reason for high effectiveness of CO_2+MQL and modified nozzle methods. Hence, the failure location altered respect to each strategy as is a function of cooling type and method as is shown in table 3 and 4. The authors believe that in scenario of CO_2+MQL, the significant reason for the tool life improvement is not only flank lubricant, because oil doesn’t penetrate as much as CO_2 on the flank wear area due to lower pressure. In this method as explained for CMQL, to some extent oil cover on workpiece and this can work as a workpiece precooling as well. Nevertheless, these effects are decreased for Inconel 718 due to higher hardening and generated temperature. Furthermore, effect of CMQL on Inconel 718 turning was more than modified nozzle along with less consumption of CO_2 into account. It points out that rake face lubricant in too hard to cut materials is more significant.

Condition	**Failure location**	**Cutting length(m)***	**Improvement** **
CO_2	Average/Maximum	42.8	-
CO_2+MQL	Average flank wear	118.9	177(%)
CMQL	Maximum flank wear	190.9	345(%)
Modified nozzle	Average/Maximum	211	392(%)

[*] Cutting length when the tool wear reached criteria

[**] Improvement in comparison to CO_2 delivery

Table 3: Tool life for each cutting condition and improvement with new alternatives during Ti6Al4V

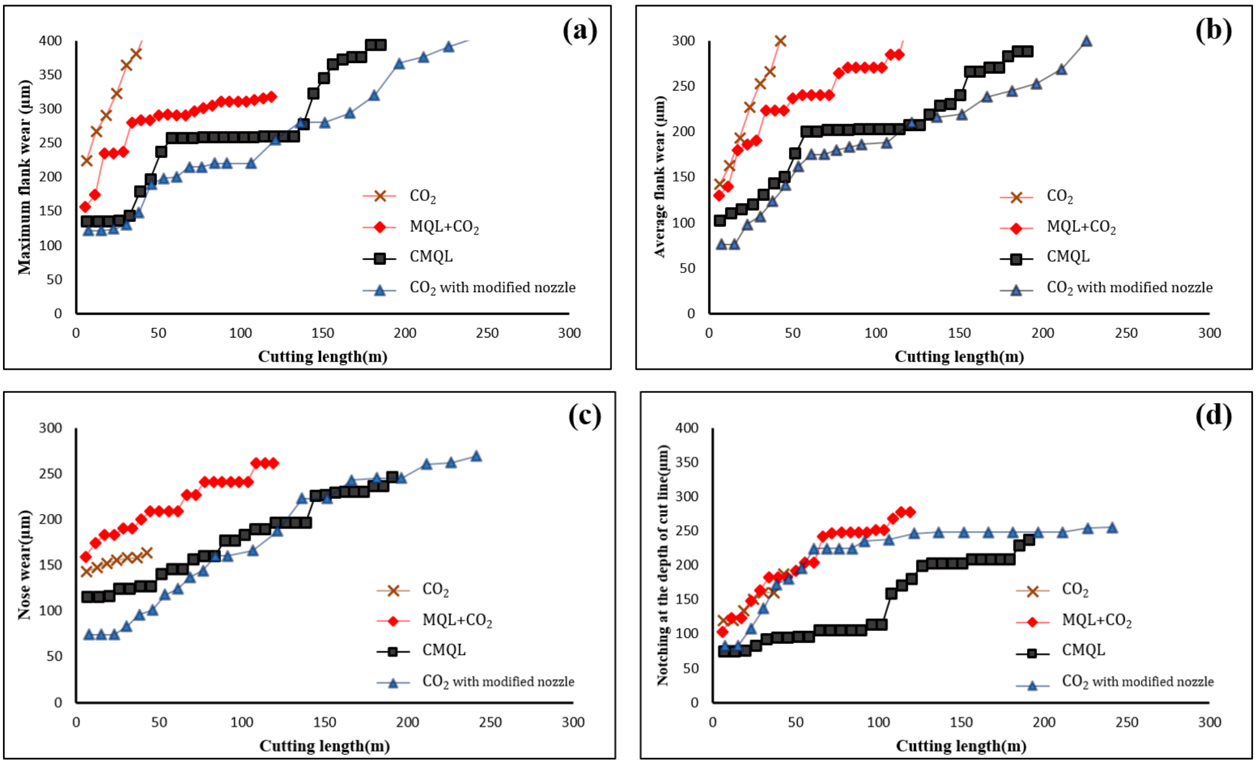


Figure 5: a) Maximum flank wear growing behavior as a function of cutting length through the cooling strategy during Ti6Al4V turning at 150m/min. b) Average flank wear growing behavior as a function of cutting length through the cooling strategy during Ti6Al4V turning at 150m/min. c) Nose wear growing behaviour as a function of cutting length through the cooling strategy during Ti6Al4V turning at 150m/min. d) Notching at the depth of cut line as a function of cutting length through the cooling strategy during Ti6Al4V turning at 150m/min.

Condition	**Failure location**	**Cutting length(m)**[*]	**Improvement** [**]
CO_2	Average flank wear	37.4	-
CO_2+MQL	Average flank wear	36.8	0(%)
CMQL	Average flank wear	51.9	30(%)
Modified nozzle	Average flank wear	42.9	14(%)

[*] Cutting length when the tool wear reached criteria

[**] Improvement in comparison to CO_2 delivery

Table 4: Tool life for each cutting condition and improvement with new alternatives during Inconel 718 turning

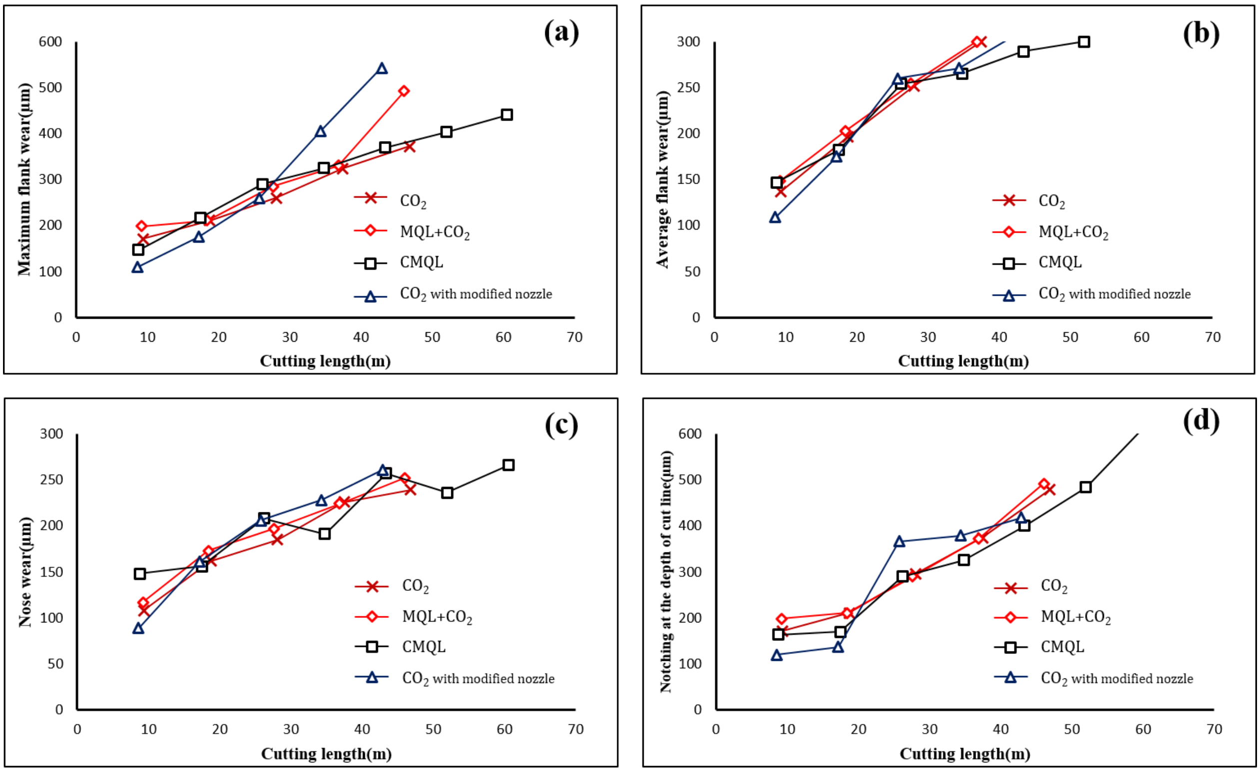


Figure 6: a) Maximum flank wear growing behavior as a function of cutting length through the cooling strategy during Inconel 718 turning at 100m/min. b) Average flank wear growing behaviour as a function of cutting length through the cooling strategy during Inconel 718 turning at 100m/min. c) Nose wear growing behaviour as a function of cutting length through the cooling strategy during Inconel 718 turning at 100m/min. d) Notching at the depth of cut line as a function of cutting length through the cooling strategy during Inconel 718 turning at 100m/min.

2.3.2. Cutting forces

Figure 7 shows force components exerted under distinct cooling method during turning operation where Fx, Fy and Fz are displaying thrust force, radial force and feed forces respectively. The study's outputs as shown in Figure 7-a exhibit that during Ti6Al4V turning, all three cooling methods with same consumption of CO_2 have the same thrust force but the less radial and feed force are generated for CMQL strategy. Nonetheless, as displayed in Figure 7-b during cutting of Inconel 718 thrust forces were found in the order of high to low as CO_2>MQL+CO_2>CMQL. The radial and feed forces was approximately equal for CMQL and CO_2+MQL whereas both were lower than CO_2 supply. In the both Inconel 718 and Ti6Al4V turning when modified nozzle compared to the CO_2 supply, the thrust force reduced but feed and radial forces have different behavior. The reason could be because of higher flow of CO_2 resulted to lower temperature as well as increasing of hardness and strength of the workpiece, then, cutting forces increase as discussed by Hong et al (2001). Bermingham et al. (2011) reported lower cutting force for simultaneously flank and rake face cryogenic cooling in comparison to only rake cooling. This idea cannot fairly apply for or judge in current study because there is no equal rake face supply between CO_2 and modified nozzle delivery. Then, in participant of two variable, comparison is not reasonable.

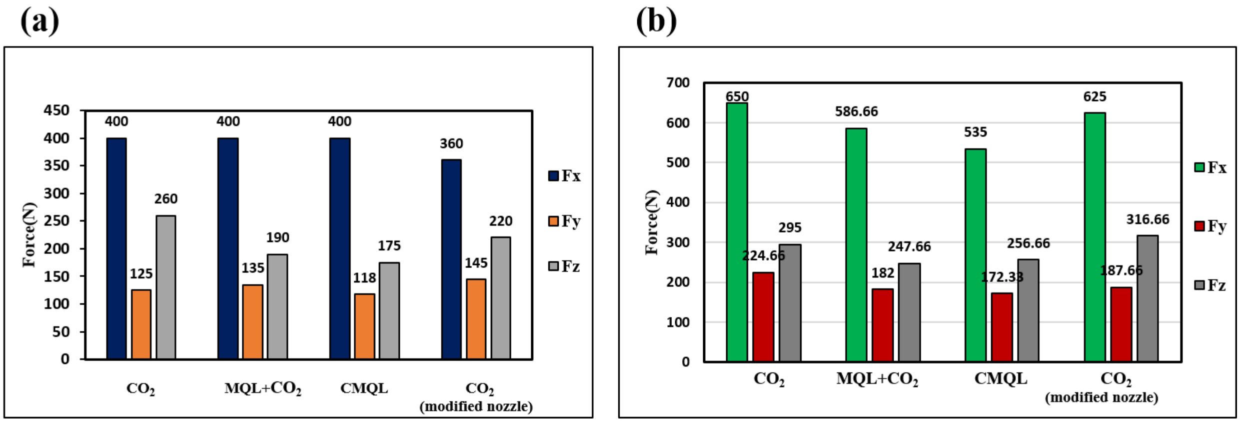


Figure 7: a) The comparison of the cutting forces through the cooling strategy during Ti6Al4V turning at 150m/min. b) The comparison of the cutting forces through the cooling strategy during Inconel 718 turning at 100m/min.

2.3.3. Surface finish

The effect of introduced cryogenic methods on surface roughness and quality have been investigated. Figure 8 for Ti6Al4V and figure 9 for Inconel 718 display surface roughness variation as a function of cutting length at different cooling methods. It is realized that the surface roughness under CMQL cooling is remarkably less than CO_2+MQL and CO_2 supply. Furthermore, for the most cases, surface roughness under CMQL is decreased in comparison to modified CO_2 delivery. Sample of machined surface between cutting length of 5 and 10 meter for both combined lubricant/cooling methods was captured with Scanning electron microscopy (SEM). As displayed in figure 10-a during Ti6Al4V turning and figure 11-a during Inconel 718 machining, it can be observed that deformed feed lines, micro-porosity and tiny pits as well as leaving some debris of working material are the consequences of CO_2+MQL supply. On the other hand, figures 10-b and 11-b indicate to the surface with better quality using CMQL method in comparison to CO_2+MQL supply. Moreover, the use of only CO_2 supply not only found the same defaults with CO_2+MQL but also tiny cracks due to chips breakage observed as shown in figure11-c. The participation of oil in CMQL can be the reason for the improvement in the surface quality. Indeed, making use of CMQL method not only yields a higher cooling performance, but it also gives rise a better surface quality where some drawbacks such as left debris, uneven feed lines and tiny cracks are absent.

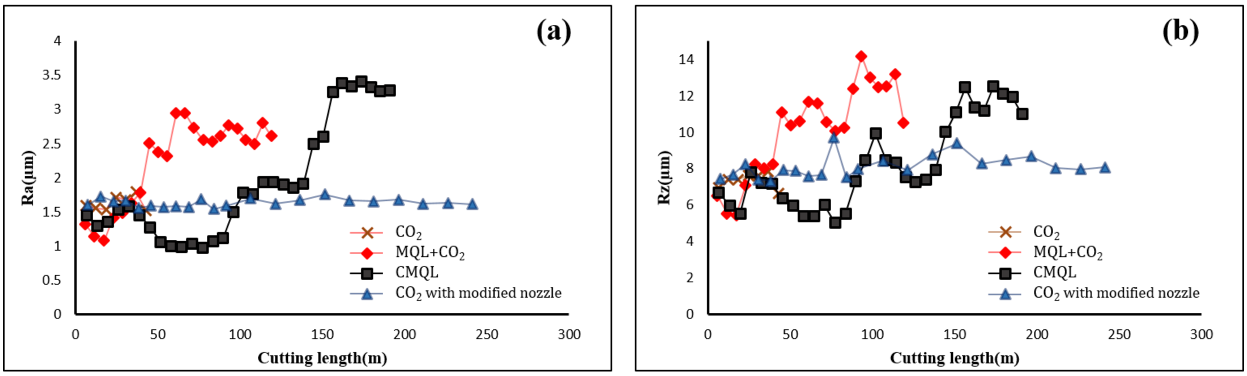


Figure 8: a) The comparison of the roughness average (Ra) of the surface under different cooling method during Ti6Al4V turning at 150m/min. b) The comparison of the mean roughness depth (Rz) under different cooling method during Ti6Al4V turning at 150m/min.

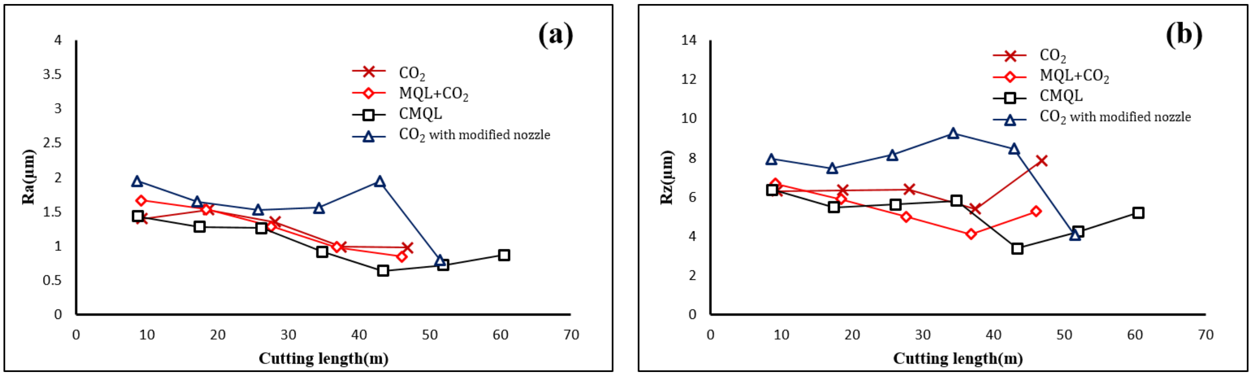


Figure 9: a) The comparison of the roughness average (Ra) of the surface under different cooling method during Inconel 718 turning at 100m/min. b) The comparison of the mean roughness depth (Rz) under different cooling method during Inconel 718 turning at 100m/min.

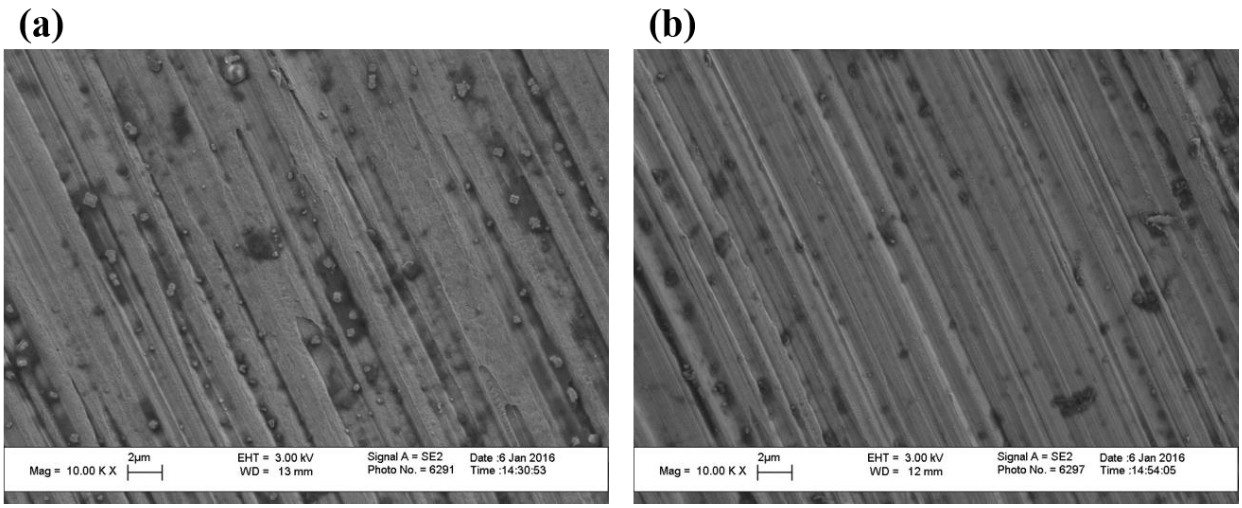


Figure 10: a) SEM image of generated surface under CO2+MQL when adopting a cutting speed of 150 m/min and a feed rate of 0.2 mm/rev in Ti6Al4V turning. b) SEM image of generated surface under CMQL when adopting a cutting speed of 150 m/min and a feed rate of 0.2 mm/rev in Ti6Al4V turning.

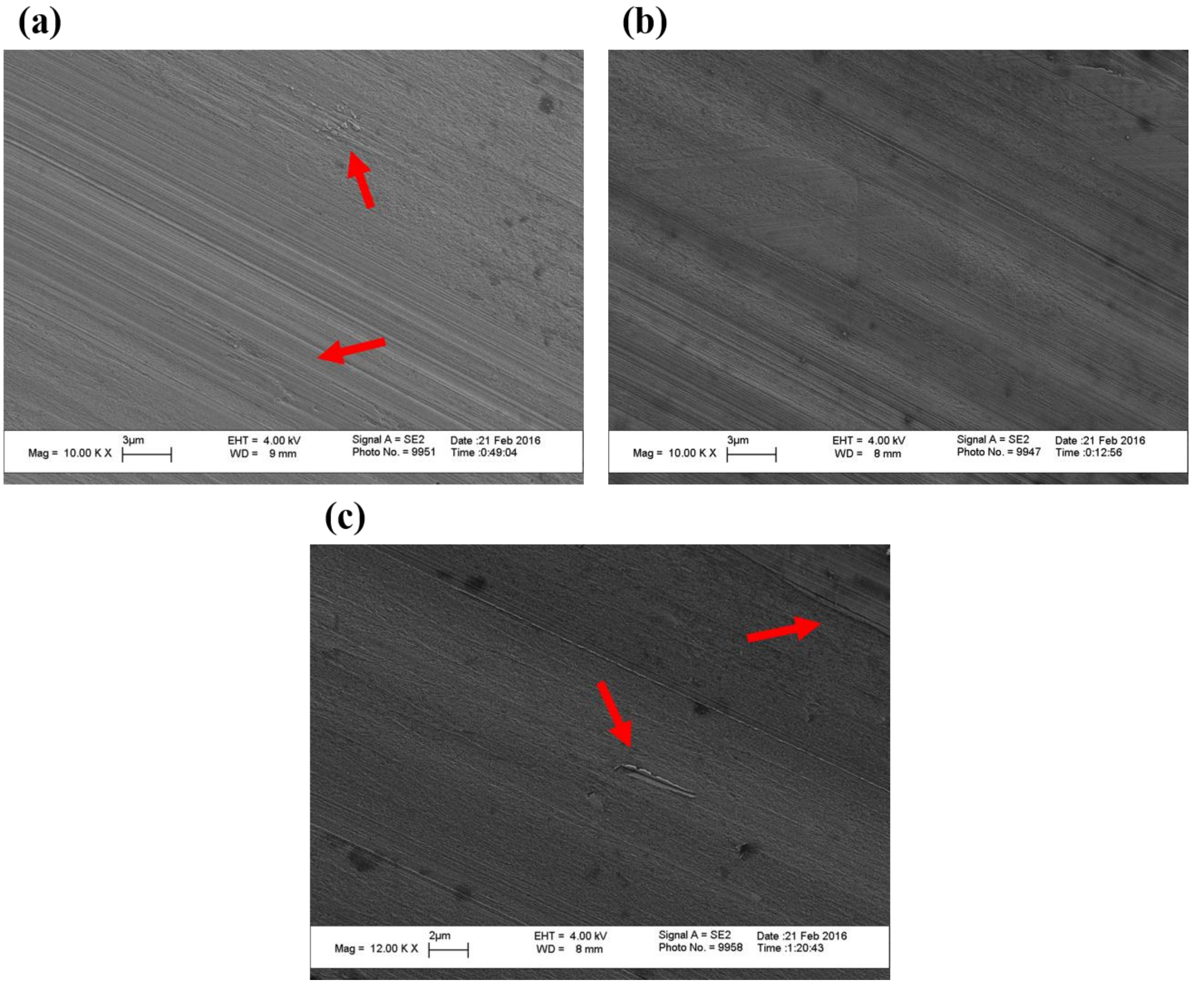


Figure 11: a) SEM image of generated surface under CO2+MQL cooling technique when adopting a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev in Inconel 718 turning. b) SEM image of generated surface under CMQL turning when adopting a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev in Inconel 718 turning. c) SEM image of generated surface under CO2 when adopting a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev during turning of Inconel 718.

2.3.4. Chip morphology

The investigation of chips under SEM was carried out to observe area of serrations, shear bands and shear zone. As shown in Figure 12 and 13 various chip morphologies created under different cooling/lubricant scenarios. The serrations of Ti6Al4V under CMQL and modification of CO_2 supply, clearly are separated by shear bands or primary shear zone and also shear bands have sharp and direct lines comparing to CO_2 delivery and CO_2+MQL strategy leading better chip breakability. Furthermore, examining back of the chips revealed that produced chips under CMQL supply have a smoother chip backside in comparison to other methods. The reason can refer to lower stick and friction of the generated chip under CMQL. When the produced heat in the tool-chip-workpiece interfaces cannot be removed rapidly and/or transfer to chip, tool and workpiece, as a consequence, elevated temperature lead to more deformation in the backside of the chip. As pointed out before, CMQL produce better lubrication which lead to decrease contact length and lower heat generation. Thicknesses of the segments under all methods of cooling are not equal, implying to different shear stresses. Mentioned effect for each cooling satisfy for generated chip during Inconel 718 turning. Since Inconel 718 is harder than Ti6Al4V, CMQL impacted on chip morphology with better diagnostic as shown in figure 13-c.

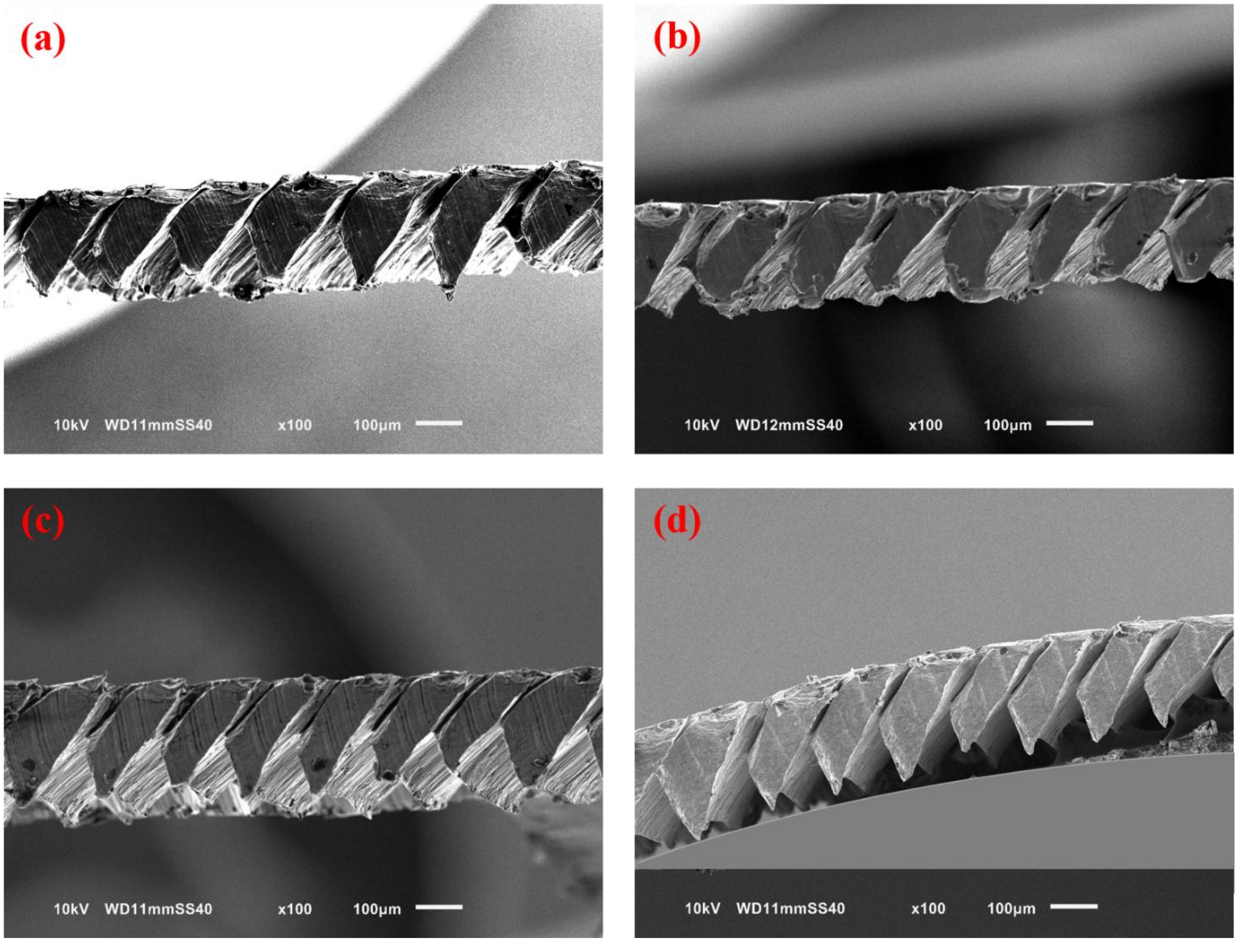


Figure 12: a) Micro-structure of resulted chips under CO2 cooling during Ti6Al4V turning at velocity of 150m/min and feedrate of 0.2 mm/rev. b) Micro-structure of resulted chips under CO2+MQL cooling method during Ti6Al4V turning at velocity of 150m/min and feedrate of 0.2 mm/rev. c) Micro-structure of resulted chips under CMQL cooling strategy during Ti6Al4V turning at velocity of 150m/min and feedrate of 0.2 mm/rev. d) Micro-structure of resulted chips under modified nozzle during Ti6Al4V turning at velocity of 150m/min and feedrate of 0.2 mm/rev.

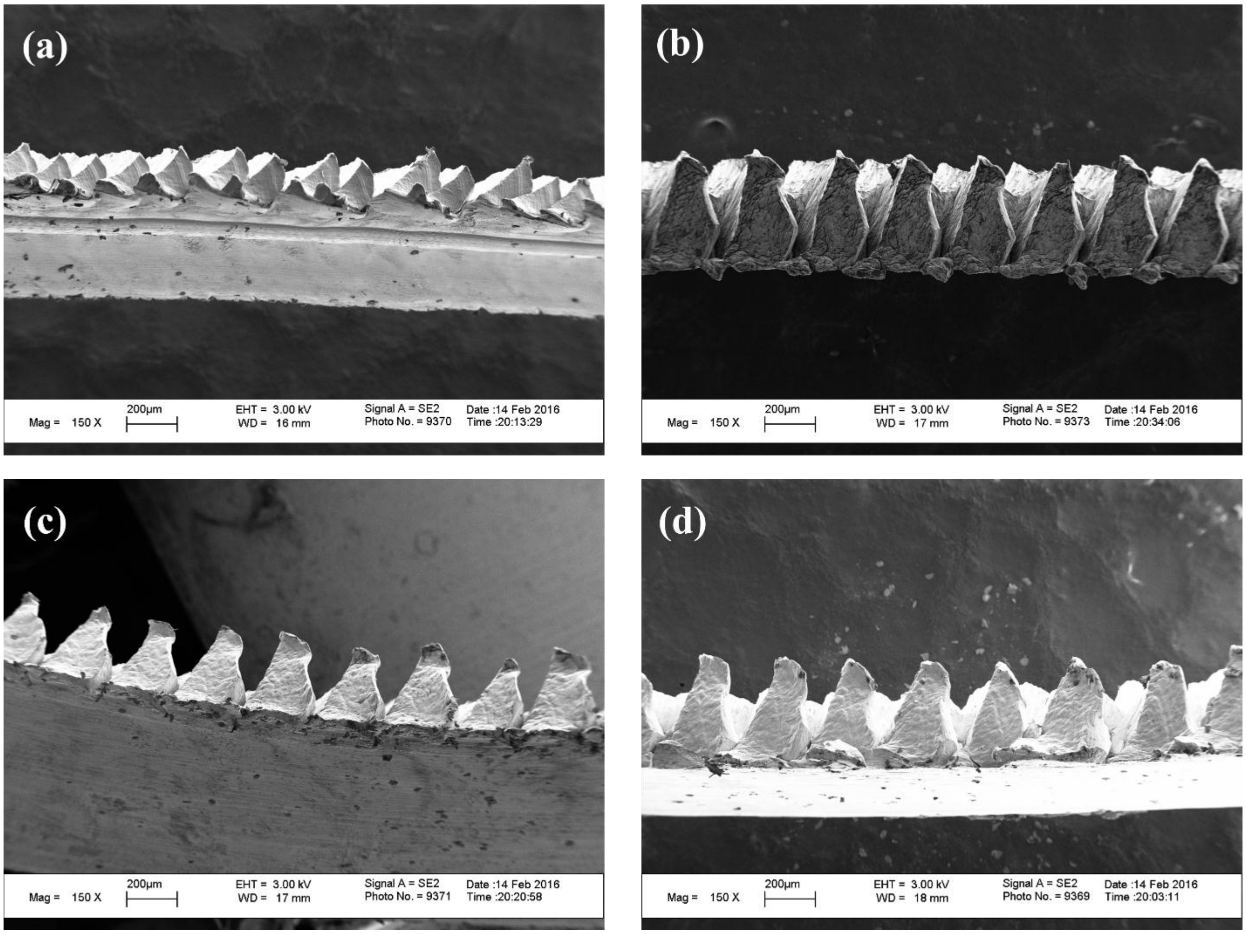


Figure 13: a) Micro-structure of resulted chips under CO2 delivery when adopting a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev during turning of Inconel 718. b) Micro-structure of resulted chips under CO2+MQL cooling method during Inconel 718 turning at velocity of 100m/min and feedrate of 0.2 mm/rev. c) Micro-structure of resulted chips under CMQL cooling strategy during Inconel 718 turning at velocity of 100m/min and feedrate of 0.2 mm/rev. d) Micro-structure of resulted chips under modified nozzle during Inconel 718 turning at velocity of 100m/min and feedrate of 0.2 mm/rev.

2.4. Summary

The present study examines modification of externally cooling for supplying cryogenic liquid (CO_2) to tool-chip-work interfaces in turning operation. A new and alternative cooling technique is proposed to improve effectiveness of cryogenic cooling in high speed machining. The combination of carbon dioxide and minimum quantity oil as a lubricant (CMQL) supplied from rake face are compared with supplying CO_2 and MQL from rake and flank face, respectively as well as only CO_2 supplied from rake face, in turning of Ti6Al4V and Inconel 718. Tool wear and surface roughness were measured on the machine during cutting tests at different stages of tool life. The workpiece and produced chips were also characterized by scanning electron microscopy (SEM). The results revealed improvement of tool life and surface finish using the modified cryogenic cooling method. Based on the systematical test results CMQL was identified as the most favorable cooling method considering tool wear, surface finish, chip formation and cutting forces as well as less consumption of CO_2.

CHAPTER 3 NEW ASSESMENT TO ENHANCE EFFICIENCY OF CRYOGENIC TURN-MILLING

3.1. Orthogonal Turn-Milling

Turn-milling is one of the new cutting processes that combines turning and milling operations. The generation of lower cutting temperatures in turn-milling operation result in longer tool life and thus, higher cutting speed can apply for the cutting process. In this study orthogonal turn-milling used for the investigation of cooling strategies. The schematic of orthogonal turn-milling operation is displayed in Figure 14. In orthogonal turn-milling the direction of the cutting tool is perpendicular to the work piece rotation axis. That is why, in orthogonal turn-milling the chip is formed by the action of bottom and side part of the cutting tool. In orthogonal turn-milling, cutting motion refer to the tool rotation and feed motion results from work piece rotation in addition to cutting tool movement which is parallel to axis of the work piece.

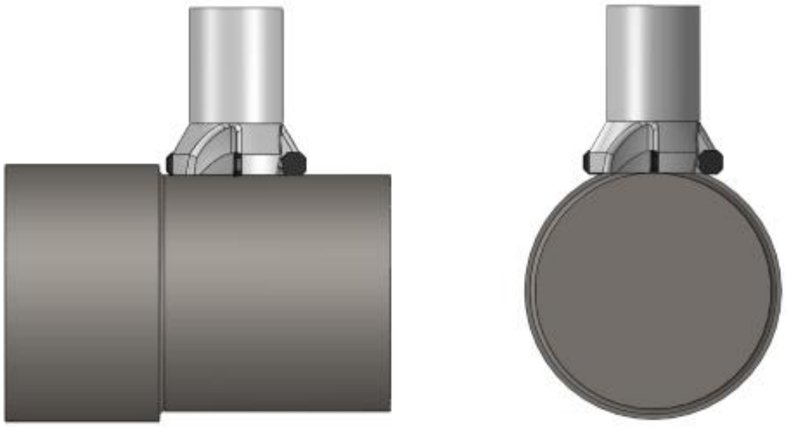


Figure 14: Orthogonal turn-milling.

In orthogonal turn-milling, it is possible to offset the tool in *Y*-axis however as result of this chip thickness changes. The distance between work piece and tool is called cutting tool offset or tool *Y*-axis compensation or shortly eccentricity. When cutting tool rotation axis and work piece rotation axis intersect, operation is called concentric orthogonal turn-milling, otherwise, if there is no intersection, operation is called eccentric orthogonal turn-milling. The cases are displayed in Figure 15.

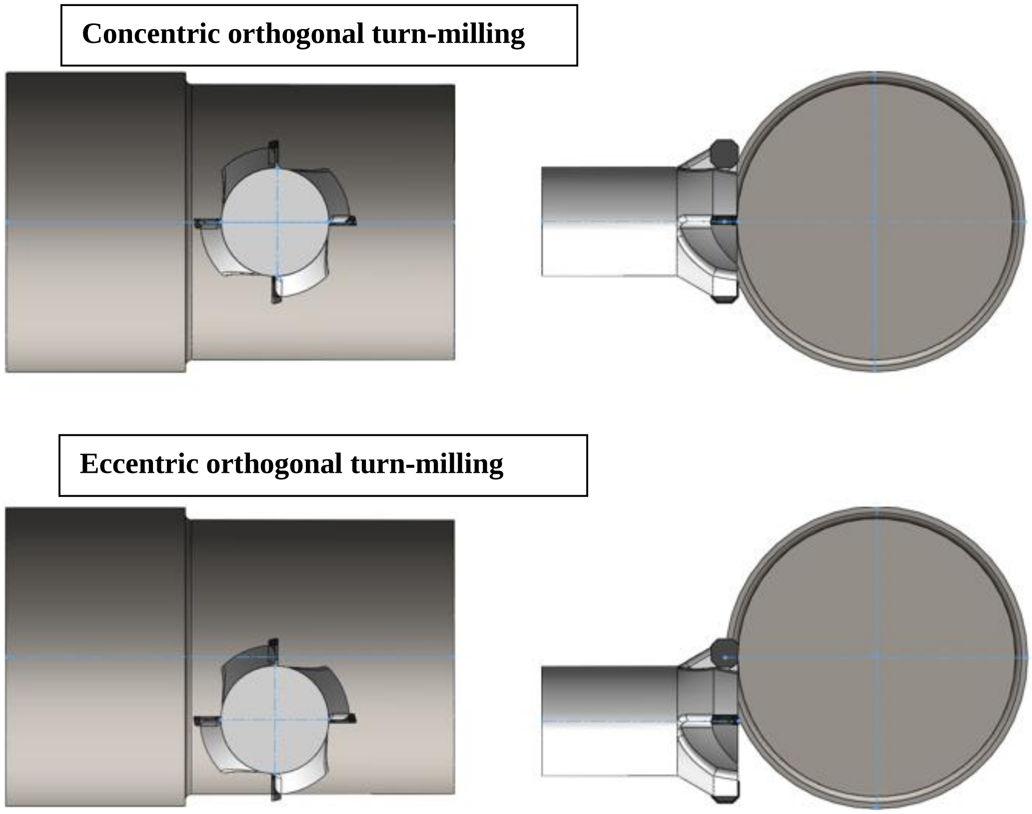


Figure 15: Cutter offset in orthogonal turn-milling.

Cutting tool offset is a particular parameter in orthogonal turn-milling. This compensation in orthogonal turn-milling lead to alter chip formation whilst offset value increases only side of the cutting tool is involved in the chip formation depending size of depth of cut.

3.2. Experimental setup

Turn-mill operation under different cooling method carried out to investigate behavior of the tool wear under each cooling strategy as is displayed in figure 14-19. The workpiece material of the Inconel 718 and steel 1050 have been used. In addition, milling tool with designation of 217.69-03 having three cutting teeth was used, whereas, inserts with grade of F40 M and MP 2500 were attached to cutting tool for the Inconel 718 and steel 1050 cutting, respectively. Cutting parameters selected as is shown in table 5. Optimum axis offset of 12.5 mm was defined for this cutting tool during the experiments. The position of nozzle for the method of MQL+CO2 were 30° and 60°

from workpiece direction for CO2 and MQL nozzle, respectably. The supply of CO2 in discontinuous CO2 cooling was selected 4second supply after 12 second stop repetitively, in which the oil was spraying during stop states of CO2 supply.

(V)Cutting speed (m/min)	**(ae)Feedrate (mm/rev)**	**(ap)Depth of cut (mm)**	**Cooling methods (varies for each listed techniques below)**
		Inconel718	
45	8	0.2	CO_2 (nozzle with diameter of 0.5 mm)
45	8	0.2	Flood
45	8	0.2	MQL with flow rate of 17mm/h
45	8	0.2	MQL+ discontinuous CO_2
45	8	0.2	MQL+ continuous CO_2
		Steel 1050	
400	8	0.5	Dry
400	8	0.5	Flood
400	8	0.5	MQL with flow rate of 17mm/h
400	8	0.5	MQL+ continuous CO_2

Figure 34: Dry

Figure 15: Flood

Figure 16: CO2

Figure 17: MQL

Figure 18: MQL+ continuousCO2

Figure 19: MQL+ discontinuous CO2

3.3. Result and discussion

Results pointed out that unlike the turning operation, CO2 cooling increases the tool wear in milling operation as is shown in figure 21 for Inconel milling. The reason can refer to the range of generated temperature. CO2 cooling is only suitable for the high speed machining which generates higher temperature, while participant of CO2 cooling can balance the temperature. On the one hand, milling operation produces lower temperature on each inserts in comparison to turning operation due to discontinuous cutting and number of cutting edge. On the other hand, low cutting speeds generate lower temperature and CO2 supply result in extra cooling. As a result, extra cooling increases cutting forces and lead to more thermal stress shocking, thereby breaking the cutting edge.

In spite of the fact that combination of CO2 and MQL produced the most effective method during turning of hard to cut material, this external strategy cannot improve machinability in the turn-mill operation and the tool wear was obtained exactly the same as CO2 cooling. This shows that oil cannot penetrate to cutting edge in continuous CO2+MQL cooling. As is displayed in figure 20 solidified CO2 on the milling tool result in solidification of the oil on the external body of cutting tool before reaching cutting zone. Besides, when the experiment was done with low depth of cut, thus, there is no enough heat generation on side edge of the cutter to liquefy frozen oil. That is why, discontinuous CO2 cooling in addition to MQL cooling such a plug and play system have been applied to create adequate time to both cooling and lubricating of cutting edges using CO2 and MQL in order. This method found longest tool life among different cooling strategies as is shown if figure 21 and 22.

Figure20: The resistance of solidified CO2 to penetration of oil to cutting zone during continuous CO2+MQL.

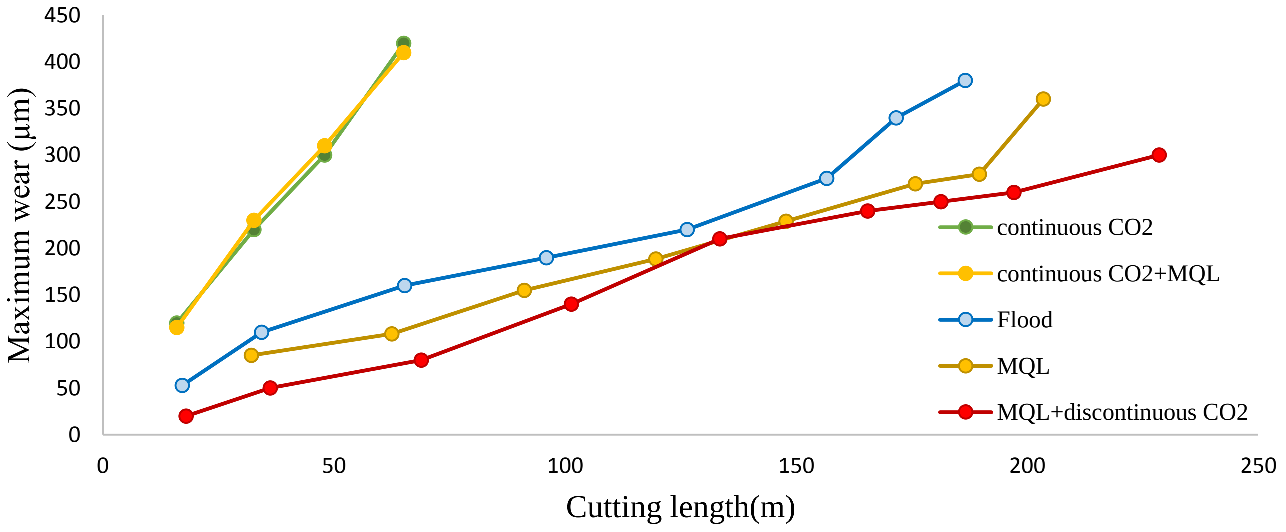


Figure 21: Tool wear results for Inconel 718 under different cooling condition in V=45m/min, ap=0.2mm, ae=8mm/rev.

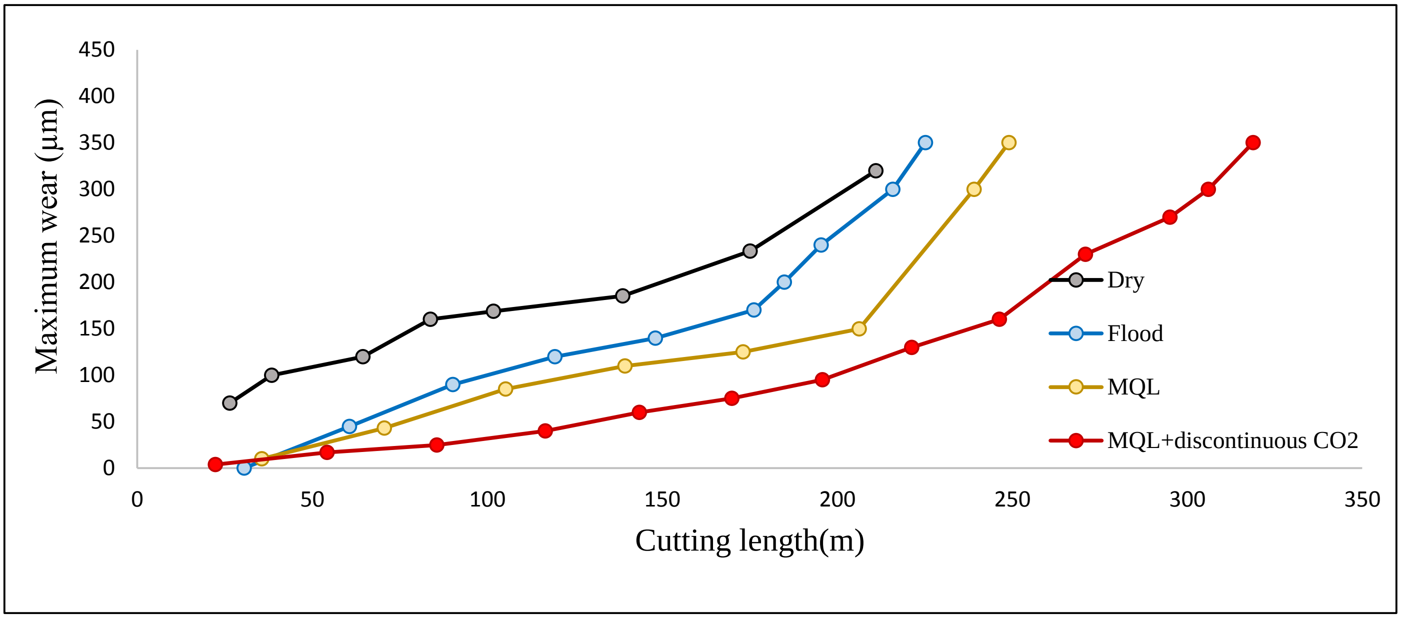


Figure 22: Tool wear results for steel 1050 under different cutting condition V=400m/min, a_p=0.5mm, a_e=8mm/rev.

To sum up, combination of MQL and discontinuous CO2 improved tool life during Inconel 718 and Steel 1050 cutting. Nonetheless, it was needed to investigate heat removal efficiency and final part quality in detail. To this purpose, cylindrical workpiece which attach to turn-milling machine was limited to examine most of the microstructural analysis, consequently, milling operation on Steel 1050 carried out to measure heat removal efficiency of each cooling method in addition to surface finish analysis. The next chapter discusses the procedure precisely.

3.4. Summary

Turn-milling operation is emerging nowadays as an alternative to conventional milling and turning. This operation provides high performance machining, leading to lower cutting forces and lower temperature as well as longer tool life and final part quality. Since cryogenic machining has been shown marginal effects in turning and milling operations in literature. Therefore, there is a need to investigate cryogenic turn-milling specifically. In this chapter, the effect of cryogenic turn-milling is investigated for the first time, yielding conclusion for the alternative method to improvement and optimization of cryogenic cooling.

CHAPTER 4 THERMAL ANALYSES AND ELEMENTAL ANALYSES OF THE GENERATED SURFACE OF STEEL 1050 MILLING FOR THE DIFFERENT COOLING METHODS

Figure 23: Test setup for measuring cutting temperature and forces.

4.1. Experimental setup

Most types of tool wear in machining such as abrasive wear, adhesive wear and diffusive wear, result from generated heat in the cutting processes. In this chapter slot-milling operation has been carried out on a CNC milling center “MAZAK NEXUS 510 CII” as is shown in figure 23. The same cooling methods for CO2 cooling and CO2+MQL which was shown in figure 16 and 19 in mill-turn operation, have been repeated for steel 1050 slot-milling. Coated carbide inserts with designation of R390-11 T3 4240 were clamped on cutting tool with diameter of 16mm of the tool manufacturer Sandvik, which was held by Kistler Piezo-dynamometer to measure forces. Data logging was done by Lab View Signal Express software. Since, high cutting speed results in higher rate of wear, spindle speed of 7961 were selected. Other cutting parameters used in the tests were f=500m/min and a_p=1mm.

To measure temperature of cutting zone, K-type thermocouples were planted into holes inside of both bottom surface and vertical wall side surface while the thermocouple measurement place were located close to cutting cutting edge as is displayed in figure 24, whereas, on the one hand there were no left material between thermocouple and cutting area, on the other hand thermocouples should not touch the milling tool at all. This phenomena control after each test using Dino-Lite digital microscopy. Otherwise, the test was rejected and the new part manufactured to repeat the test. The holes were filled using silicon cement with high thermal conductivity to ensure good heat conduction between the tool material and the thermocouple bead. The generated bottom surface and vertical wall side surface characterized by scanning electron microscopy (SEM) and Energy dispersive X-ray spectroscopy (EDX).

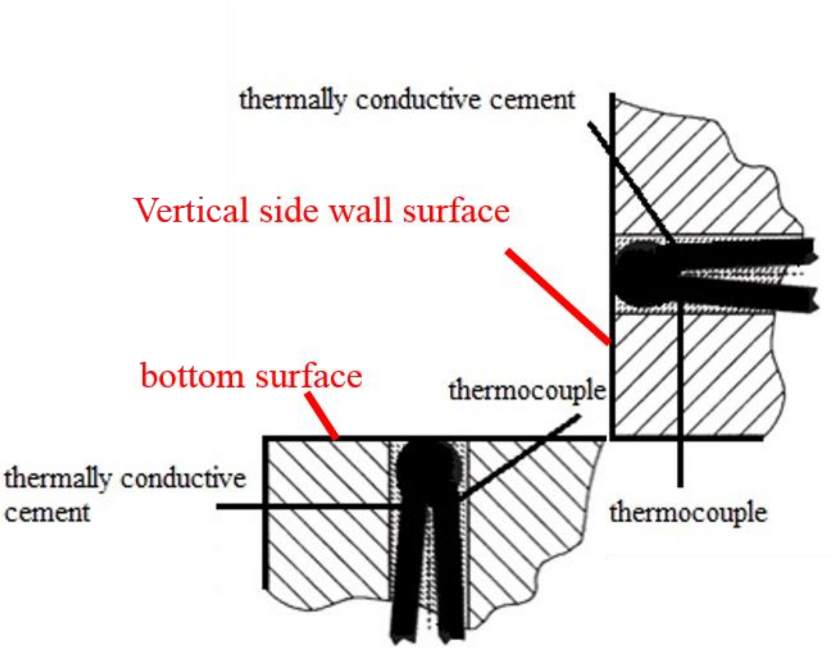


Figure 24: thermocouple implanted workpice after cutting

4.2. Result and discussion

Figure 25 and 26 show SEM image of bottom of machined surface under CO2 and CO2+MQL cooling respectively. As can be seen in figure 25, generated surface under CO2 have some re-deposit of work material and higher roughness than for CO2+MQL. The reason of rougher surface of CO2 cooled could be lower lubrication or lower temperature than for generated under CMQL cooling.

The obtained results from measurement of the temperature could support the hypothesis. Figure27 shows complete thermal behavior of the each cooling measured with 3 thermocouple implemented bottom surface of slot milling. The results pointed out that average maximum temperature in the order of high to low were as MQL>CMQL>CO2. Furthermore, average minimum temperature were found in the order of high to low as MQL>CO2>CMQL as is shown in figure 28 and 29. Nonetheless, the behavior of temperature for CO2 cooling in comparison to CMQL cooling on the vertical side wall surface and bottom surface was different. When CO2 cooling shows higher temperature on vertical wall, it shows that CO2 evaporate locally and thus, cannot penetrate to the cutting area and plays role of lubricant.

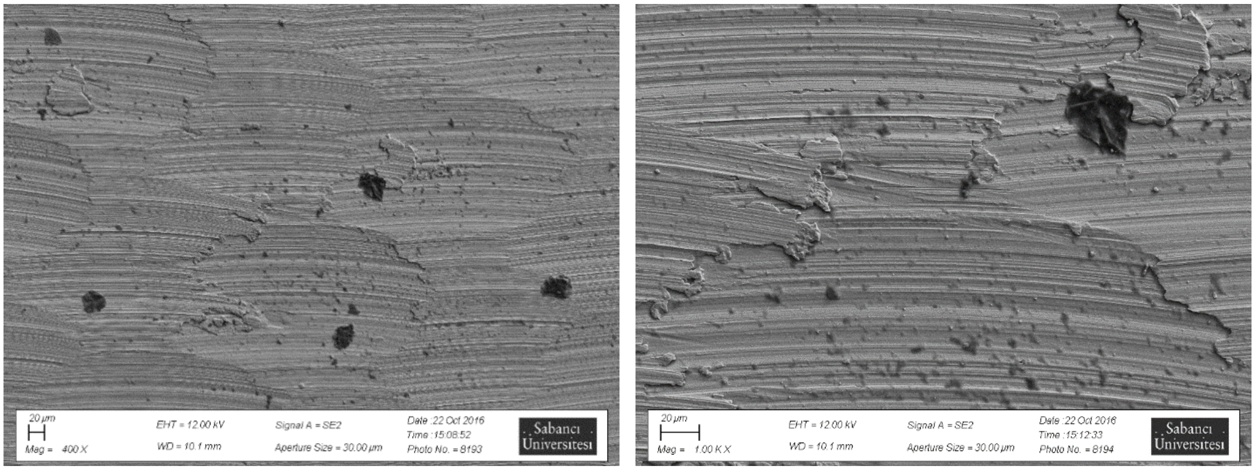


Figure 25: SEM image of generated bottom surface of slot milling under CO2 cooling

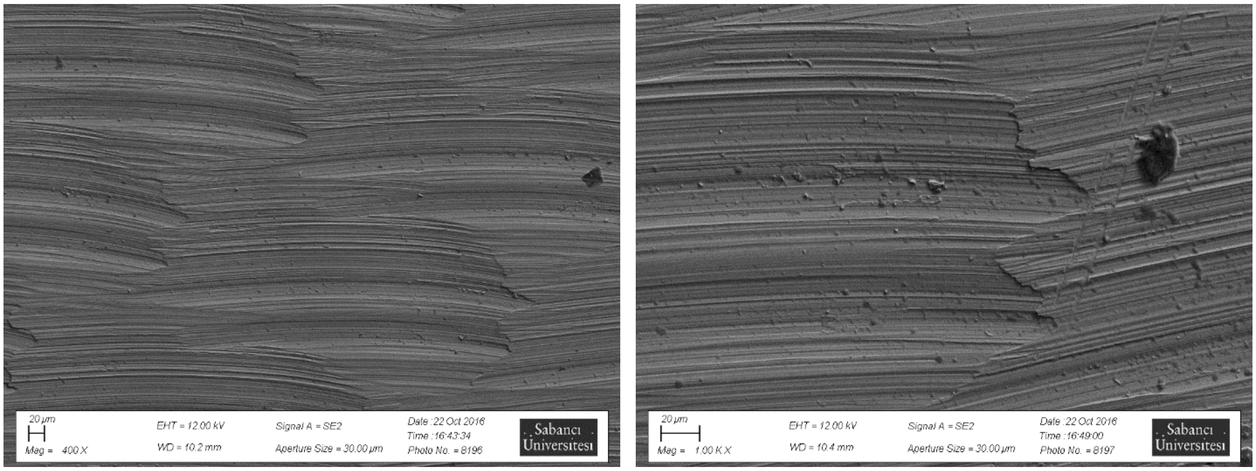


Figure 26: SEM image of generated bottom surface of slot milling under CO2+MQL cooling

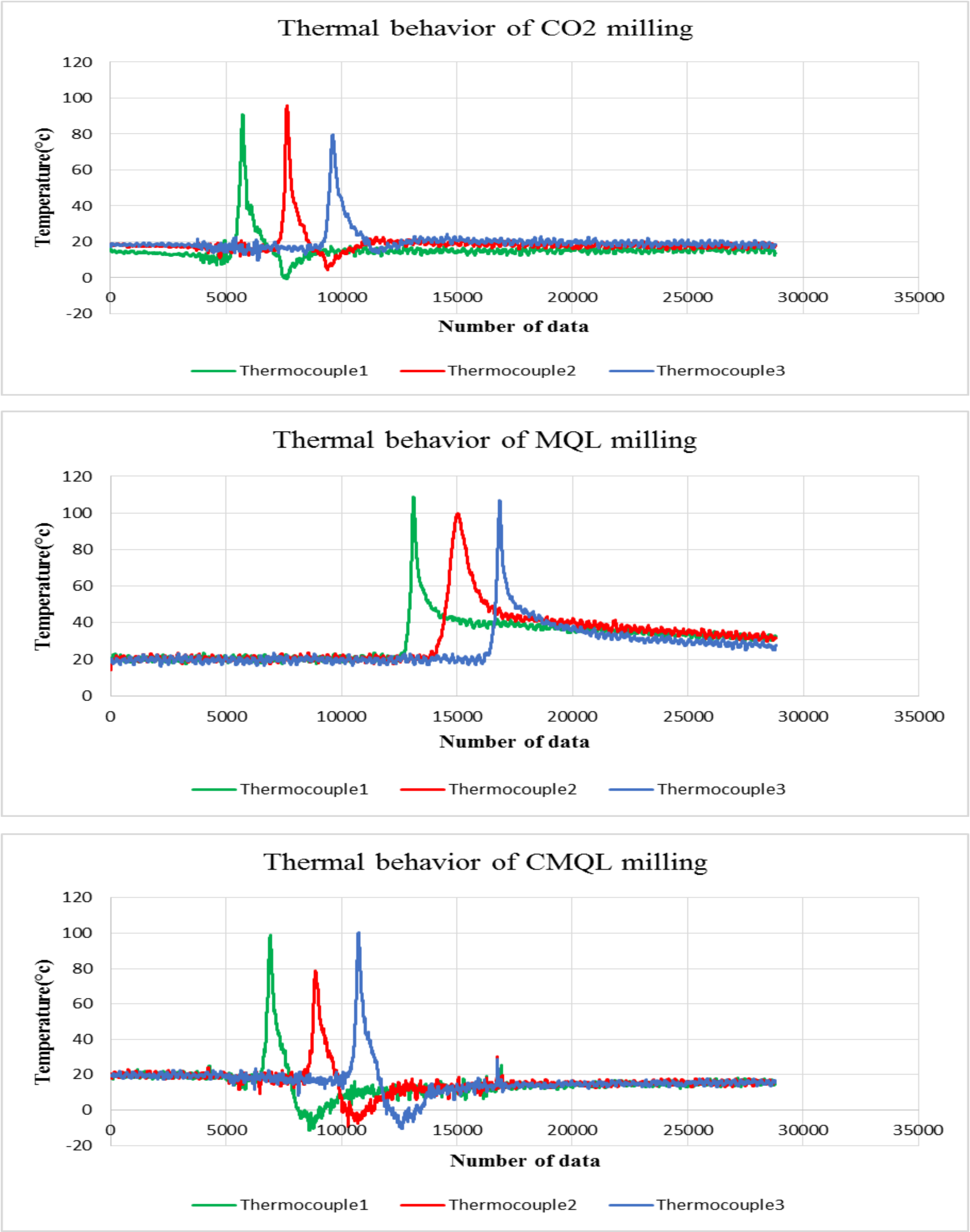


Figure 27: Thermal behavior of each cooling strategy measured from bottom surface of slot milling

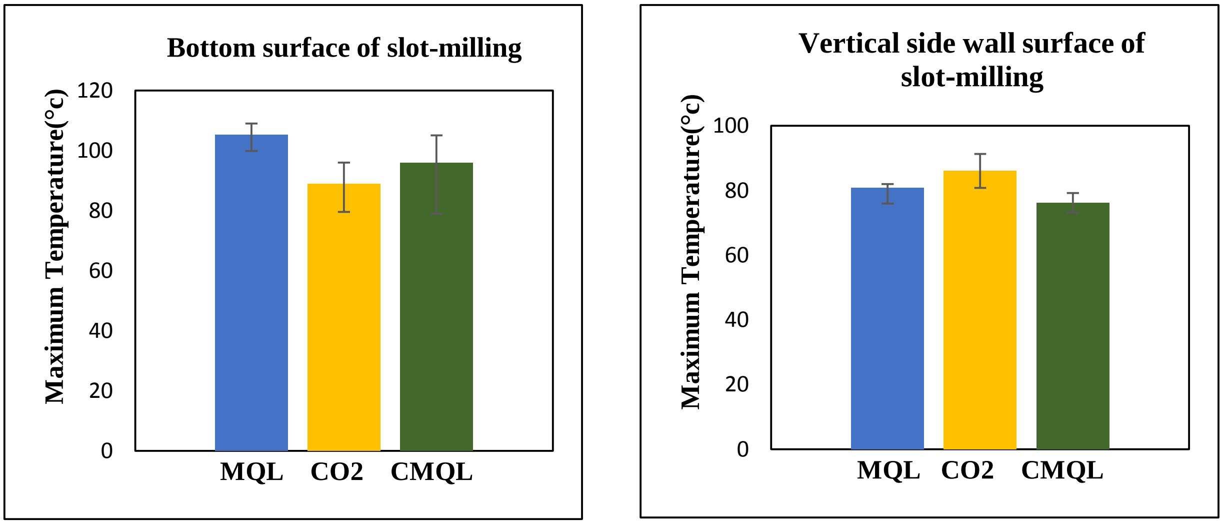


Figure 28: Maximum temperature measured on bottom and vertical side wall surface of slot milling

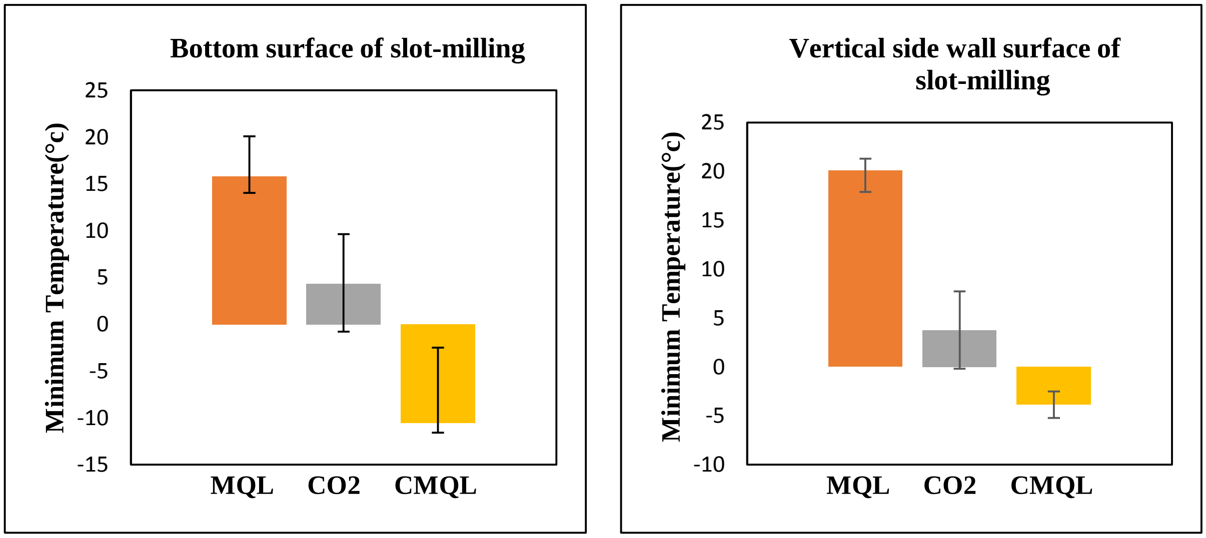


Figure 29: Minimum temperature measured on bottom and vertical side wall surface of slot milling

4.3. Elemental Analysis of the Specimens

Energy dispersive X-ray spectroscopy (EDX) was employed to determine the presence and quantities of chemical elements by detecting characteristic X-rays, emitted from atoms irradiated by electron beam for the specimens which were machined under two different cooling strategies.

In EDX spectroscopy, chemical species are identified by using the energy of characteristic X-rays of elements that are present in the specimen. When electron beam with a particular energy bombards the sample, it strikes an electron in the inner shell of an atom and knocks an electron out of its original position in an atom (ionization). The atom will quickly return to its normal state after refilling the inner electron vacancy by an outer shell electron (relaxation). The energy difference between the outer shell electron and the inner shell electron will generate a characteristic X-ray of that particular atom which is unique for each element and can be regarded as a fingerprint for identification of elements.

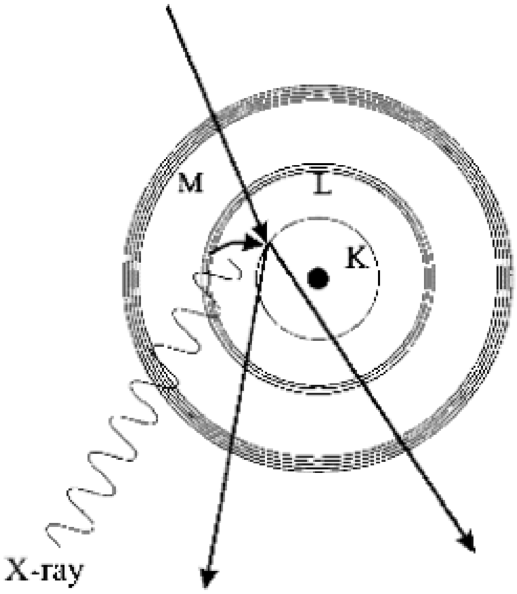
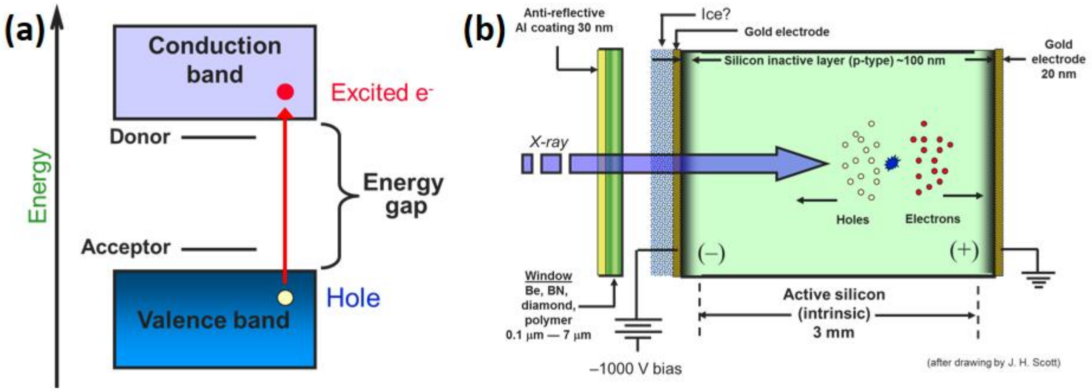


Figure 30: Generation of characteristic X-ray as a result of electron-mater interaction during EDX elemental analysis.

The generated characteristic X-rays are then collected by a detector which is made of a semiconductor silicon crystal. Absorption of x-ray energy excites electrons from filled valence band to conduction band of the Si detector and generates electron-hole pairs (Fig.31.a). The number of electron-hole pairs created is directly proportional to the energy of the X-ray photon.

By applying a bias across the crystal, the holes are swept to one side, the electrons to the other, producing a weak charge. The pulse is digitized and the X-ray energy that generated the pulse is computed (Fig.31.b). The number of counts per second is then plotted versus the energy of X-rays on the spectrum which is known as the elemental analysis.



(after drawing by J. H. Scott)

Figure 31: Mechanism of characteristic X-ray absorption by EDS detector.

Figure 32 shows the electron micrograph and corresponding qualitative elemental analysis of the generated bottom surface under CO2 cooling conditions. As can be seen, beside the main elements, i.e Fe and C, the presence of a small amount of Al can be observed which can be due the penetration of Al from the cutting tool into the specimen. The distribution of existing elements in the surface of the CO2-cooled sample is also displayed in the map micrographs as is displayed in figure 33.

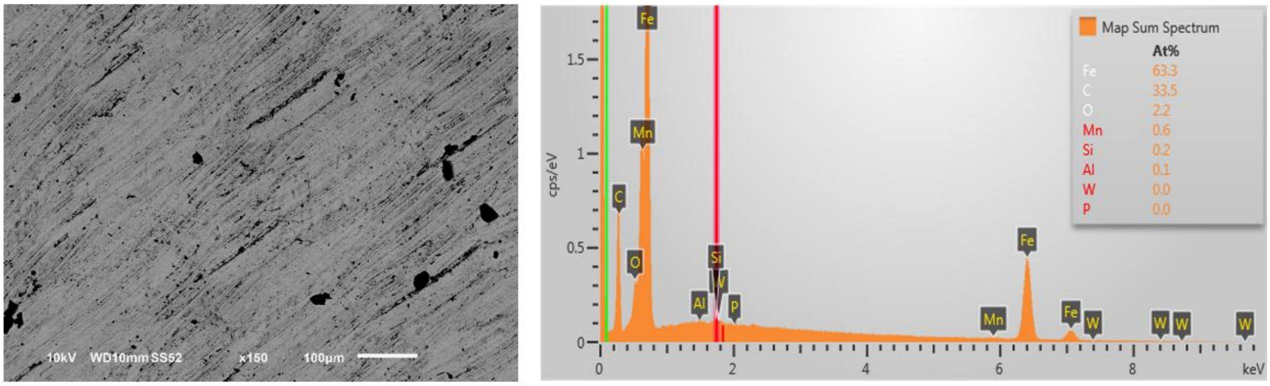


Figure 32: SEM image and EDS Spectrum of CO2 sample.

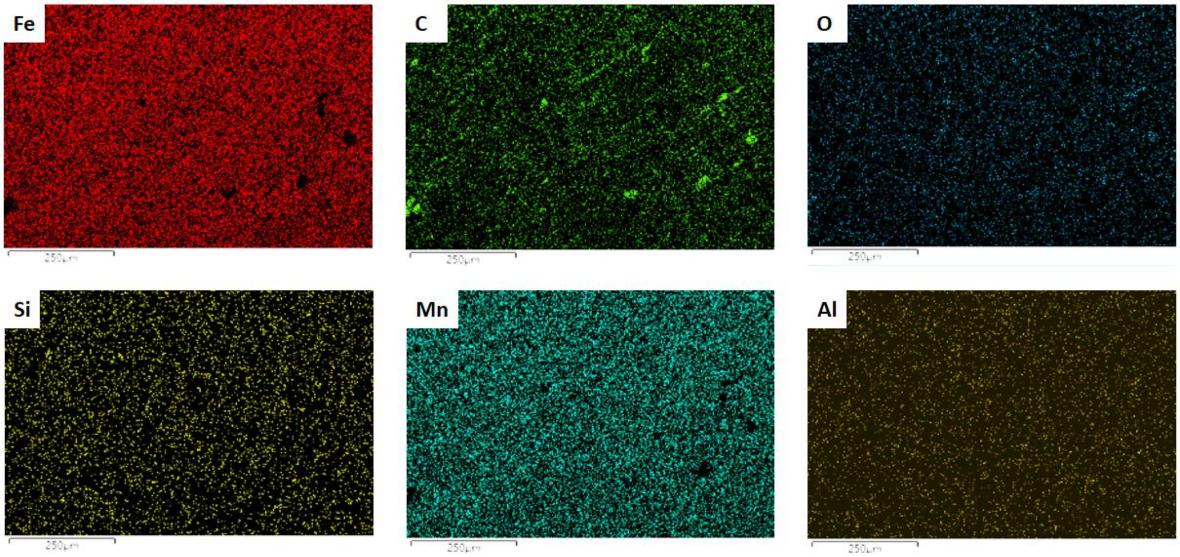


Figure 33: Distribution of elements over the sample of the generated surface under CO2 cooling.

Figure 34 shows the SEM image of the wall side surface (cutting affected zone) during slot milling operation in the CO2 specimen. As can be seen, macroscopic left debris and considerable surface roughness are present on the surface of the specimen when it is cooled by CO2 during cutting operation.

In addition, EDX point analyses were performed on different locations of the vertical side wall surface and the results are shown in figure 35. As is shown, the content of Al entered to the wall from the cutting tools in this regions are clearly detectable.

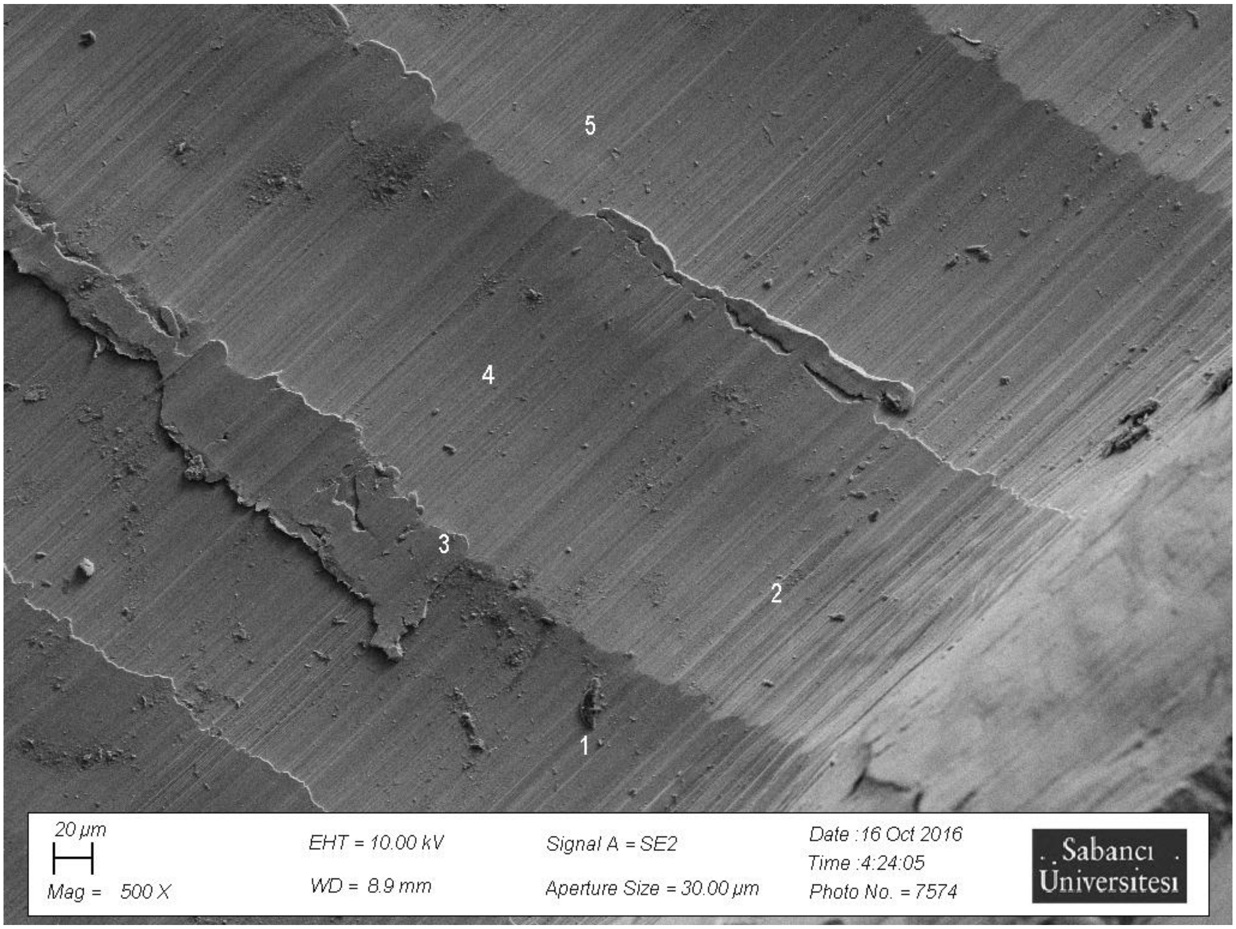


Figure 34: SEM image of the wall side surface under CO2 cooling

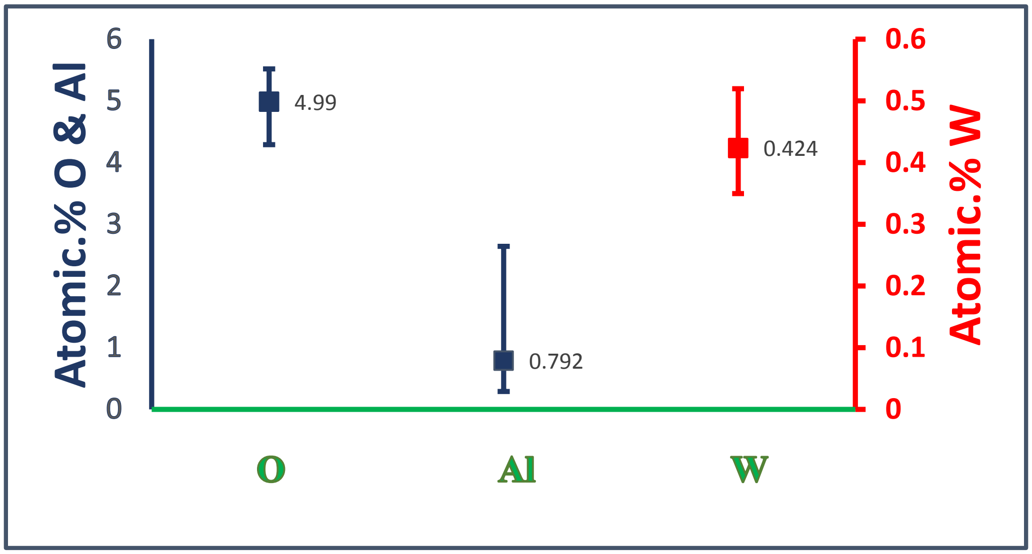


Figure 35: EDX point analyses of the wall side surface under CO2 cooling

SEM image and the corresponding qualitative EDX analysis of the sample from bottom surface of cooled with CMQL method is illustrated in figure 36. It reveals that when the specimen is cut under CMQL cooling conditions, there is no Al present in the surface of the sample. The distribution map of elements in the surface of the sample is presented in figure 37.

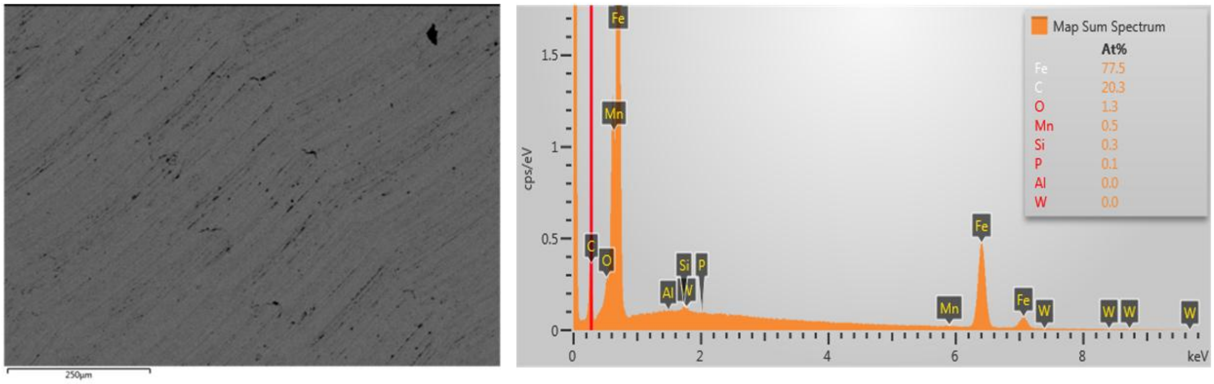


Figure 36: SEM image and EDS Spectrum of the generated surface under CMQL cooling.

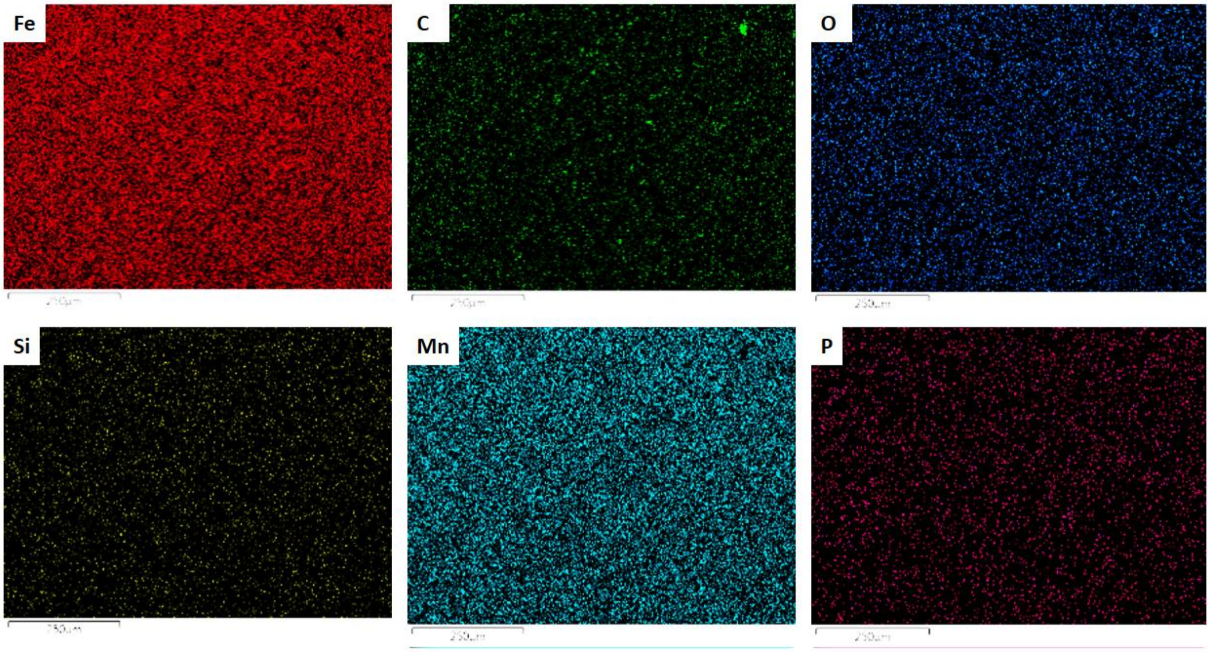


Figure 37. Distribution of elements over sample of generated surface under CMQL cooling.

Figure 38 shows the SEM image of the wall (cutting affected zone) during slot milling operation in the CMQL specimen. Under this cooling method the magnitude of surface roughness are quite low in comparison to that of CO2 cutting. EDX point analyses (Fig 39) clearly confirms that there is no Al residual in the cutting region. Likewise, the amount of oxygen is higher than its counterpart

Figure 38: SEM image of the wall side surface under CMQL cooling

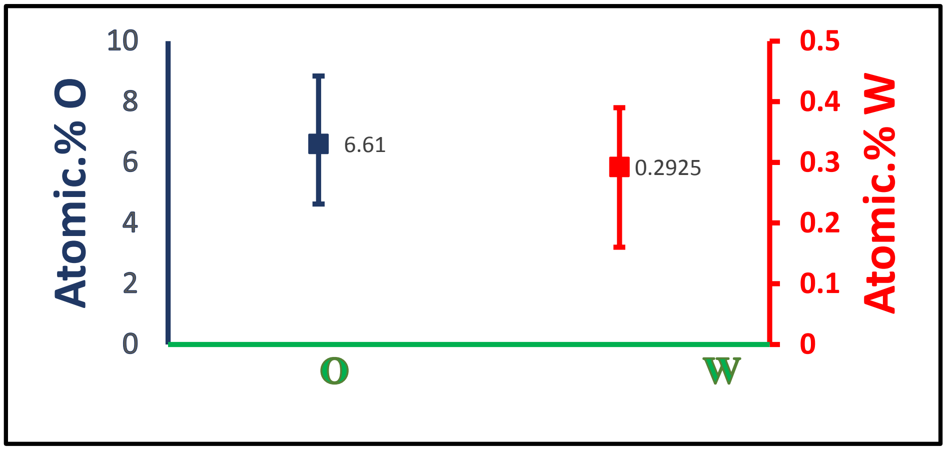


Figure 39: EDX point analyses of the wall side surface under CMQL cooling

in the CO2 cooled sample. The elemental analyses supported better heat removal and lubrication effects in CO2+MQL cutting.

4.4. Summary

In this chapter CO2+MQL is applied to slot milling of steel 1050. With the purpose of identifying the cooling strategy for the most effectively using cryogenic cooling, this study evaluated cutting temperatures generated under various cooling methods. In addition, elemental analyses carried out to show the effect of each cooling in cutting zone.

CHAPTER 5 CONCLUSION

This study has presented new and alternative cooling method to enhance efficiency of cryogenic machining. The major conclusions drawn are as follows:

- CMQL technique introduced as an alternative cooling technique enhanced productivity and final product quality with low cooling rate consumption.
- The modification of cryogenic supply could improve cooling condition in turning of hard to cut materials.
- CMQL supply reduced tool wear and developed surface quality in comparison to other scenarios.
- CMQL method with fixed cooling rate and lubricant increased tool life up to 60% and 30% during Ti6Al4V and Inconel turning in order, along with increasingly enhanced surface quality in comparison to CO_2+MQL supply method.
- Investigation of microstructural study from generated surfaces and chips pointed out that CMQL technique result in higher heat removal efficiency in addition to reduction of tool-chip contact length due to better generated surface and smoother chip backside with compare to other methods.
- Different behaviour of cutting forces observed under cooling scenarios for Ti6Al4V cutting in comparison to Inconel 718 turning.
- CMQL supply enhanced tool life about 16% with compare to modified nozzle during Inconel 718 cutting. Despite the fact that tool life under CMQL strategy during Ti6Al4V machining is decreased 9% compared to modified CO_2 nozzle, the consumption of CO_2 for CMQL is 25% of that of the modified CO_2 nozzle system
- CMQL delivery not only reduces the use of CO2 but also decreases the cost of inventory and transportation of CO2 tubes. Mentioned method can be integrated to lathes as an automated permanent system.
- Continuous hybrid cooling cannot improve machinability in the turn-mill operation
- The CO2 cooling in addition to MQL supply such a plug and play system found longest tool life among different cooling strategies in steel 1050 turn-milling
- Thermal analysis of steel 1050 slot milling showed higher heat removal for the CO2+MQL cutting in comparison to CO2 and MQL

- The elemental analyses and SEM images of surfaces generated in slot milling revealed the lower friction and better surface finish for the CO2+MQL supply

Further work proposed are listed as fallow:

- Where the pressure of the cryogenic liquid will be problematic to apply for the micromachining, CMQL can be effective due to lower flow of CO2 and substantial merits to increase machinability.
- Investigation of the phase transformation and the residual stresses in CMQL machining of hard to cut materials will be beneficial for the special applications in industry.
- Elemental analyses of the generated surface under alternative cooling method in machining of materials for the medical application would be a beneficial investigation. The transition of the materials due to chemical wear to the generated surface can decrease quality of the final part and increase corrosion.
- Optimization of the CMQL and CO2+MQL supply in turn-milling and milling operation is needed to improve the effect of the supply in which power consumption and cost should be investigated as well.

References

[1] Byers, Jerry P., ed. Metalworking fluids. Crc Press, 2016.

[2] Cassin, C., and G. Boothroyd. "Lubricating action of cutting fluids." Journal of mechanical engineering science 7.1 (1965): 67-81.

[3] De Chiffre, Leonardo. "Function of cutting fluids in machining." Lubr. Eng(1988).

[4] El Baradie, M. A. "Cutting fluids: Part I. characterisation." Journal of materials processing technology 56.1 (1996): 786-797.

[5] Hong, Shane Y. "Lubrication mechanisms of LN2 in ecological cryogenic machining." Machining science and technology 10.1 (2006): 133-155.

[6] Shaw, Milton C. "On the action of metal cutting fluids at low speeds." Wear2.3 (1959): 217-227.

[7] Adler, D. P., et al. "Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns." Machining Science and technology 10.1 (2006): 23-58.

[8] Shokrani, Alborz, Vimal Dhokia, and Stephen T. Newman. "Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids." International Journal of Machine Tools and Manufacture 57 (2012): 83-101.

[9] Geier, Johannes, et al. "Contact sensitizations in metalworkers with occupational dermatitis exposed to water-based metalworking fluids: results of the research project “FaSt”." International archives of occupational and environmental health 77.8 (2004): 543-551.

[10] Cornelis, Rita, et al., eds. Handbook of elemental speciation II: species in the environment, food, medicine and occupational health. Vol. 2. New York, NY, USA: John Wiley & Sons, 2005.

[11] Jawahir, I. S., et al. "Cryogenic manufacturing processes." CIRP Annals-Manufacturing Technology 65.2 (2016): 713-736.

[12] Klocke, F., and G. Eisenblätter. "Dry cutting." CIRP Annals-Manufacturing Technology 46.2 (1997): 519-526.

[13] Weinert, K., et al. "Dry machining and minimum quantity lubrication." CIRP Annals-Manufacturing Technology 53.2 (2004): 511-537.

[14] Byrne, G., David Dornfeld, and B. Denkena. "Advancing cutting technology." CIRP Annals-Manufacturing Technology 52.2 (2003): 483-507.

[15] Lemmon E.W., McLinden M.O., Friend D.G., 2011, NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Thermophysical Properties of Fluid Systems, http://webbook.nist.gov

[16] Jerold, B.D., Kumar, M.P., 2012. Experimental comparison of carbon-dioxide and liquid nitrogen cryogenic coolants in turning of AISI 1045 steel. Cryogenics 52(10), 569–574

[17] Wang, Z.Y., Rajurkar, K.P., 2000. Cryogenic machining of hard-to-cut materials. Wear 239 (2), 168–175.

[18] Hong, S.Y., Ding, Y., 2001. Cooling approaches and cutting temperatures in cryogenic machining of Ti–6Al–4V. Int. J. Mach. Tool Manuf. 41 (10), 1417–1437.

[19] Venugopal, K.A., Paul, S., Chattopadhyay, A.B., 2007. Growth of tool wear in turning of Ti–6Al–4V alloy under cryogenic cooling. Wear 262 (9), 1071–1078.

[20] Bermingham, M.J., Kirsch, J., Sun, S., Palanisamy, S., Dargusch, M.S., 2011. New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. Int. J. Mach. Tool Manuf. 51(6), 500-511.

[21] Rotella, G., Umbrello, D., 2014. Finite element modeling of microstructural changes in dry and cryogenic cutting of Ti6Al4V alloy. CIRP Annals-Manufacturing Technology 63(1), 69-72.

[22] Kaynak, Y., Lu, T., Jawahir, I.S., 2014. Cryogenic machining-induced surface integrity: a review and comparison with dry, MQL, and flood-cooled machining. Mach. Sci. Technol. 18 (2), 149–198.

[23] Supekar, S.D., Clarens, A.F., Stephenson, D.A., Skerlos, S.J., 2012. Performance of supercritical carbon dioxide sprays as coolants and lubricants in representative metalworking operations. J. Mater. Process. Technol. 212(12), 2652–2658.

[24] Clarens, A.F., Hayes, K.F., Skerlos, S.J., 2006. Feasibility of metalworking fluids delivered in supercritical carbon dioxide. Journal of Manufacturing Processes 8(1), 47-53.

[25] Hyatt, J.A., 1984. Liquid and supercritical carbon dioxide as organic solvents. The Journal of Organic Chemistry 49 (26), 5097–5101.

[26] Pusavec, F., Deshpande, A., Yang, S., M'Saoubi, R., Kopac, J., Dillon O.W., Jawahir, I.S., 2014. Sustainable machining of high temperature Nickel alloy–Inconel 718: part 1–predictive performance models. Journal of Cleaner Production 81, 255-269.

[37] Biermann, D., Abrahams, H., Metzger, M., 2015. Experimental investigation of tool wear and chip formation in cryogenic machining of titanium alloys. Advances in Manufacturing 3(4), 292-299.

[28] Cordes, Susanne, Fabian Hübner, and Thomas Schaarschmidt. "Next generation high performance cutting by use of carbon dioxide as cryogenics." Procedia CIRP 14 (2014): 401-405.

[29] Tyler, Christopher T., and Tony L. Schmitz. "Examining the effects of cooling/lubricating conditions on tool wear in milling Hastelloy X." Proceedings of NAMRI/SME 42 (2014).

[30] Pereira, Octavio, et al. "The Use of Hybrid CO 2+ MQL in Machining Operations." Procedia Engineering 132 (2015): 492-499.