Department of Mechanical Engineering

Sustainable End Milling of Difficult-Materials

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for award of any other degree or diploma in any university.

Signature:

Yogie Rinaldy Ginting

Date: June 2017

ABSTRACT

Three difficult to cut materials, Titanium Alloy (Ti-6A1-4V), Inconel 718 and Aluminium Metal Matrix Composites (AMMC) are extensively used in the automotive and aerospace industries due to their favorable mechanical properties. When machining these materials, a substantial financial burden is added as a consequence of using traditional flood cooling. It is proposed to investigate alternatives to using flood machining for these difficult to cut materials to minimise the environmental burden. Clearly sustainability is a very important issue for many aspects in the metal cutting industry. Dry machining may be adopted as it can be considered as the optimal sustainable machining process, though it is not always a practical alternative due to the resulting poor tool life. This creates a further onus on organisations to satisfy their environmental responsibilities. The consequence of ignoring the increasing awareness of environmental issues will untimely cause governments to legislate, and customers to find alternative green-resource efficient suppliers.

As a result of the need to dissipate the generated heat, sustainable cooling has become an important issue for metal cutting. Experimental work was carried out by combining apropriate machining parameters with a sustainable cooling method. The robustness of the experimental results was obtained by using the Design of Experiment method in carrying out the testing strategy. Surface finish, cutting force and the machine power requirements were used as the machinability criteria. The intention of this research was to investigate the effects of Liquid Nitrogen (LN_2), and Minimum Quantity Lubrication (MQL) as alternative cooling methods. Test results were analysed using the Taguchi S/N ratio to determine the optimum sustainable cutting method, and to establish the best machining parameters that give longest tool life. The Pareto ANOVA was used to determine the percentage contribution of each parameter on the output parameters. This experiment data was then used to help develop a tool wear model to predict the wear in end milling, and hard to machine materials using different cooling methods.

Interestingly, the Pareto ANOVA analysis provided important parameter effects to the materials being cut. For instance when Titanium Alloy (Ti-6A1-4V) is being machined

the force was affected by the contribution made by coolant (88%), indicating the need to have the ideal cooling method. On the other hand, the effect on Inconel was reduced to (59%), with the cooling technique also having a major contribution to the effect on the power used (89%). When AMMC was machined the coolant effect was even more remarkable on the cutting force as it was influenced by as much as (90%). The power for cutting indicated the cooling process contributed to (79%) to the effect of the amount needed.

Experimental analysis showed that MQL brought about the best performance while machining Titanium alloy for all three performance outputs: surface roughness, cutting force and power requirement. MQL can therefore be recommended as a replacement cooling method for this material. Using MQL while machining Inconel also gave the best surface roughness, and required the lowest cutting force, whilst using similar power to cryogenic cooling. Therefore MQL can also be considered as a suitable cooling replacement for Inconel 718 machining. Cryogenic cooling provided the best surface roughness when machining the AMMC, while MQL required the lowest cutting force, and power. Consequently, cryogenic cooling or MQL can be selected as alternative cooling methods for machining, depending on what output is most important.

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LIST OF PUBLICATIONS

Peer-reviewed Publications

1. Y. R. Ginting, B. Boswell, W. Biswas, and N. Islam, "Advancing Environmentally Conscious Machining," *Procedia CIRP*, vol. 26, pp. 391-396, 2015.

2. Y. R. Ginting, B. Boswell, W. Biswas, and M. N. Islam, "Investigation into Alternative Cooling Methods for Achieving Environmentally Friendly Machining Process," *Procedia CIRP*, vol. 29, pp. 645-650, // 2015.

3. Y. R. Ginting, B. Boswell, W. K. Biswas, and M. N. Islam, "Environmental Generation of Cold Air for Machining," *Procedia CIRP*, vol. 40, pp. 649-653, // 2016.

4. B. Boswell, M. Islam, Y. Ginting, and J. Ong, "Grinding Using Cold Air Cooling," in *Proceedings of the World Congress on Engineering*, 2016.

5. M. Islam, B. Boswell, and Y. Ginting, "Effects of Canned Cycles and Cutting Parameters on Hole Quality in Cryogenic Drilling of Aluminum 6061-6T," *World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, vol. 10, pp. 872-880, 2016.

6. B. Boswell, M. N. Islam, I. J. Davies, Y. R. Ginting, and A. K. Ong, "A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining," *The International Journal of Advanced Manufacturing Technology*, pp. 1-20, 2017.

Honors and Awards

M. Islam, B. Boswell, and Y. Ginting, "Effects of Canned Cycles and Cutting Parameters on Hole Quality in Cryogenic Drilling of Aluminum 6061-6T" has been selected as the best paper in ICME 2016: 18th International Conference on Manufacturing Engineering granted by World Academy of Science, Engineering and Technology (WASET)

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NOMENCLATURE

b	parameter of regression weights
D	tool diameter (m)
D_T	temperature difference
f	tool feed rate (mm/min)
f_z	feed per tooth (mm/rev)
F_c	cutting force (N)
F_T	cutting force (N)
F_f	feed force (N)
F_{fN}	feed normal force (N)
F_p	passive force (N)
I	input current to the module (A)
K_M	thermal conductance of the module
N	rotational speed of tool spindle (rpm)
P_c	machine power (kW)
R_a	surface roughness (µm)
R_M	electrical resistance of the module
S_M	Seebeck coefficient of the module
t	cutting time (s)
Tw_F	tool wear under flood (µm)
Tw_N	tool wear under liquid nitrogen (µm)
Tw_M	tool wear under MQL (µm)
T_c	cold side temperature (K)

T_h hot side temperature (K)

v cutting speed (m/min)

X independent variable

Y dependent variable

z number of teeth of milling tool

Chapter 1

INTRODUCTION

1.1 Background

The machining process has been the main stay of manufacturing since the Industrial Revolution. Since that time period numerous changes have occurred, and present concerns are economic and environmental issues. Machine tools used are capable of working unattended for long periods of time. It is essential that the cutting action of tools is fully understood.

The cutting process consists of a number of cutting actions performed by a machine tool to remove excess material from a workpiece to obtain the desired geometry [1, 2]. Typical cutting processes are turning, drilling, boring, milling, shaping, planning, broaching and sawing, all of which are used to form various products. Dimensional reduction, producing holes and making complicated profiles such as gears are only some of the complicated operations that are carried out. These processes are of vital importance in the field of manufacturing [3]: about 80% of the total manufacturing throughout the world is composed of metal cutting [4].

Unfortunately, the machining process over the years has become notorious for environmental pollution, as it requires relatively large amounts of energy and generates copious amount of liquid coolant waste [5]. These need to be environmentally disposed of, which contributes to the cost of the part, reported to be as much as 16% of the manufacturing cost [6].

Coolant has been an essential part of the cutting process for decades, especially for difficult-to-cut materials. This includes cooling the cutting tool and workpiece, reducing friction by lubricating the contact surface of the tool and the workpiece, and also removing chips from the machining zone [7, 8]. However, the use of coolant in machining processes is a major contribution to environmental pollution [9]. Coolant uses 31.8% of the total energy machining process, whereas the machining process itself requires only 14.8% [10]. For example, the cost of coolant purchase and disposal for aluminium made the transmission component reach 36%, which is very large compared to 4% for the cutting tools cost. (Figure 1.1).

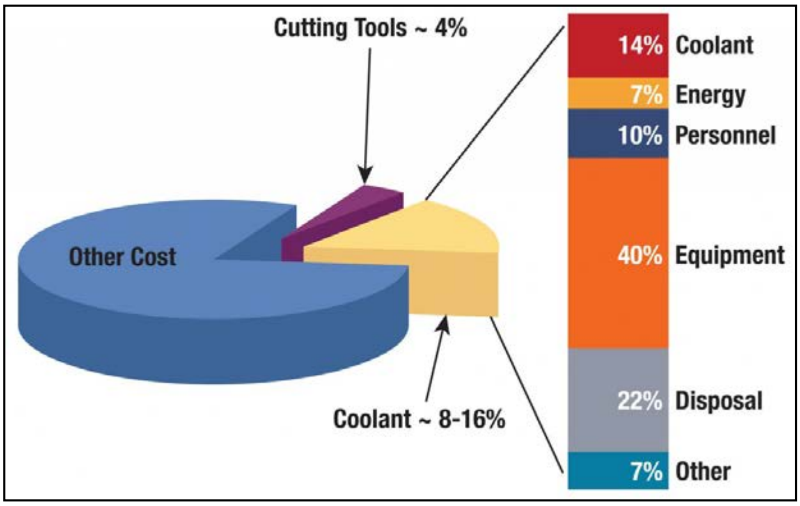


Figure 1.1 Machining cost of aluminium transmission component [6]

In an effort to reduce environmental pollution, many countries have introduced regulations to encourage the manufacturing industry to pay more attention to the negative impact of their production processes. Generally called “sustainable manufacturing”, this is where the process is performed with regard to energy saving, natural resource preservation, and minimation of the negative impacts on the environment and the society [11].

Many governments have introduced regulations regarding waste disposal, insisting it is absolutely necessary for companies to spend a considerable amount of money on handling their coolant waste [12]. Therefore, economic and ecological pressures are making companies seek methods for reducing coolant consumption [13]. Companies that are able to reduce or eliminate coolant from the machining process will have a distinct advantage and may be considered as an “environmentally friendly company”, while also managing to reduce their costs [14].

The best solution is to use a process known as dry machining, not liquid cooling, in the cutting process. The use of dry machining has been investigated by a number of researchers, and has successfully replaced wet machining for certain machining conditions [15, 16]. In all cases however, dry machining used for cutting metal generates high heat which promotes the wear mechanism. The result of this causes the tool life to be significantly reduced [5]. Generally this problem can be alleviated by lowering the cutting parameters to allow the tool to have a reasonable tool life. The consequences of this though is an increase in the machining time. When cutting difficult-to-cut materials, dry machining cannot be used without significantly reducing both the cutting speed and feed rate.

In an attempt to extend tool life and to maintain product quality, solutions have been identified. Most importantly, there is a need for an alternative cooling method that is able to eliminate the use of traditional coolant from the machining process. A number of alternative cooling methods have been studied by various researchers, such as Liquid Nitrogen cryogenic cooling (LN_2), cold air, and Minimum Quantity Lubrication (MQL). Alternative cooling methods are being examined for their suitable use with the milling process when machining difficult-to-cut materials. To date there is still scant knowledge about milling these materials when using alternative cooling methods. If the optimal solution for machining difficult-to-cut materials can be found, then these results could be applied with relative ease to other materials. The ultimate goal of this research is to establish a function which can be further refine Taylor's equation, which gives the effectiveness of tool life with respect to the cooling method.

1.2 Aim and Scope of Research

The primary objective is to eliminate or reduce the use of conventional coolant when machining difficult to machine materials. In doing so, health and environmental problems will be much improved, and at the same time the manufacturing costs should decrease. The challenge is to provide a sustainable and effective alternative cooling method capable of reducing tool wear, and maintaining product quality at an economical cost.

This research will compare the performance of conventional flood coolant with LN_2 and MQL to determine an alternative cooling method which can replace the traditional coolant, for similar output quality. LN_2 and MQL cooling methods selection were based on previous studies showing that both are relatively safer, more environmentally friendly and less expensive to apply.

In addition, the best combination of cooling methods and machining parameters - such as cutting speed and feed rate - are investigated, allowing the cutting power and the machining power to be reduced. Using the optimum parameters will increase the rate of material removal and shorten the machining time.

The difficult-to-cut materials used in this research are:

- Titanium alloy (Ti-6Al-4V),
- Inconel 718, and
- Aluminium Metal Matrix Composite (AMMC).

The performance of machining parameters and cooling methods will be measured using three quality parameters, namely:

- cutting force (F_c),
- machine power (P_c), and
- surface roughness (R_a).

The important areas of this research are determining the best cooling method and the optimum machining parameters for each difficult-to-cut material and reducing the machining costs while maintaining product quality.

1.3 Importance of the Project

The increased use of difficult-to-cut materials for products is most noticeable in various areas such as medical implants, aerospace, and the automobile industry. It is imperative therefore that the machining processes must be completed effectively and efficiently. Manufacturers still rely on flood coolant to assist most of the the machining processes. The use of coolant increases machining costs significantly as additional payments are required for maintenance and waste management [6]. Reduction or elimination of coolant from the machining processes will certainly reduce the cost of products and thereby improve its competitiveness in the market.

The alternative cooling methods used in this research should provide comparative results to those currently obtained by machining processes when cutting difficult-to-cut materials. The dependency of the machining industry to use flood coolant will be substantially reduced.

This research is beneficial to the machining industry as it contributes to reducing machining costs and adverse engineering effects in the environment by using a more environmentally friendly cooling method and optimised machining parameters.

1.4 Outlines of Thesis

This thesis consists of seven chapters, the objectives of each chapter are presented below:

Chapter 1: provides a general overview and background of the research on the need for coolant and its impact on machining costs and the environment. The aim and scope of this research and the importance of the project are also presented in this chapter.

Chapter 2: presents a literature review related to this thesis. The discussion covers the theory of machining and cooling methods. The results of previous studies on sustainable machining are also discussed, especially the influence of cooling method and machining parameters on the machining results.

Chapter 3: provides an overview of the experimental methodology and the description of machine, materials, proposed cooling methods and measuring equipment used in this research.

Chapter 4: contains the experiments conducted for the initial investigation to support this research.

Chapter 5: provides the results of experiments conducted, as well as data analysis and discussion. The effects of cooling method, cutting speed and feed rate on surface roughness, cutting force and required machine power are examined.

Chapter 6: investigates the performance of cooling methods on tool wear. Multiple regression analysis are performed to create a model to compare the performance of alternative coolants with flood coolant.

Chapter 7: presents the achievements and concludes the findings of this research and lists out some recommendations for future studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

As described in Chapter 1, it is almost impossible to machine difficult-to-cut materials effectively under dry condition. An alternative cooling method, therefore, is required so that the machining process of difficult-to-cut materials can be achieved without sacrificing machining performance or product quality, in a sustainable manner. In this chapter the relevant theory is presented, and the state of the art in the study area is identified by conducting an extensive literature review.

This chapter summarizes the findings and the problems faced by previous researchers in their efforts to find the best way to machine difficult-to-cut materials. Machining parameters and cooling methods affecting the machining performance and surface quality are assessed. The limitations of previous research and the research gaps are presented at the conclusion of this chapter.

2.2 The Milling Process

The machining process is one of the most important processes, as 80% of the world's manufacturing industry is in this area. This process is performed to remove material from the workpiece to produce the desired shape and size [1]. The machined workpiece can be derived from raw materials or unfinished products, to improve the dimensional quality of the workpiece.

The tool cutting action generates heat as the chips break away. Heat is the biggest problem in the metal cutting process as it promotes tool wear, which in turn affects the dimensional accuracy of produced parts [17, 18]. Most machining processes require the application of coolant to remove the heat, and consequently reduce friction from the cutting zone.

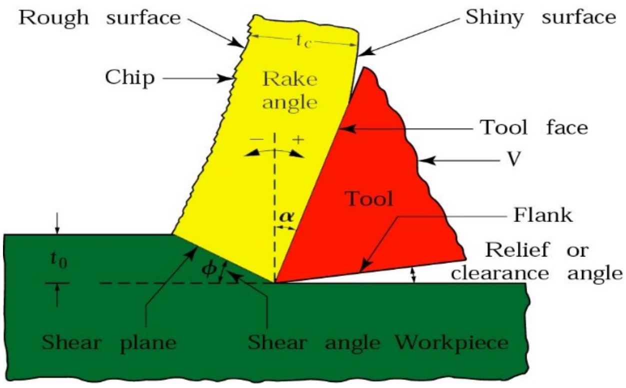


Figure 2.1 Principle of machining process [2]

A number of alternative cooling methods such as cold air, compressed air, cryogenic cooling, and Minimum Quantity of Lubrication (MQL) have been investigated by researchers to reduce the use of conventional coolant. All of these have had limited success when used with milling, due to the intermittent nature of the cutting action.

Milling is one of the most widely used processes in metal cutting as this action/procedure is capable of generating complex shapes. The cutting action is carried out with a multi-tooth cutter rotated as it moves across a workpiece, using the face or the periphery of the cutter to produce a flat surface, a form or a slot [2, 19].

The milling process has an invaluable role in the manufacturing of Titanium alloy components for the automotive and aerospace industries [20]. However, there has been little research into the machining of difficult-to-cut materials using milling machines, procedures which normally rely on the copious amount of cutting fluid being used. It is also essential for modern manufacturing to carry out the machining of difficult-materials in a sustainable manner. Therefore, in this research it is a necessity to optimize machining parameters in the milling process of difficult materials, such as titanium alloy.

In this research, a Computer Numerically Controlled (CNC) milling machine will be used to provide exact parameter values, and to obtain products with high dimensional accuracy. The CNC milling machine will facilitate the end milling process of the workpiece, which will produce parts with similar dimensions by varying cutting parameters.

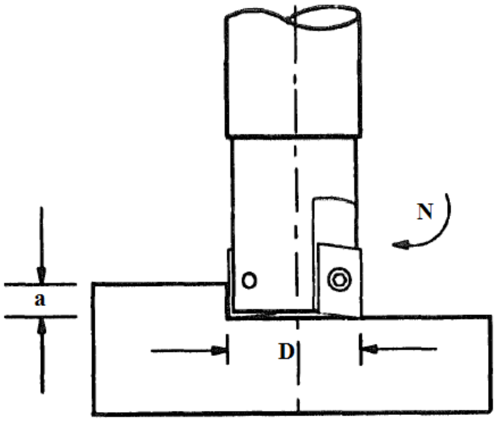


Figure 2.2 End milling process with insert tip [21]

Cutting speed, feed rate and depth of cut are three important parameters in the machining processes. These three parameters affect cutting forces, machine power requirement, tool life and surface finish of the product. Optimization of these three parameters will determine the success of the machining process.

2.2.1 Cutting speed

In machining practice, cutting speed is selected based on factors such as tool material, workpiece material and machining operation. A high cutting speed will increase the rate of material removal, or in other words reduce machining time. However, since the increase of cutting speed is also followed by the increase of machining temperature [22], it is necessary to determine the optimum cutting speed to achieve the best machining performance. In this research, cutting speed for each process was selected from tool manufacturer recommendation, so that any findings of this research can be used practically in the real world.

Cutting speed (v) in milling process can be calculated as:

$$v = \pi N D \ (\text{m/min}) \qquad (2.1)$$

Where:

N = the rotational speed of tool spindle (rpm)

D = tool diameter (m)

There are two groups who have different opinions regarding the significance of the effect of cutting speed on tool wear. Brun *et al.*, Sahin and Sur, and Namb *et al.* were in a group who said cutting speed increases tool wear [23-25]. While Cronjager and Meinster and also Davim and Antonio's findings proved that cutting speed is not significant to tool wear [26, 27].

2.2.2 Feed rate

Feed rate plays an important role in determining the performance of machining processes. In the milling process the feed rate is determined by considering a number of factors, including: workpiece and tool materials, type of tool and tool diameter. Desirable machining results such as surface finish quality, tool wear rate and machining time, can also be considered in the selection of feed rate [28, 29].

Various studies have shown that feed rates have a great influence on tool life [30, 31]. Also, the feed rate can greatly affect the surface finish of the product [29, 32-34]. The feed rate for a milling process (f) can be calculated by using the formula:

$$f = f_z \, . \, z \, . \, N \text{ (mm/min)} \quad (2.2)$$

Where:

f_z = feed per tooth (mm/rev),

z = the number of teeth,

N = the rotational speed of the spindle (rpm)

2.2.3 Depth of cut

The depth of cut in a face milling process is the penetration of the milling tool below the original surface of the workpiece. Since previous research found that the influence of depth of cut is not significant to the output parameters, especially on surface roughness and tool wear, in this research the depth of cut was not not used as one of the test parameters [35, 36]. The same values of depth of cut were used for all tests.

2.3 Difficult-to-Cut Materials

To meet the material requirements for automotive and aerospace industries, materials with special characters are developed such as harder, corrosion resistant, and high temperatures resistant. However, with this particular ability, the machining process of these materials also becomes more challenging so that this material group is also known as difficult-to- cut materials. For that reason, various researches have been completed to improve the performance of machining processes of these materials as measured by longer tool life, better surface quality and less energy consumption.

A material is classified as difficult to cut when certain difficulties are encountered in the machining process of the material. This difficulty is caused by certain characters possessed by the material. The difficulties themselves are varied such as the hardness of the materials, high machining heat, short tool life or the difficulties in obtaining good surface quality. The classification of the difficult-to-cut material also changes. For example, twenty years ago stainless steel was included in difficult to cut materials, but today it is a very common material to be cut. This is due to the production of better machine tools (rigidity and capability) and the discoveries of new tool materials, so that the main problems in the machining process such as hard materials and high temperature can be solved. Advances in machining technology will make the classification is also still likely to change in the future.

Classification of the difficult-to-cut materials, according to Shokrani *et al.* [14], can be viewed in Figure 2.3. From the picture it can be seen that until now there are three classes of material that can be called difficult to cut, namely: hard material, ductile materials and non-homogeneous materials.

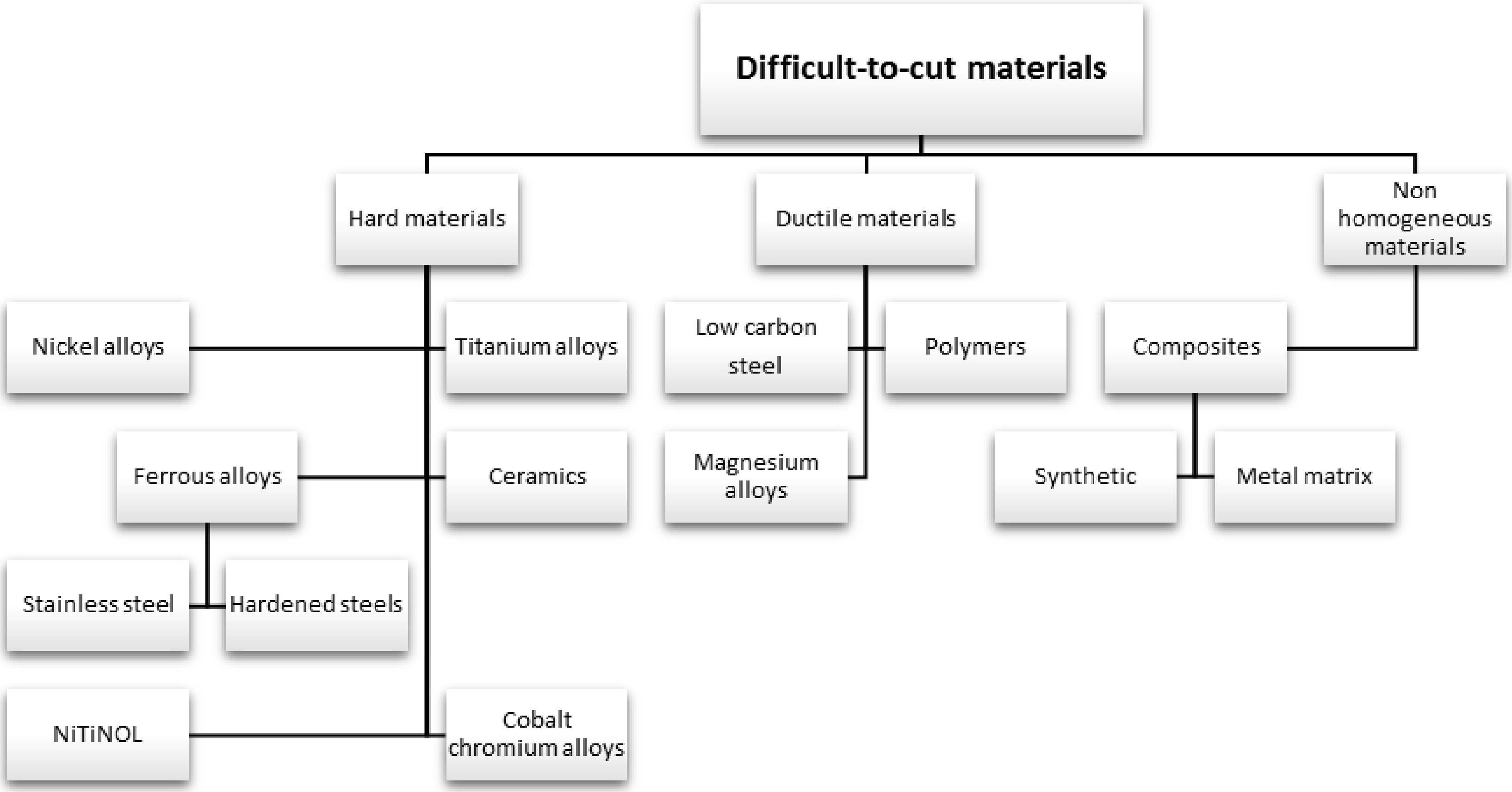
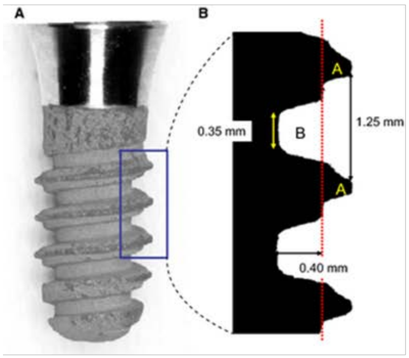


Figure 2.3 Classification of the difficult-to-cut materials, adapted from [14]

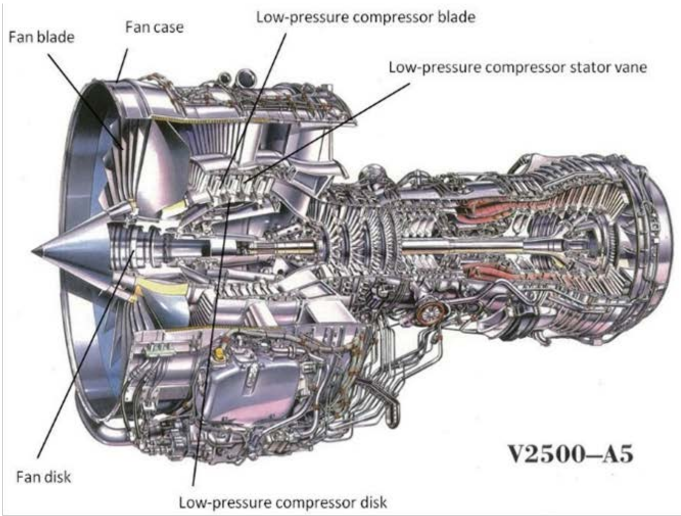
The selection of Titanium alloy, Inconel 718, and AMMC as test materials in this experiment are due to their good characteristics and their extensive use in industry. The different characteristics of these three materials also caused different difficulties in their cutting processes. For example, cutting Inconel is challenging since cutting tool wears at high rates and good surface quality is difficult to obtain [37]. AMMC also considered as difficult-to-cut materials since in most cases good surface finish is difficult to achieve [38, 39]. Surface finish can be improved slightly by increasing cutting speed, but with increasing machining temperature, the wear rate of the tool is also increased [40].

2.4 Titanium alloy (Ti-6Al-4V)

Titanium alloy is lighter but stronger than steel making it a widely used material in various fields [41, 42]. Titanium is used in many industries ranging from dental implants to aerospace structures (Figure 2.4). However, this excellent characteristic becomes a challenge when it comes to machining parts with Titanium material [43, 44]. Its ability to maintain its strength and hardness at high temperatures makes this material difficult-to-cut [45, 46]. High cutting temperatures and rapid tool wear are the major problems in the cutting process of Titanium alloys [47, 48].



(a)



(b)

Figure 2.4 Titanium alloy application for dental implants and aero engines [49, 50]

The machining speed of Titanium alloy endorsed by manufacturers for coated carbide tool tips under flood cooling is 30-80 m/min [51]. Conventional Titanium cutting is performed with a low cutting speed, less than 60 m/min, low feed and a copious amount of coolant [52-54]. This condition will maintain the cutting temperature since the thermal expansion of the tool and the workpiece will reduce tool life and decrease surface finish quality [55, 56].

Ezugwu and Wang [57] reported that, for the most part, about 80% of Titanium alloy machining heat was distributed to the tool, and only a small part was eliminated with the chips. However, they also found that cutting forces needed for Titanium alloy are found to be similar compared to that of steels. Comparison machining heat distribution between Titanium alloy and steel CK 45 is illustrated in Figure 2.5.

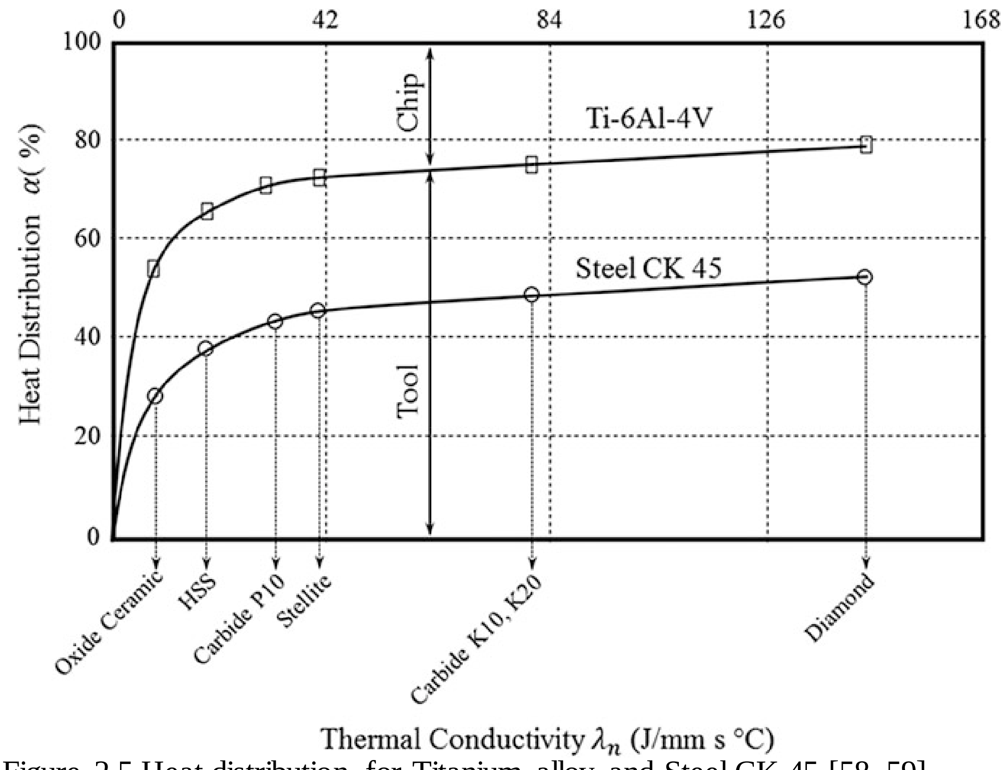


Figure 2.5 Heat distribution for Titanium alloy and Steel CK 45 [58, 59]

2.5 Inconel 718 (Nickel-based alloys)

Inconel is known as a high strength material, tough and with a high corrosion resistance [60, 61]. In addition, Inconel also has resistance to creep deformation at high temperatures, up to 700˚C [62]. Due to its good properties, Inconel is widely used from aerospace engines, nuclear reactors, to marine equipment [63, 64]. Unfortunately, its excellent characteristics also include Inconel as one of the difficult-to-cut materials [65]. Rapid tool wear and the difficulty in obtaining good surface finish are two main problems in cutting Inconel. Jawaid *et al.* [66] found that the tool only lasted for one minute for milling process of Inconel 718 with cutting speed 75 and 100 m/min and feed rate 0.14 mm/rev. Liao *et. al.* [67] recommend cutting speeds of 90-110 m/min for milling slots. This is due to the fact at high speed, temperatures increase rapidly, and it is hard to remove chips from the machining zone.

According to Ravi and Kumar [68], a lower cutting temperature under a cryogenic cooling application, on the end milling of hardened steel, reduces the cutting forces and slows the tool wear. Fernandez *et. al.* [69] discovered that the best surface roughness was given by conventional cooling compared to dry machining, cryogenic and cold air. For the milling process, Zhang and Wang [70] found that machinability of Inconel 718 was improved under a combination of MQL and cold air cooling.

Since conventional cutting of Inconel using flood cooling is difficult already, its cutting process with an alternative cooling method would be interesting to investigate. To obtain optimum machining results without coolant, it is necessary to find the best combination of machining parameters and an alternative cooling method.

Since the previous experiment result showed that feed rate 0.3 mm/rev caused a lot of broken tips with any cutting speed, in this research the highest feed rate used was 0.2 mm/rev.

2.6 Aluminium Metal Matrix Composites (AMMC)

AMMCs have been developed to overcome the limitation of aluminium alloys to their poor high-temperature performance and wear resistance [33, 71]. Compared to homogeneous aluminium, AMMC has a high strength to weight ratio, allowing this material to be widely used in the automotive and aircraft industries that require lightweight components. However, high tool wear rates are still the major problem in the machining industry due to the abrasive nature of the reinforcements [72, 73]. As it is hard to get a good surface finish from this material, AMMCs are classified as non-homogeneous difficult-materials [38, 39].

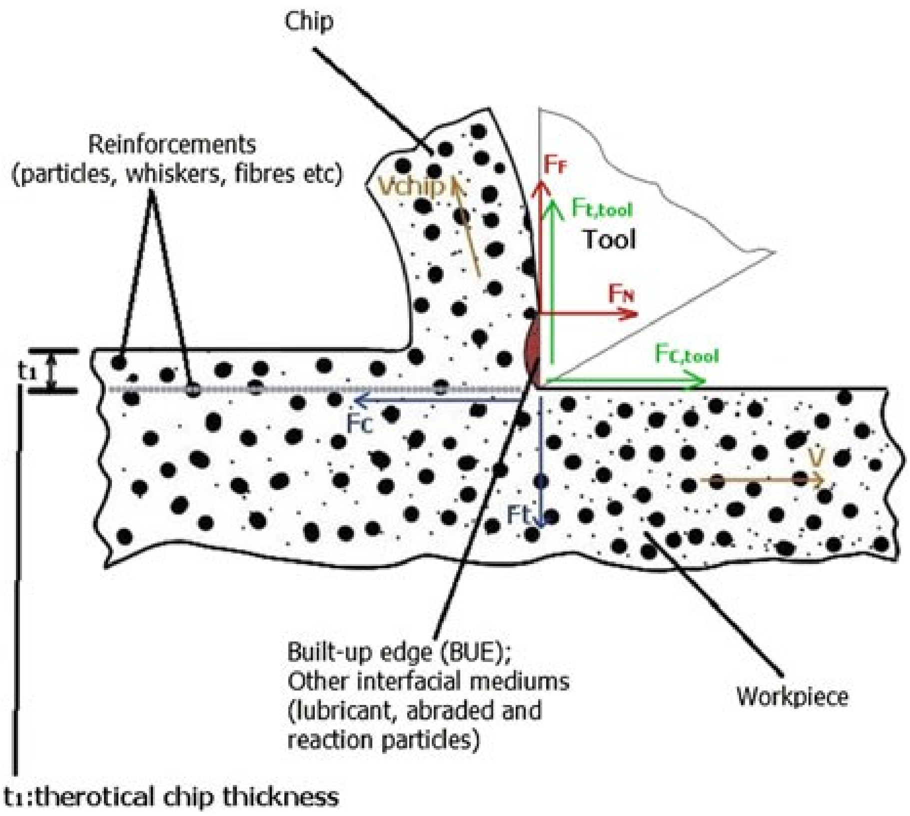


Figure 2.6 Machining process of AMMC with abrasive reinforcement [73]

In this research, a relatively new MMCs material, Boron Carbide Particle Reinforced Aluminium Alloy (AMMC), will be used as a test-material. The reason is due to this material's suitability for automotive components (Figure 2.7), and it also meets the requirements for use in the aerospace industry. Furthermore, Boswell *et al.* [74] found a very interesting fact, that in certain conditions, this material has a better surface finish when being cut with a higher feed rate. Szaloki *et al.* [75] reported a similar result for an AMMC end milling process by using cold air as a cooling method. A higher feed rate would be very supportive to the purpose of this research, because a high feed rate means faster machining. This research will continue to further investigate the range of the feed rate which produces a better quality of surface finish.

(a) (b)

Figure 2.7 AMMC application for connecting rod and piston, adapted from [76]

The sticky properties of aluminium usually cause an accumulation of residual chips on the tool, and it will reduce tool life although the tool has not yet experienced significant wear [77]. Therefore, the selection of appropriate machining parameters will play a significant role in avoiding high temperatures and maintaining tool life, especially in the absence of cutting fluids.

2.7 The Role of Cutting Fluid in the Machining Process

Cutting fluids are important requirements in machining processes, and have been used for decades [78-80]. For example, most of the machining processes for automotive components was performed with the assistance of cutting fluid [81, 82]. Metal cutting using coolant as a cooling method is known as wet machining. Soluble oil is the most widely used coolant in the industry [83]. Soluble oil consists of 95% water mixed with 5% oil with emulsifiers and additives. The use of vegetable oil as a more environmentally friendly coolant is also being studied [84, 85]. Cutting fluid, when supplied to the cutting zone, has considerable functions such as cooling the tool, lubricating and reducing friction between tool and workpiece, and taking away the chips in the machining process [19, 81, 86].

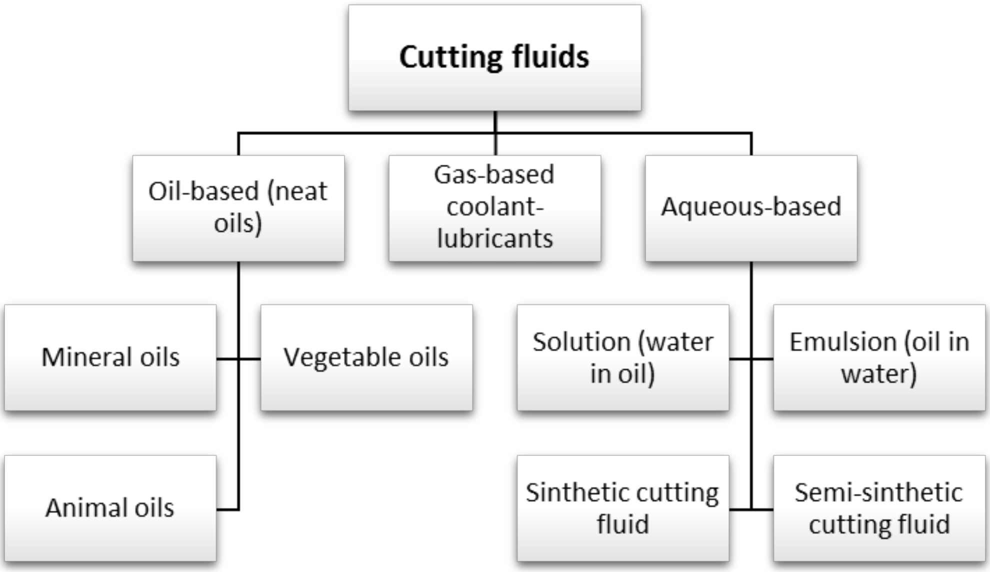


Figure 2.8 Cutting fluids classification, adapted from [85]

The high temperature in machining processes occurs due to the contact of the cutting tool with the workpiece. Despite the heat of machining mostly carried by the chips, high temperatures will accelerate the tool to wear and affect the dimensional accuracy of a produced part [87]. The constant flow of coolant, which is mainly composed of a water-based emulsion of oil, will carry the heat from the tool and the workpiece and reduce the heat of the machining zone [88]. The cooling effect of the coolant is a support for raising the machining parameters such as cutting speed, feed rate and depth of cut, since the tool wear rate decreases as machining temperature decrease.

Friction between the tool and the workpiece is also reduced by the lubrication effect of coolant. When the coefficient of friction reduces, the chips flow much more smoothly and reduce the possibility of the formation of a built-up-edge (BUE), especially in the machining process of sticky materials such as aluminium alloys [86].

Coolant also flushes away the chips as they are produced, out of the way of the tool and cleaning the work area [19]. This function is important since recutting chips can scratch and damage the surface of the workpiece. The clean path will also reduce the possibility of chips coating the tool or piling on it. When a tool is coated with chips, the tool temperature is getting higher. It is the more likely to experience a built-up edge, or in some cases it will be easily broken.

Table 2.1 Coolants types with advantages and disadvantages, adapted from [89]

Advantages and disadvantages	Straight oils	Soluble oils	Semi-synthetics	Synthetics
Lubricity	Excellent	Good	Poor	Poor
Cooling	Low	Good	Good	Excellent
Rust control	Excellent	Low	Good	Good
Create a mist or smoke	Fire hazard	Low	Foam easily	Non-flammable, non-smoking
Easily contaminated	No	By bacterial growth	By other machine fluids	By other machine fluids
Other	Limited to low-speed and heavy cutting operations	Evaporation losses	Stability affected by water hardness	Reduced misting and foaming problems

A machining process assisted by a cutting fluid application has been shown to improve the surface quality and dimensional accuracy, extend tool life, and also increase the production rate with increasing material removal rates.

2.8 Dry Machining as the Most Environmentally Friendly Method

Cutting fluid, which has huge benefits in the machining process, was discovered to increase the production costs and cause serious problems for the environment and human health [90-92]. Negative effects of coolant on health began to reduce with the introduction of environmentally friendly coolant to the manufacturing industry [93]. However, this friendly coolant has limited success due to its low machining performance [94]. According to Kuram *et al.*, as a good replacement, a friendly coolant should provide the same productivity compared to the conventional coolant [93]. Other factors that brought about an increase in production costs and environmental pollution mean that the coolant application should still be reduced or even eliminated in the machining process [95, 96].

Due to various problems caused by wet machining, many types of research conducted have performed the process of metal cutting without coolant. Machining processes without coolant are known as dry machining. This method is certainly the most environmentally friendly because it does not generate waste coolant, and is more energy-efficient because it does not require a coolant pump. This method is also relatively safer for the operator due to the absence of contact with the coolant. Economically, the cost of dry machining processes also become less expensive because they do not require the purchase cost, maintenance, and handling of the waste of coolant.

To maintain tool life and the quality of produced parts, dry machining should be able to overcome the consequences caused by the absence of coolant, such as friction tool and workpiece, high cutting temperature, and chips that may interfere with the machining process. Hadi and Hadad found that the highest temperature dry machining of steel grinding would reach is 960˚C, or more than three times that of conventional cooling (305˚C) [97]. Dry milling of the Titanium Alloy Ti-6A1-4V conducted by Ginting and Nouari shows that the cutting temperature reaches 1020˚C, which is much higher than high temperature cutting (> 850˚C) [55].

A number of researchers show that, for certain materials and conditions, dry machining results are even better than conventional coolant. The success of cutting metal under dry conditions depends on many factors such as: the tool material, the type of machining process, the workpiece material, and the machining parameters chosen. According to Streejith *et al.* [81], dry machining is a machining solution of the future, and success of this process will depend on the progress of tool materials technology. By using a coated tool, certain dry machining processes are possible, especially turning and milling processes.

A dry milling process with coated cemented carbide is recommended by Ibrahim since it produces an acceptable surface finish [15]. Unfortunately, although the cutting speed and feed rate used were quite high, 95 m/min and 0.35 mm/rev respectively, the depth of cut selected only 0.1 mm. Machining processes on various type of steel show that dry machining has the lowest performance in terms of tool life and surface roughness compared to that of palm oil, fatty and flood coolant [98].

When turning Inconel 718, Devillez *et al.* [16] found that the surface roughness from dry turning was better than wet turning with a similar cutting force. However, the optimum cutting speed they recommended was only 60 m/min. Muthukrishnan and

Davy found that for Titanium Alloy (Ti-6Al-4V) materials, in addition to wet turning providing better surface roughness, tool life was also increased by 30% when compared with dry turning [25].

From the findings above, it can be seen that a number of necessary adjustments are needed in the application of dry machining in order to overcome the effects arising from the absence of coolant from the machining zone.

2.9 The Necessity of Alternative Cooling Methods

With the invention of new materials for flood coolant, health hazards for operators who are exposed to coolant is diminishing [3]. However, the use of coolant still leaves a considerable problem in terms of cost (in this case the cost of purchase and disposal), power (since it requires a pump to distribute coolant in large amounts), and the environment (pollution of soil and water).

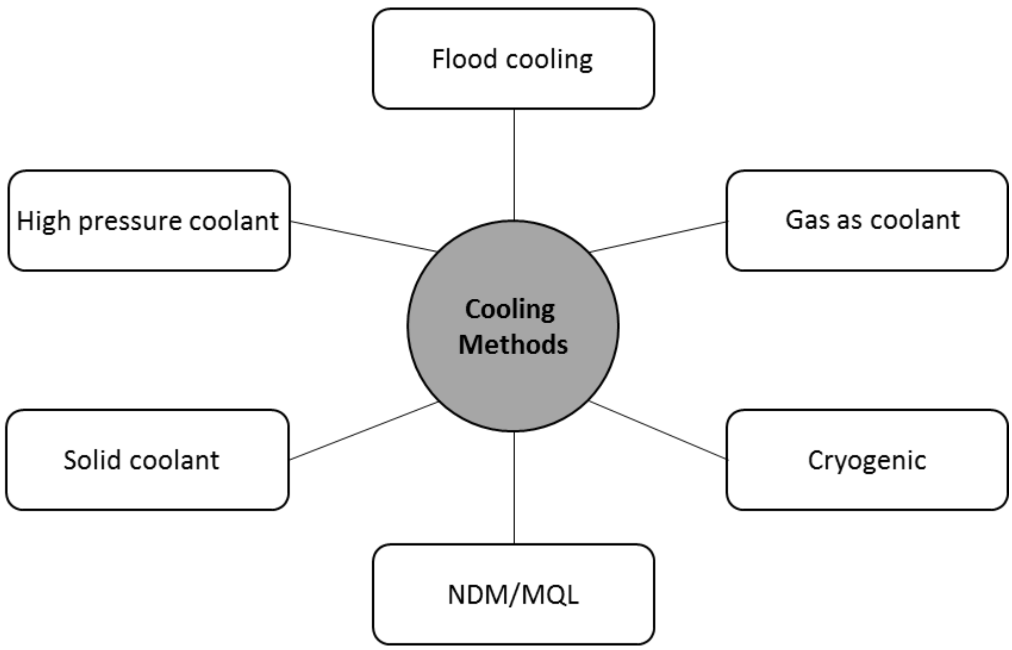


Figure 2.9 Cooling methods in machining operations, adapted from [99]

High costs caused by traditional coolant is the main reason that it should be reduced, or if possible removed from the machining processes. In the USA it costs about US

$48 billion a year, and in Japan it costs about 71 billion yen per year while the disposal cost alone is about 42 billion yen [100, 101]

Various alternative cooling methods such as cold air, compressed air, cryogenic cooling, and the Minimum Quantity of Lubrication (MQL) have been investigated by researchers in an effort to reduce the use of conventional coolant [102-105].

According to Dixit *et al.* [11], in order to qualify to replace traditional coolant, alternative coolants must meet the following requirements:

- be less expensive
- be more environmental friendly
- provide similar or even better quality, measured from surface finish, Material Removal Rate (MRR), machining force and machine power.

For example, the use of coolant can reduce the temperature of machining up to 30%, so it helps to extend tool life [106]. It is necessary for alternative cooling to provide at least the same tool life.

2.10 Cryogenic Cooling with Liquid Nitrogen (LN_2)

Liquid nitrogen selection, as an alternative cooling method in this research, is based on its good characteristics such as environmentally friendly, harmless (because the actual air contains 78% nitrogen) and its ability to cool the cutting zone quickly with a temperature below 120 K or below -150˚C [107, 108]. Heat is the greatest significant parameter for tool wear in metal cutting processes [18, 109, 110]. Cryogenic cooling maintains the tool temperature below the softening temperature, thereby slowing the tool wear [111, 112]. In addition, it is also necessary to reduce undissipated heat from the surface of the component due to the low thermal conductivity [109].

Research conducted by Gupta *et al.* [113] indicates that the turning process of AISI 1040 under LN_2 cooling requires less cutting force and produces better surface quality when compared with dry turning.

According to Hong [114], total production costs per machining part under LN_2 are lower compared to flood coolant. LN_2 usage cost per actual cutting hour ($ 1.33/h) is much cheaper than the cost of purchase and disposal of flood coolant ($ 3.36/h). If the cost of power for the coolant pump is also included in this calculation, the cost of flood coolant would increase. In addition, Hong also found that if the tool life reached 67% improvement, it reduces tool changing time and reduces machining time.

One thing that needs to be considered when using LN_2 as a cooling method is that too low a machining temperature can make the workpiece harder to cut. Hong [52] reported with decreasing temperature in the machining process, the hardness of titanium alloy is also increased.

Regarding practical use, even though nitrogen is an environmentally friendly gas due to its very low temperature, direct contact with LN_2 or LN_2 equipment could harm the operator. This may disrupt the operator's flexibility, and appropriate Personal Protective Equipment (PPE) may be required.

When machining Al 7075-T651 alloys, Rotella *et al.* [115] reported that the cutting force required by cryogenic cooling was lower compared to dry machining. Cryogenic cooling also produced a better surface finish. Furthermore, they also concluded that cryogenic cooling is more environmentally friendly than flood and MQL. Another experiment by Rotella *et al.* [116] showed that turning Ti6Al4V alloy under cryogenic cooling improved surface finish due to grain refinement, and this cooling method is more sustainable compared to flood and MQL.

When comparing dry, cryogenic and flood, Islam *et al.* [117] showed that cryogenic performance was the best in terms of diameter error, but it produced the worst circularity. Hong and Ding [118] concluded that, when cutting titanium alloy under cryogenic cooling, cutting speed can be increased two-fold compared to flood cooling, while maintaining tool life. One thing needs to be considered in the use of cryogenic cooling, as Hong's [52] findings showed, that titanium alloy hardness increases with the decreasing of temperature. Since Titanium is also known to be reactive to oxygen, hydrogen and nitrogen, the influence of cryogenic chilling on the surface hardening needs to be examined (in this research) [119, 120].

2.11 Minimum Quantity Lubrication (MQL)

In this research, Minimum Quantity Lubrication will be utilised to assist the milling process of difficult-to-cut materials since research on these materials is still very limited [121], especially when sustainable cooling methods are being applied [121].

MQL selection is one of the alternative coolants in this research, based on its success in helping various machining processes performed on various materials. MQL is one cooling method considered as the solution to replace the role of coolant in machining processes, and is already used in the industry. In addition, MQL is environmentally friendly because it is made from vegetable oil or biodegradable synthetic esters, and it is always applied in a minuscule quantity (10-100ml/h) [122, 123].

Boswell and Islam [124] show that when A356 Al alloy was cut by the milling process, MQL gave the smallest cutting force and the most excellent surface finish compared to other cooling methods, including MQL combination with the other. (Figure 2.10)

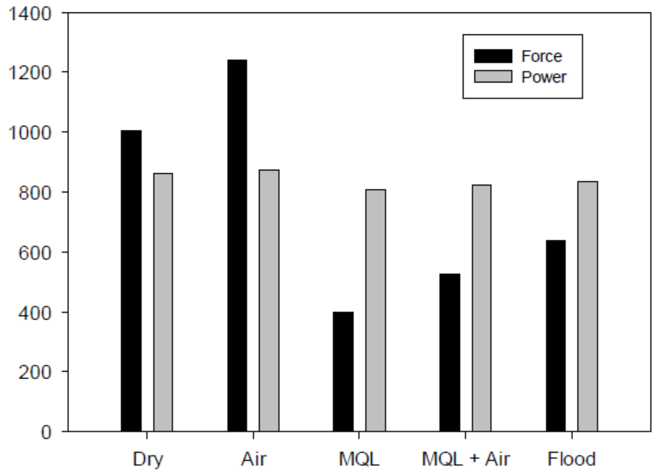


Figure 2.10 Cutting force and power for milling Al alloy A356 [124]

Kishawi *et al.* [125] have shown that MQL is able to replace the function of flood coolant during high-speed machining of Aluminium alloy. In the process of high-speed machining of aluminium alloy, MQL gave lower flank wear trend than that of coolant [125]. In addition, cutting speed can be increased up to 5200 m/min so that machining time can be reduced significantly.

MQL application when turning AISI 4340 high tensile steel prolonged tool life and gave better surface roughness [126, 127]. For the same material, Li and Chou [128] found that MQL application improved tool life - about 60% - compared to dry milling. Davim *et al.* [129] reported brasses turning under MQL lubrication reduced machining cost and environmental hazards. When applied to drilling process magnesium alloys MQL helps prolong tool life and reduces drilling torque [130].

According to Lopez *et al.* [131] MQL application is more effective for intermittent process end-milling compared to the turning process when cutting aluminium alloy. Rahman *et al.* [132] reported MQL and coolant give a similar value of surface roughness for steel end-milling, where dry machining was rejected due to a rough finish. Turning AISI 4340 high tensile steel under MQL increased tool life and improved surface finish [126, 127].

Davim *et al.* [130] reported that turning under MQL gave a better result compared to that of flood cooling. Wang *et al.* [133] discovered that MQL could provide a similar cooling effect to flood cooling when turning Titanium alloys with low feed rate. Similarly, Pervaiz *et al.* [134] conclude that MQL produces a better surface finish on the turning process of Ti6Al4V alloy due to its ability to provide lubrication to the cutting zone, thereby reducing friction.

The application of MQL during the drilling process of magnesium alloys reduced drilling torque and improved tool life [129]. For the milling process, Jiang *et al.* [135] found that MQL was the best cooling method of Ti6Al4V alloy in terms of surface finish. However, other research on grinding processes of Titanium alloys proved that MQL had low effectivity in cooling effects [136].

2.12 Surface Roughness

The product quality in this experiment was assessed by measuring the surface roughness (R_a) of the machined parts. The value of surface roughness is greatly influenced by machining parameters (feed rate, cutting speed, and depth of cut) used in the workpiece cutting process [137]. In addition, workpiece mechanical properties and cutting tool material and geometry are also important factors that affect the quality of the surface of the produced part [138]. Theoretically, the surface roughness can be calculated from nose geometry and feed per tooth [139]:

$$R_a = \frac{r - \sqrt{r^2 - (\frac{f_t}{2})^2}}{2} \tag{2.3}$$

2.13 Cutting Force

In the machining process the cutting force should be kept to a minimum to reduce the pressure encountered by tools and workpieces. It is essential to measure the cutting force accurately since it has a close relationship with the tool wear [140, 141]. Originally, cutting force was obtained from the power required by the machine. Recently, more accurate results can be obtained by real time measurement using a dynamometer.

For a milling process, cutting force can be measured with a dynamometer mounted on the milling machine. The workpiece is clamped onto a dynamometer so that the sensors can record three component forces that the workpiece receives for three different directions during the cutting process (Figure 2.11).

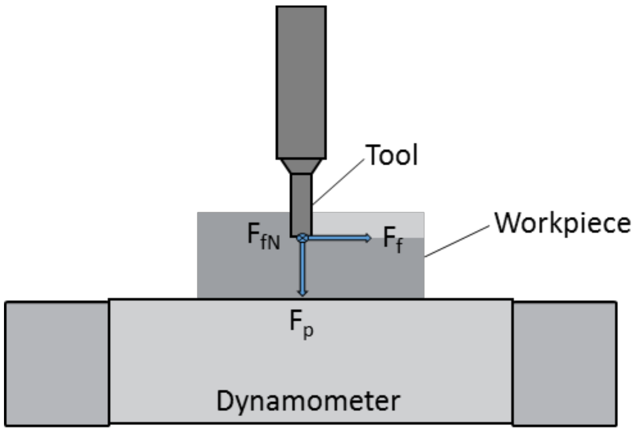


Figure 2.11 Cutting force measurement with dynamometer

Three forces: Feed force (F_f), Feed normal force (F_{fN}), and Passive force (F_p) were measured to calculate the total cutting force [134]:

$$F_{total} = \sqrt{{F_f}^2 + {F_{fN}}^2 + {F_p}^2} \qquad (2.4)$$

2.14 Machine Power

Machine power requirement can be used as a test parameter to assess the performance of a machining process, since the lower required power, the lower cost and the environmental impact will be. Machining power, P_c (kW) theoretically can be calculated from cutting force and cutting speed [101].

$$P_c = F_c . v \tag{2.5}$$

Machine power can also be measured directly in real time with a power analyser. Power analysers are used to measure a variety of power, such as idle engine power, pump power, and total engine power when cutting off workpieces.

2.15 Tool Life

The tool life is defined as the point when the tool has reached the end of its useful life. The tool life ends when it can no longer perform the required task effectively, for example producing the desired surface finish [142, 143] or acceptable dimensional accuracy [144, 145]. It does not mean that the tool is no longer capable of disposing of material, it is just not suitable for further use.

The definition of tool life depends on its use, and its use most of the time is varied. The variations in the definition make the comparison of tool life data from different sources difficult, since the criteria used are also different. The criteria used in measuring tool life include parameters such as the total volume of removed metal, the total time achieved, the total length of the tool path achieved, and the number of components successfully produced [146, 147].

In the machining process, the use of a tool until its total fail is undesirable since it is likely to damage the component being worked on. For this reason the use of tools needs to be stopped before the total failure. Therefore, the tool life information is important to predict the time limit of its use. Dolinsek *et al.* [148] reported that it is difficult to predict the tool life based on previous research. In this research, real tool life will be measured by experimental procedure, and the tool life prediction equations will be developed by using the experiment result.

Tool wear occurs due to the friction of the tool and the workpiece on the shear plane that converts the mechanical energy of cutting into heat energy. Tool wear can be reduced in various ways including the selection of suitable machining parameters and the use of appropriate cooling methods [149]. It is necessary to have a deeper knowledge regarding the role of cooling methods in reducing tool wear [150]. Therefore, this research will investigate the effectivity of cooling methods on prolonging the tool life.

2.16 Concluding Remarks

This research is important to improve the machining performance of difficult-to-cut materials with optimisation of machining parameters. Since previous research indicates that it is not possible to obtain the same machining performance when coolant is removed, alternative cooling methods are required. This alternative cooling method must pass the test to prove that it is capable of providing similar or even better machining quality and tool life.

Tool life is an important factor in the machining process, as it plays a role in determining product quality and machining performance. Sudden tool failure is undesirable in the machining process, since it will cause damage to the workpiece. Tool wear is expected to occur gradually, so that the tool life can be predicted and a replacement can be used before the tool fails. In addition, the tool wear rate can also be decreased by using the optimum machining parameters and utilisation of an effective cooling method to reduce machining temperatures.

This research aims to determine the most dominant machining parameters or cooling methods in influencing surface finish, cutting force and power requirement. The optimisation of each parameter and cooling method was also performed to obtain the desired machining output. Further, this research also aims to examine the performance of alternative cooling methods in reducing the tool wear rate and comparing it with flood coolant. A prediction of tool life for each cooling method application also needs to be made to prevent a tool from catastrophic failure.

Chapter 3

METHODOLOGY

3.1 Introduction

The milling process will be carried out with selected cutting parameters (feed rate, cutting speed, and depth of cut) to produce similar slots on three different material samples under three different cooling methods.

In this research, the quality of the machining process will be measured by power requirement, cutting force and surface finish. The experiment needs to be robust, so that the required number of experiments can be minimized. The forces required to cut the workpiece will be measured with a dynamometer, and real time power consumption of the CNC machine will be measured using a Yokogawa CW140 clamp type power analyser. The samples from the machining process will be used to measure surface finish quality. The surface finish of each product will be determined after the milling process, using a surface roughness tester, and scanned using a microscope.

The Design of Experiment (DOE) method will be used to control the experiments. Three output variables of the experiments, power consumption (kW), cutting force (N) and surface roughness (µm) will be examined and optimised. In this case all of the output characteristics are smaller-the-better, where it is preferred to get the lowest values. The optimum cutting conditions for different materials will be determined and verified by separate experiments.

The performance of cooling methods on the tool life will also be investigated in further experiments. At this stage, similar cutting speeds and feeds will be used for the whole test. Cooling methods and time will be used as the main comparative parameters.

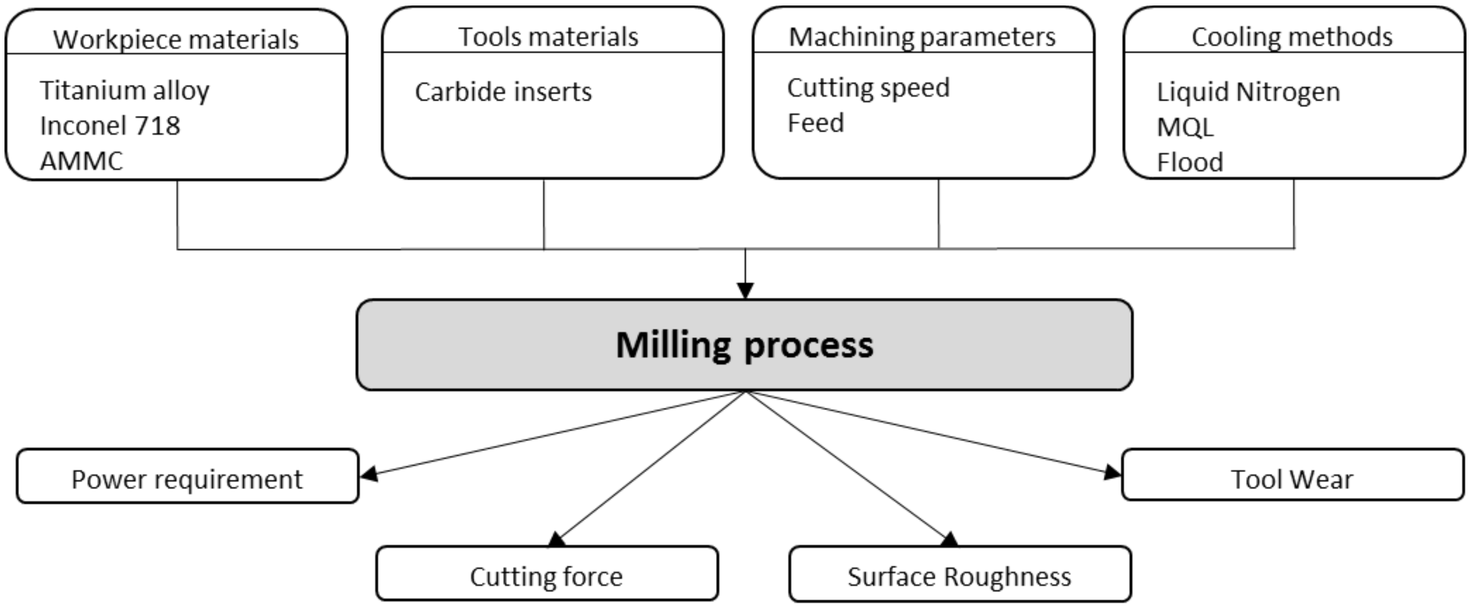


Figure 3.1 Methodology for sustainable machining of difficult materials

3.2 Machine and Equipment

3.2.1 CNC Milling Machine

The machining process for this research was conducted on a Leadwell V-30 CNC Milling Machine. This machine has four motors to rotate the spindle and the movement of each axis X, Y and Z.

Figure 3.2 Leadwell V30 CNC Milling Machine

The specification of the machine can be seen in Table 3.1. The end milling process was performed to make the slots with 1 mm depth along the surface of the workpieces.

Table 3.1 Specification of Leadwell V-30 CNC Milling Machine

Parameters	Value	Unit
X axis travel	760	mm
Y axis travel	410	mm
Z axis travel	410	mm
Spindle speeds	8000	rpm
Spindle motor	7.5	kW

X-axis feed motor	1.2	kW
Y-axis feed motor	1.2	kW
Z-axis feed motor	1.8	kW
Constant torque	8	Nm
Thrust force	410	Kgf
Coolant pump motor	0.5	kW
Electrical power supply	25	kVA

3.2.2 Dynamometer

The cutting force was measured in real time by using a Kistler piezoelectric dynamometer and Dynoware Software. The workpiece was clamped onto the dynamometer so that the sensitive piezoelectric system could detect and measure forces applied in three different axes (X, Y and Z). Data acquisition software Dynoware was used to display the value of the force for each axis and display graphs during data retrieval.

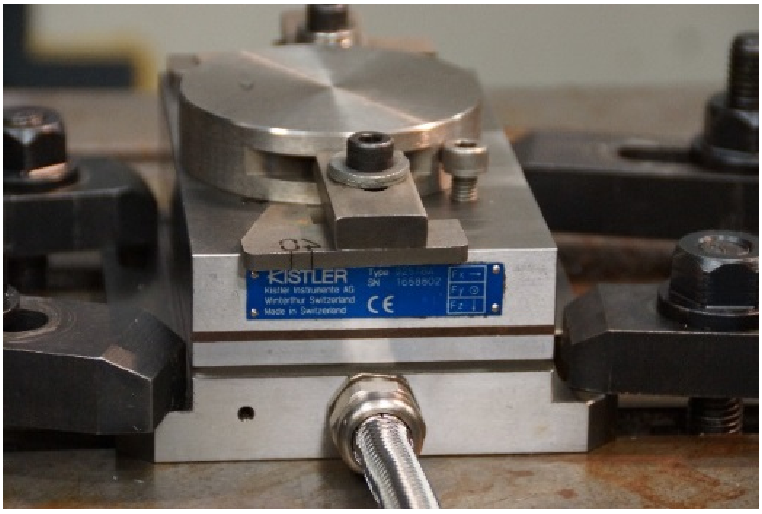


Figure 3.3 Kistler piezoelectric dynamometer

3.2.3 Power Analyser

A clamp type power analyser - Yokogawa CW140 was used to measure real time power consumption of the CNC machine.

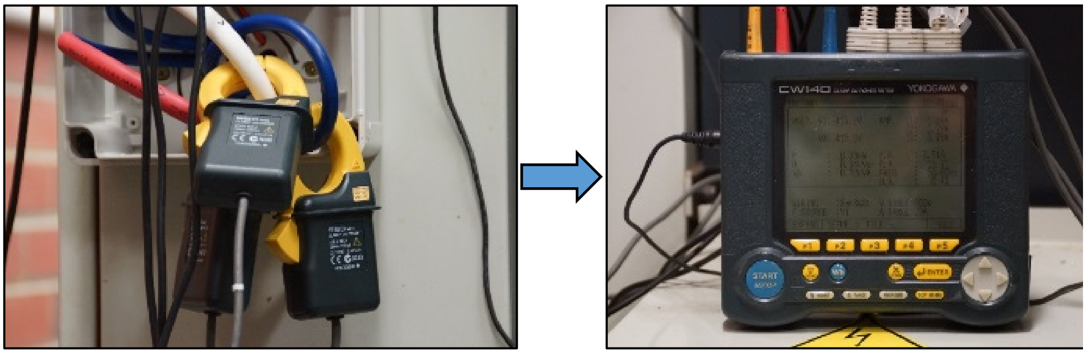


Figure 3.4 Power analyser

This device was used as it is able to measure the required machine power without interrupting the machining process.

3.2.4 Surface Roughness Tester

The surface condition of each workpiece was checked by using a Mitutoyo SJ-201 Surface Roughness Tester. Surfpak data acquisition software was used to obtain the value of surface roughness, and display a graph of surface roughness values and the travelled distance of the stylus.

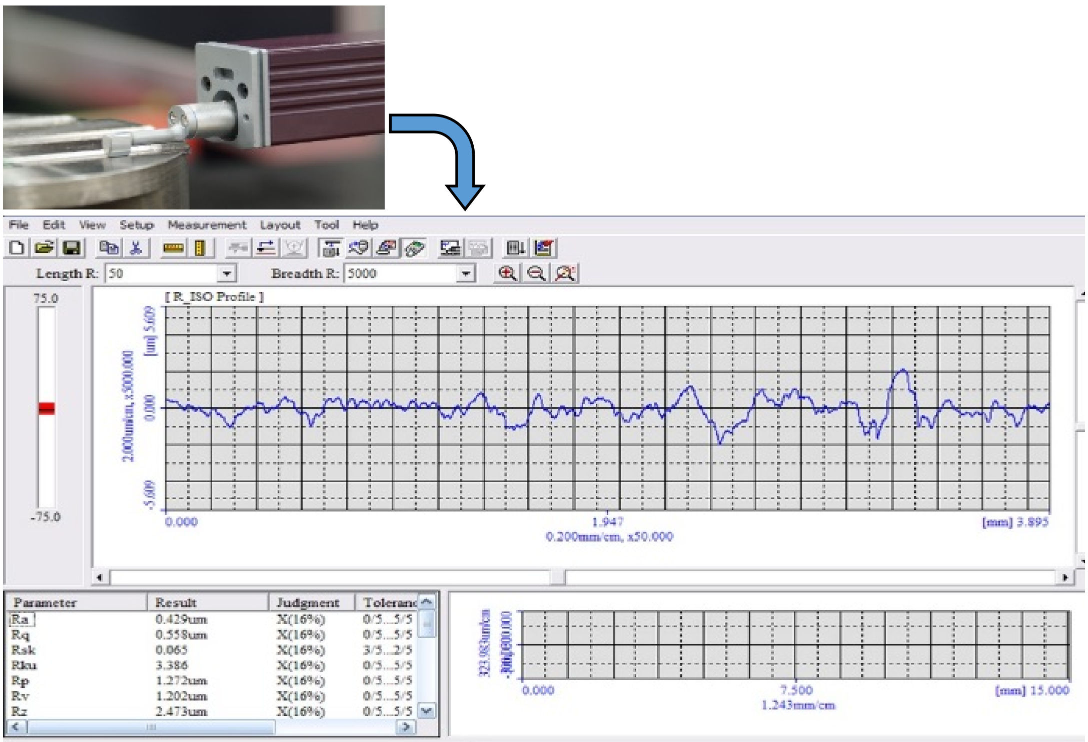


Figure 3.5 The surface roughness tester and the software

Roughness values were measured as Roughness Average (R_a), with consideration of Ra as the most widely used as a roughness parameter. Surface roughness was measured three times for each workpiece. The length of measurements was set on 4.8 mm, while the number of measurement points are 9600. R_a can be calculated with formula 3.1 [151].

$$R_a = \frac{1}{L}\int_0^L |Y(x)|\, dx \qquad (3.1)$$

Where:

Y= the vertical deviation from the nominal surface

L= the specified distance measured

3.2.5 Optical Microscope

An Olympus Microscope BX51M with Olympus Stream Image Analysis Software was used to examine the surface profiles of the workpiece and the wear of tool insert. Using an Extended Focal Imaging (EFI) feature, many frames of workpiece surface or tool surface images with different depth of focus were acquired and joined to produce a single sharp image. The microscope also has a feature that can be used to measure tool wear with high accuracy.

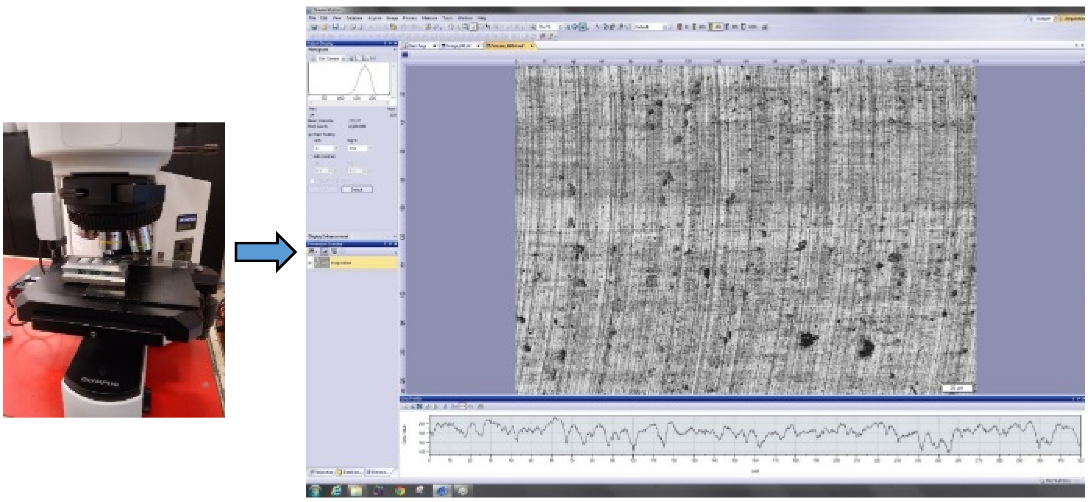
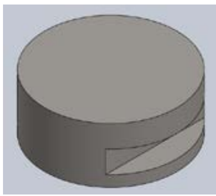
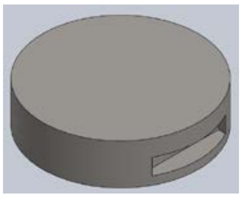
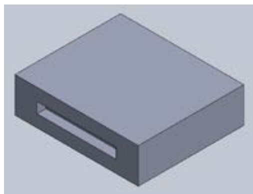


Figure 3.6 Optical microscope and analysis software

3.3 Test Materials

In this research, Titanium alloy (Ti-6Al-4V), Inconel 718 and Aluminium MMC (AMMC) were used as work materials for experimentation. The material information of these work materials is shown on Table 3.2.

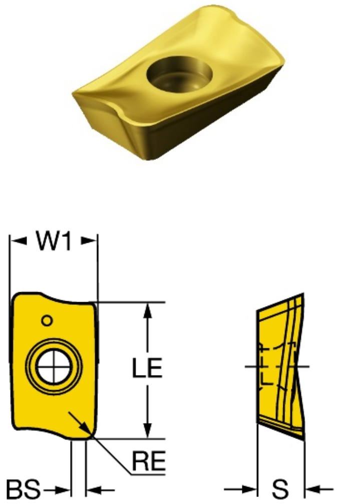
Table 3.2 Work materials details

Material	Titanium alloy (Ti-6Al-4V)	Inconel 718	Aluminium MMC (AMMC)
Specimen shape			
Size, mm	ø60x25	ø95x25	l=70, w=60, t=20
Mechanical properties			
Density, g/cc	4.42	8.19	2.6-2.9
Hardness, BH	334	341	
Modulus of Elasticity, kN/mm^2	113.8	204.9	69-79
Tensile Strength, Mpa	925	1375	545
Chemical composition (weight %)			
	Al 5.94 Fe 0.173 O 0.13 Ti Balance V 4.1	Ni 52.85 Cr 18.47 Nb 4.86 Mo 3.02 Ti 0.95 Al 0.55 Co 0.14 Mn 0.04 Cu 0.02 P 0.004 S 0.003 Fe Balance	Cr 0.1 Cu 3.8-4.9 Fe 0.3 Mg 1.2-1.8 Mn 0.3-0.9 Si 0.2 Ti 0.15 Zn 0.25 Others Balance

3.4 Cutting Tool Inserts and Holders

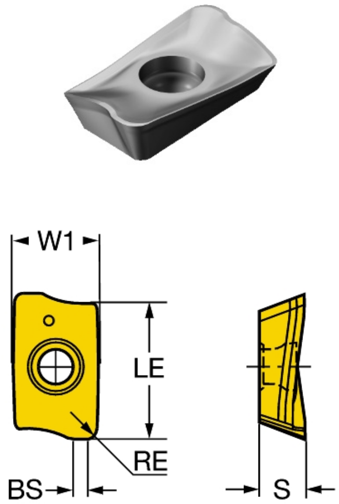
Tool selection is a very important step in determining the success of the metal cutting processes. Specific tools in material, shape and size are required for certain workpiece materials and machining processes. As recommended by the tool manufacturer, cutting tool inserts used for cutting Titanium alloy and Inconel 718 were CoroMill R390-11 T3 31M PM S40T (coated Tungsten Carbide) and CoroMill R390-11 T3 04E NL H13A (uncoated Tungsten Carbide) for cutting AMC. Tool holder used for both cutting inserts was R390-012A16-11L. The geometry of the cutting inserts and the tool holder can be seen in Figure 3.7.

In order to simplify the milling analysis, in this research a single cutter with 12 mm cutting diameter was used, and a new insert was inserted for each test.



L_a= 11mm, iW=6.8mm,
BS=1.2mm, RE=0.8mm,
S=3.5mm

(a) R390-11 T3 31M PM S40T



L_a= 11mm, iW=6.8mm,
BS=1.2mm, RE=0.8mm,
S=3.5mm

(b) R390-11 T3 04E NL H13A

(c) R390-012A16-11L

Figure 3.7 Cutting inserts geometry (a, b) and tool holder (c)

3.5 Cooling Methods

Three different cooling methods are compared in terms of performance in this research, namely Cryogenic Liquid Nitrogen, Minimum Quantity Lubrication and Traditional Flood Coolant. Each cooling method was used to assist the cutting processes of nine test materials by varying the cutting speed and feed rate.

3.5.1 Cryogenic Liquid Nitrogen

Cryogenic cooling was performed by spraying liquid nitrogen directly into the machining zone to cool the tool. The temperature of the liquid nitrogen when it reaches the surface of the tool was -141°C, with an average flow rate of 1.08 kg/min.

Figure 3.8 Cryogenic cooling

3.5.2 Minimum Quantity Lubrication (MQL)

In these tests, Coolube 2010, a vegetable related and natural esters lubricant, was delivered via Unist MQL Application System. With this system, the flow rate of MQL oil can be precisely set. For the MQL cutting tests, the flow rate was set at 80 mL/h.

Figure 3.9 MQL cooling system

3.5.3 Traditional Flood Coolant

The type of coolant used in this research was an emulsion Rocol Ultracut with 5% concentration diluted with water. Coolant was pumped with a flow rate of 48 L/min.

3.6 Sustainable End Milling of Difficult Materials

A Design of Experiment method was used to control the experiments [152, 153]. Optimization of control parameters was performed to reduce the number of tests while maintaining the accuracy of test results. With this method the experimental time and costs can be reduced significantly, and the method can be easily applied in the real world.

For this research, 27 tests were carried out with combinations of cooling method, cutting speed, and feed as input parameters, optimised by Design of Experiment methods L_{27} orthogonal array. Cutting speeds and feeds values were selected based on the values recommended by the tool tip manufacturer. Input parameter values for each level are displayed in Table 3.3.

Table 3.3 Input parameters and levels

Input parameter	Symbol	Levels		
		Level 0	Level 1	Level 2
Titanium alloy (Ti-6Al-4V)				
Cooling method	A	cryogenic	MQL	flood
Cutting speed (m/min)	B	60	80	100
Feed (mm/rev)	C	0.1	0.2	0.3
Inconel 718				
Cooling method	A	cryogenic	MQL	flood
Cutting speed (m/min)	B	40	60	80
Feed (mm/rev)	C	0.1	0.15	0.2
Aluminium Metal Matrix Composites (AMMC)				
Cooling method	A	cryogenic	MQL	flood
Cutting speed (m/min)	B	50	100	150
Feed (mm/rev)	C	0.1	0.2	0.3

Output variables for the experiments are cutting force (F_c), machine power (P_c) and surface roughness (R_a). Three different formulas for signal-to-noise ratio are given below:

$$\frac{S}{N} = -10 \log \frac{1}{n} \left(\sum_{i=1}^{n} y_i^2 \right) [\mathrm{dB}] \qquad (3.2)$$

$$\frac{S}{N} = 10 \log \left(\frac{\bar{y}}{s_y^2} \right) [\mathrm{dB}] \qquad (3.3)$$

$$\frac{S}{N} = -10 \log \frac{1}{n} \left(\sum_{i=1}^{n} \frac{1}{y_i^2} \right) [\mathrm{dB}] \qquad (3.4)$$

Where:
n = number of observations,
y = the observed data.

In this case the output characteristics are smaller-the-better (equation 3.2), where it is preferred to get the lowest value of the output parameters [154, 155]. A statistical analysis of data collected from the experiments was conducted to investigate and compare the effects of each machining parameter in generating the desired surface finish. Further, it will be used to determine the combination of cutting speed, feed rate and cooling method, which produce the best quality of surface finish, lower cutting force and lower power. Furthermore, Pareto ANOVA adapted from [152, 156] is implemented in analysing the contribution of each machining parameter and their interactions.

3.7 Cooling Methods Performance on Tool Life

The performance of cooling methods was also tested further by using the same cutting speed and feed rate for the three test materials. Forty-five tests were conducted to see the growth of the tool wear over time. Since this experiment aims to compare the rate of the tool wear, the same type of tool tip, CoroMill R390-11 T3 31M PM S40T was used for each test.

A multiple regression analysis using SPSS software was performed at this stage to create a model that is able to compare the performance of alternative coolants with flood coolant. The multiple regression equations of Y on X is given by:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_n X_n \qquad (3.3)$$

Where:

b = parameter (regression weights)

X = independent variables

Since the coolant methods are a categorical variable, in this analysis flood coolant will be used as the reference level, while LN_2 and MQL will be the dummy variables.

3.8 Concluding Remarks

In this chapter, a design of experiment method has been introduced to investigate the most dominant machining parameters and cooling method in influencing the predefined output quality parameters. Therefore, the most optimum machining parameters can be determined based on the expected machining results.

The multiple regression method is also discussed to compare the performance of each cooling method in reducing the rate of tool wear. Regression coefficients generated by SPSS software can be used to develop equations to predict the tool life based on the cooling method applied.

Chapter 4

PRELIMINARY INVESTIGATION

4.1 Introduction

As discussed in previous chapters, flood coolant has been shown to cause environmental problems and also increase the total cost of production. Various studies have been done to maintain the performance of machining, product quality and tool life by using alternative cooling methods. These have been tested on various metal cutting processes to find the most effective and efficient one to replace the flood coolant. Cold air is one of the cooling methods that has been studied for many years, and has proven successful in certain stages in reducing machining heat and the wear rate of the machining tool [157, 158].

In the first part of the preliminary test, the performance of three types of environmentally friendly cold air were examined. The purpose of this test was to determine whether cold air can be proposed as one of the alternatives for flood cooling. This section has been published as peer-reviewed paper (Paper 3).

The second part of the preliminary test was conducted to test the method to be used in this research on AISI 4340 steel which is relatively easier to cut. In this experiment the flood cooling performance was compared with MQL as a proposed replacement cooling method. Pareto ANOVA and Taguchi S/N ratio are used to analyse the surface finish of produced parts and machine power requirement as the output parameters of machining performance. This section has also been published as peer-reviewed paper (Paper 1).

4.2 Cold Air Generation for Sustainable Machining

In order to avoid various problems caused by using flood coolant, machining industries have been utilised cold air (CA) as an alternative cooling method. There are a number of methods to generate the cold air which may be applied in the machining process. In this research the performance of vortex tube (VT), thermoelectric cooling (TEC) and cryogenic cooling of compressed air (CCA) will be investigated. The effectiveness of these three methods will be judged by calculating their Coefficient of Performance (COP), and how much energy is needed to produce cold air.

4.2.1 Vortex tube (VT)

The vortex tube is able to separate compressed air entering through the inlet channel into the hotter air on one side and cooler on the other as shown in Figure 4.1. The advantage of the vortex tube in producing cold air lies in its ease of use and no maintenance required since it has no moving parts [159]. The vortex tube is widely applied to reduce the temperature of a machining process due to its ability in generating low temperature air (as low as -40^{o}C), and requires only compressed air. However, since the VT needs a relatively large amount of air, it requires the use of a large-capacity compressor.

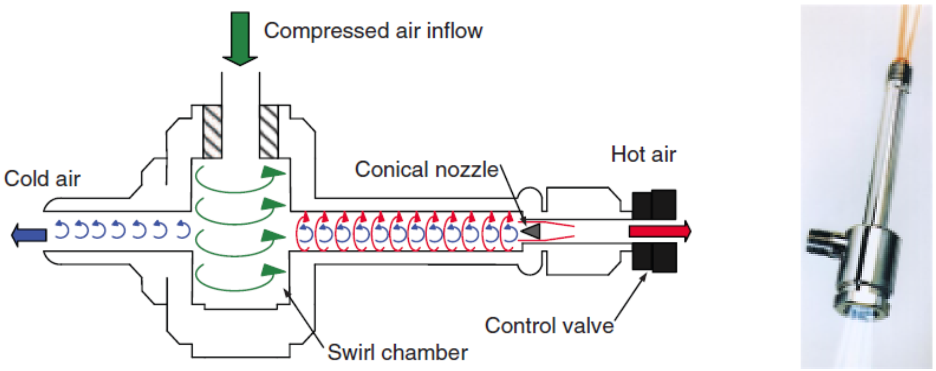


Figure 4.1 Vortex tube principles [105, 159]

From the recorded test data, VT with 3mm output diameter and 0.275MPa inlet air pressure, can provide expected cold air temperature, as presented in Table 4.1.

COP of VT can be calculated by the following formula:

$$COP = \frac{\Delta \dot{H}_c}{\dot{W}} \tag{4.1}$$

Table 4.1 Vortex tube experiment result

Parameter	Value
Cold Mass Fraction	0.605
Inlet Temperature (˚C)	22.4
Cold Outlet Temperature (˚C)	-16.8
Hot Outlet Temperature (˚C)	66.6
Inlet Volumetric Flow Rate (SLPM)	1095
Hot Outlet Volumetric Flow Rate (SLPM)	425
Cold Outlet Volumetric Flow Rate (SLPM)	651

COP value for this experiment was found to be 0.173 which is much lower than that of the refrigerator with average COP of 3. However, when considering the ease of installation and use, VT can still be applied as a replacement of liquid cooling for machining process.

4.2.2 Thermoelectric cooling (TEC)

Thermoelectric cooling is a method that has been applied in different fields, ranging from medical equipment to military. In the machining processes, thermoelectric cooling (TEC) is required to produce cold air. This process requires a flow of cold air that reduces in temperature when it is passed over a TEC pile, cooling the air in the coil heat exchanger.

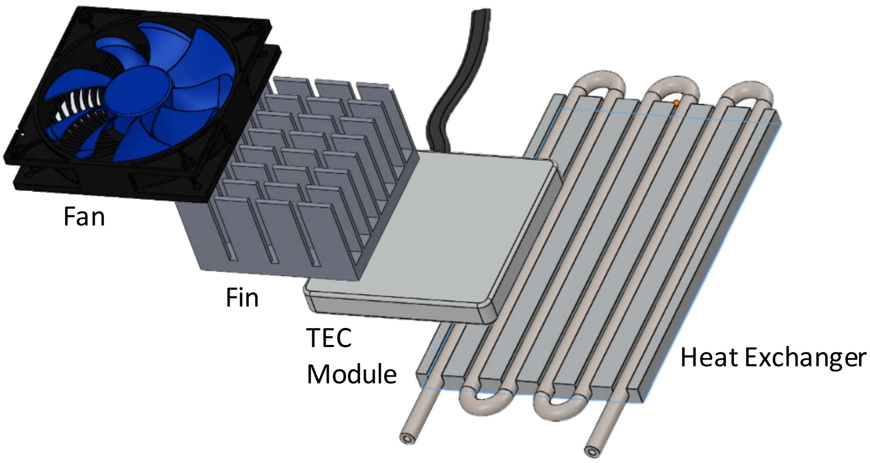


Figure 4.2 The components of TEC

The machining processes with a TEC system is considered more sustainable since they do not produce any waste [160]. This thermoelectric module is easy to apply in the cutting process since it has a relatively small size of 2.4-50 mm square and height of 2.5-5 mm [161]. In addition, the TEC system powered by electricity makes it easier to control the flowrate of the cold air produced.

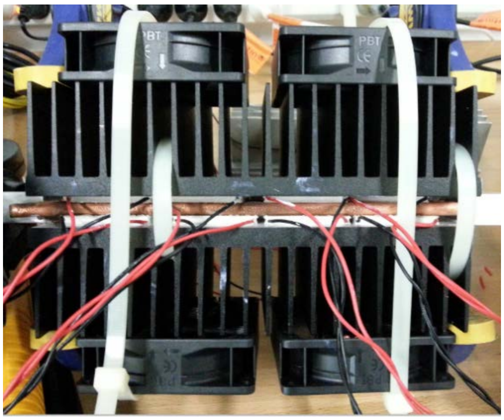


Figure 4.3 The TEC assembly

For this test a prototype of a TEC system was made using an 8 cel thermoelectric, as shown in Figure 4.3, and the specifications for each cell can be seen in Table 4.2. A small centrifugal pump was used to supply air on the inlet of the prototype. Thermocouples were used to measure the cold side of TEC, fin, copper tube, outlet nozzle and ambient temperatures.

Table 4.2 Specification of TEC1-12706

Parameter	Value
Dimensions (mm)	40 x 40 x 3.8
Voltage (V)	12
U max (V)	15
I max (A)	6
Q max (W)	72
Temperature Difference (˚C)	65
Power drawn (kW)	0.036

The COP calculation was based on the amount of power required to produce cold air. This COP was calculated using the following heat transfer formula:

$$Q_c = (S_M \text{ x } T_c \text{ x } I) - (0.5 \text{ x } I^2 \text{ x } R_M) - (K_M \text{ x } D_T) \quad (4.2)$$

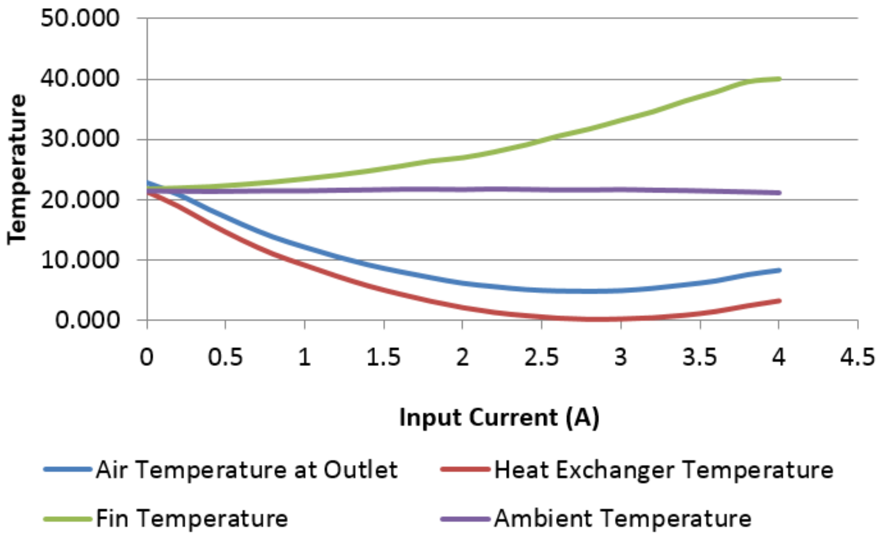


Figure 4.4 Measured cold air temperature

The test results in Figure 4.4 show that the TEC prototype was capable of producing cold air at a rate of 2 m/s to 4 m/s with the current of 3 A to 5.75 A. The COP was found to be 0.011 which seems under VT performance. However, with some improvement the COP of the prototype can be increased.

4.2.3 Cryogenic Cooling Compressed air (CCA)

To improve the performance of machining processes most researchers applied liquid nitrogen directly to cool the cutting process. However, the main limitation of this cooling method is its extremely low temperature. With the temperature as low as -146°C, without proper isolation and protective equipment the application of LN_2 can be harmful to the operator and the surrounding environment. Furthermore, good ventilation is required as LN_2 may cause oxygen deprivation due to increased amounts of nitrogen caused by the evaporation process. For added safety this cold air generation avoids the direct use of LN_2 in the machining process. (Figure 4.5)

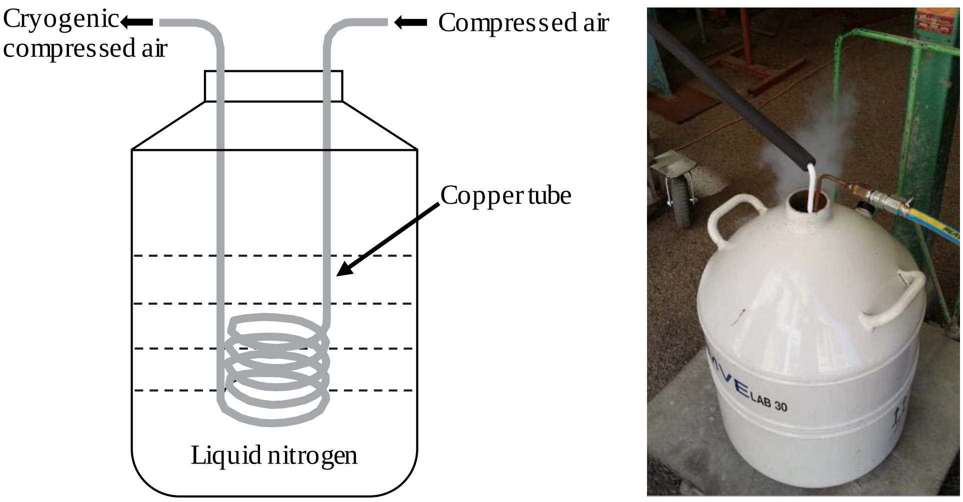


Figure 4.5 Cryogenic cooling compressed air

Sun *et al.* [162] proved that CCA is safer to use and capable of producing extremely low temperature cold air. To produce cold air the compressed air was passed through the copper tube coil immersed in LN_2 Dewar. Pressurised air was delivered through the inlet section of the the copper tube at 5.5 bar pressure. After two minutes the temperature of the cold air was below -70 ˚C, and below -80 ˚C after eight minutes. The flowrate of cold air during the test was 41 m/s to 45 m/s.

Table 4.3 Energy consumption estimation of CCA

Time (min)	Evaporated LN_2 (kg)	Energy consumed in cooling (kWh)	Outlet temperature (C)
1	0.24	0.12	-60.3
2	0.48	0.24	-69.3
3	0.72	0.36	-71.7
4	0.96	0.48	-73.7
5	1.20	0.60	-73.3
6	1.44	0.72	-74.7
7	1.68	0.84	-76.0
8	1.92	0.96	-76.3
9	2.16	1.08	-77.7
10	2.40	1.20	-82.3

Test results in Table 4.3 show that every minute there was a reduction of 0.24 kg LN_2 due to the evaporation process. The required power to generate 1 kg of LN_2 is estimated to be 0.5 kWh [163]. The total energy required by the CCA can be calculated by summing up the compressor's power with the energy required to generate LN_2. The total required power to generate cold air for 10 minutes was 720 W. The COP of this system calculated in regard to the evaporation of LN_2 was found to be 1.58.

4.2.4 Conclusion

The COP results showed that VT is not as efficient as cooling air by LN_2, and the TEC prototype performed lower than VT. However, its ease of use and small size give a distinct advantage. CCA is proven to be very effective in producing cold air, although an enormous amount of energy is needed to provide LN2, becoming another challenge. It is clear that the COP of CCA is the best when compared to VT and TEC in producing cold air.

Taking in all of the above considerations it was evident that the best option for the future research for this work is by using a VT. This was chosen for its ease of use and being able to perform reliably at the required temperatures. It must be noted that with further work the TEC system would be more than suitable. Using the CCA system may have shown to have the best COP, but this would need to be paid for by the higher cost of using LN_2.

4.3 Advancing Environmentally Conscious Machining

Metal cutting processes inevitably produce waste in the form of coolant waste and metal chips. Stringent environmental regulations make companies need to handle their waste efficiently to reduce their impact on the environment. The objective of environmentally conscious manufacturing is to consume energy efficiently and to produce minimum waste (atmospheric emissions, liquid and solid).

This research was inspired as a result of an SME Company in Perth and their experience of pollution caused by the leakage of coolant waste from the chips' storage. Their aim was to eliminate flood coolant as the source of the pollution from their machining processes. However, the absence of coolant greatly affected the cutting parameters in order to produce similar surface finish and tool life.

A series of tests were carried out to determine the MQL performance based on the value of the machining parameters used for the flood cooling. It is important for the industry to determine the optimum combination of machining parameters such as cutting speed, feed rate, depth of cut to make the product at a reasonable cost and in a sustainable manner.

4.3.1 Experimental Work

The Taguchi method allows testing of various combinations of machining parameters with a minimum number of tests. In this experiment L8 orthogonal array was selected with two level control parameters as shown in Table 4.4. The optimum parameters in the turning process of AISI 4340 steel workpiece were determined under two different cooling methods, MQL and flood.

Table 4.4 Machining parameters

Input parameter	Symbol	Levels	
		Level 0	Level 1
Cooling method	A	MQL (2.4 mL/min, 50 Psi)	Flood (12.3 L/min)
Cutting speed (m/min)	B	170	210
Depth of Cut (mm)	C	1	2.5
Feed rate (mm/rev)		0,25	0,25

A CNC lathe was used to produce parts with 200 mm length and 42 mm diameter. Cobalt coated turning inserts WNMG 080408 – TF IC8150 5507835 mounted to DWLNR 2525M 08 were used as cutters in this experiment. A new tip was used for each test.

Table 4.5 Workpiece composition [164]

Workpiece composition	AISI 4043 (C= 0.38–0.43%, Mn= 0.60–0.80% Mn= 0.60–0.80%, P= 0.035%, S= 0.040%, Si= 0.15–0.35%, Ni= 1.65–2.00%, Cr= 0.70–0.90%, Mo= 0.20–0.30%)

The surface finish of the part was acquired by Mitutoyo SJ-201 Surface Roughness Tester. Pro MicroScan 5908 was used to examine tool wear, and a Yokogawa CW140 was used to measure the required power.

Table 4.6 Physical and chemical properties of cooling methods

Properties	MQL	Flood coolant
Physical state	Low viscous oil	Low viscous liquid
Viscosity	10 mm^2/s (cSt) at 40°C	350 cSt at 21°C
Color	Yellowish fluid	Clear brown concentrate
Odor	Vegetable oil related (Slight sulphur smell)	Mild
Flash point (Open Cup)	>200 °C, >400F(COC)	>150 °C
Pourability	-12 to -20 °C	Not available
Vapor pressure	Negligible under normal conditions	Not available
Density (20°C)	Approx. 890 kg/m^3	950 kg/m^3
Solubility in water	Insoluble	Soluble
Solubility in organic solvents	Soluble	Not available

4.3.2 Result and Analysis

Pareto ANOVA [165] was used to analyse the contribution of each machining parameter and their interactions. ANOVA Pareto Analysis [6] was applied for surface roughness of the part and the required power. ANOVA Pareto Analysis identified control parameters that affect the quality of the produced bolt (Table 4.7).

Table 4.7 Experiment result

No	Cooling method	Cutting speed (m/min)	Depth of cut (mm)	Machine power (kW)	R_{a1} (μm)	R_{a2} (μm)	R_{a3} (μm)
1	A0	B0	C0	4.43	1.86	1.88	2.04
2	A0	B0	C1	7.44	2.00	2.00	1.95
3	A0	B1	C0	5.27	1.54	1.55	1.55
4	A0	B1	C1	9.56	1.66	1.67	1.69
5	A1	B0	C0	4.84	1.93	1.86	1.94
6	A1	B0	C1	7.96	1.88	1.83	1.84
7	A1	B1	C0	5.63	6.09	6.07	6.02
8	A1	B1	C1	9.65	5.85	5.86	5.85

4.3.2.1 Surface Roughness

Figure 4.6 shows that MQL cooling and lower cutting speed appear to offer better surface finish. The depth of cut does not seem to affect the machining performance.

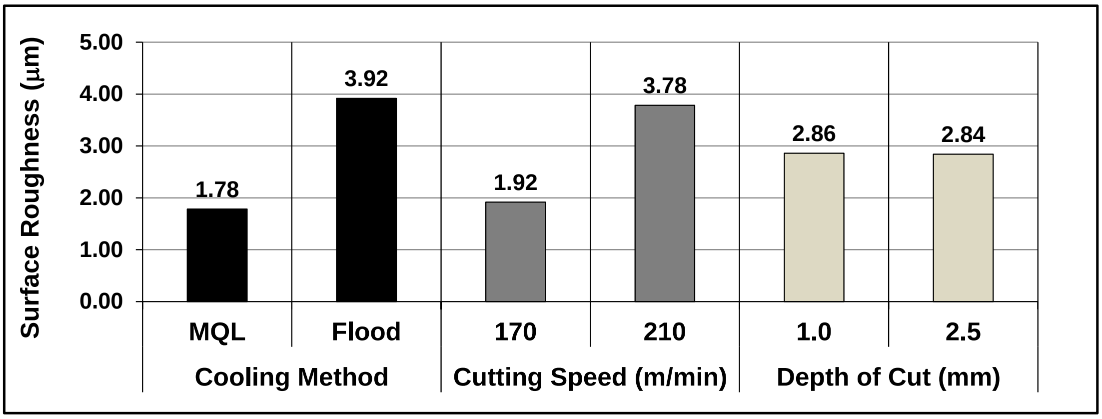


Figure 4.6 Measured surface roughness based on average response

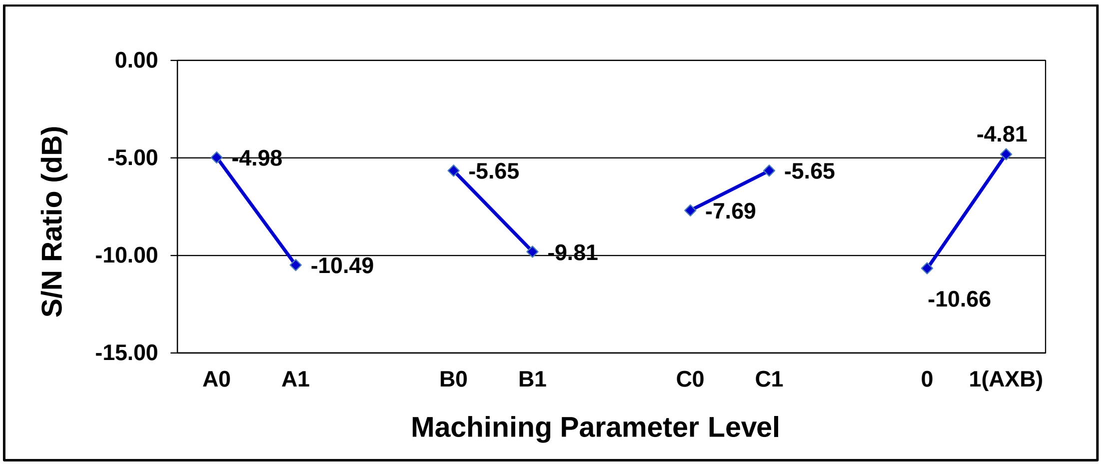
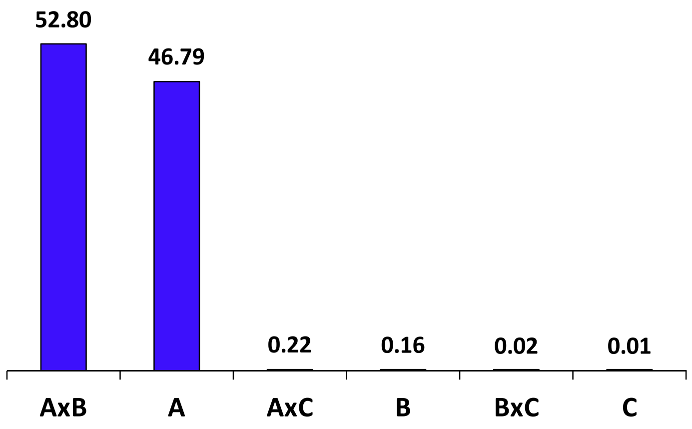


Figure 4.7 Measured surface roughness based on S/N ratio

Pareto ANOVA analysis in Table 4.8 indicates that the cooling method is the most dominant contributor to the quality of surface finish. Consideration of interaction with cutting speed only increased the factor level from 46.8 to 52.8.

Table 4.8 Pareto ANOVA analysis for surface roughness

Sum at factor level	Factor and interaction					
	A	B	AxB	C	AxC	BxC
0	-19.91	-22.62	-42.65	-30.76	-30.18	-31.15
1	-41.96	-23.91	-19.23	-31.11	-31.69	-30.73
Sum of squares of difference (	486.28	1.67	548.67	0.12	2.28	0.17
Contribution ratio (%)	46.79	0.16	52.80	0.01	0.22	0.02
Pareto diagram						
Cumulative contribution	52.80	99.59	99.81	99.97	99.99	100.00
Check on significant interaction		AXC two-way table				
Optimum combination of significant factor level		A0B0C1				

4.3.2.2 Machine power

From Figure 4.8 and Figure 4.9 it can be clearly seen that the power requirements of MQL cooling are lower than that of flood. For depth of cut 1 mm and 2.5 mm, MQL requires power of 4.43 kW and 7.44 kW respectively, while flood requires of 4.84 kW and 7.96 kW. The significant decrease in power requirements under the application of MQL occurs for all tests.

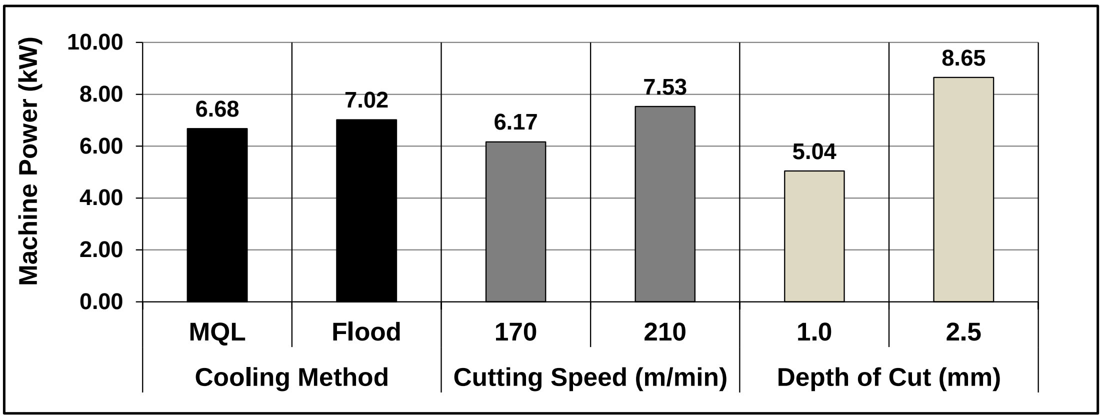


Figure 4.8 Measured machine power based on average response

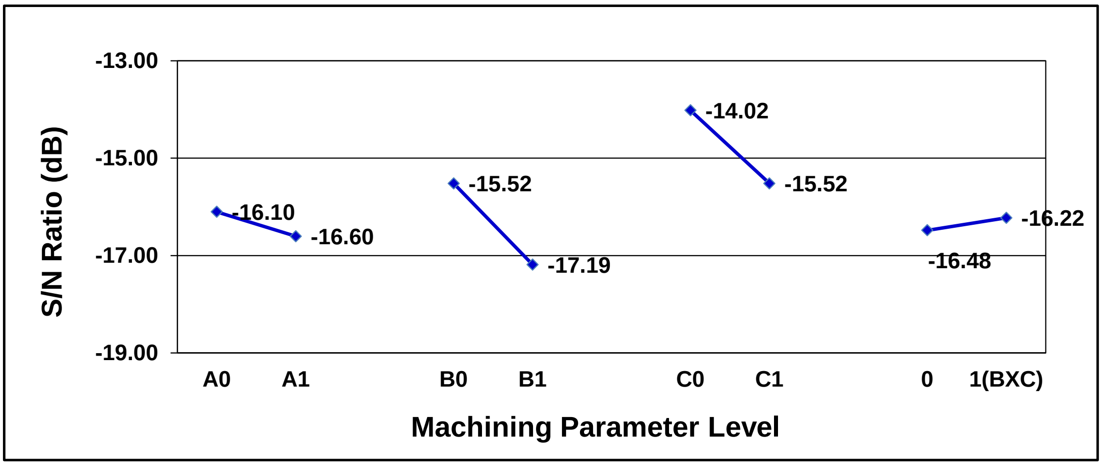
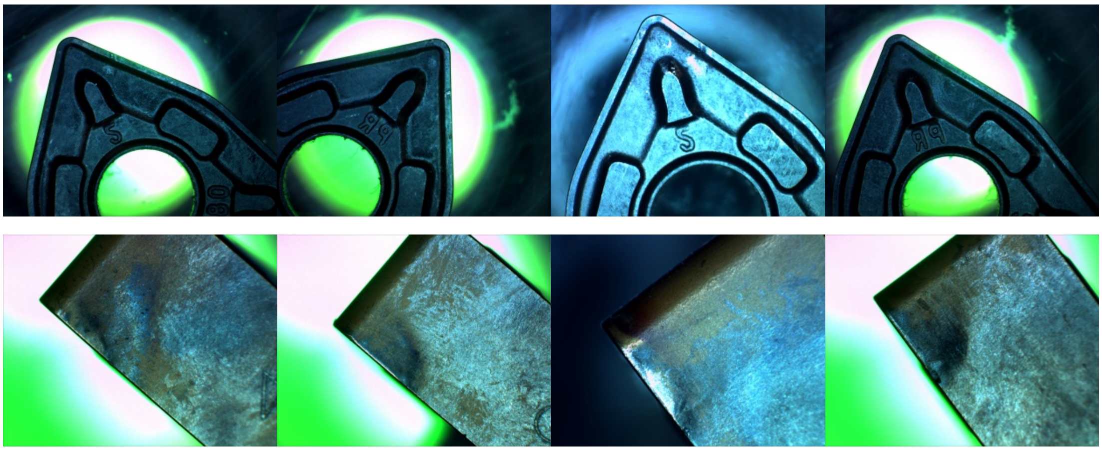


Figure 4.9 Measured machine power based on S/N ratio

Both figures also show that MQL cooling proved effective in reducing the tips wear rate during the machining process of the bolts. Since there was only a small amount of wear, as shown in Figure 4.10, it is difficult to use tool wear to judge the performance of the cooling methods. It would be more reasonable to use surface roughness of the product to estimate the tool life.



A0B1C1 after 2 cuts A1B1C1 after 2 cuts A0B0C0 after 4 min A1B1C0 After 4 min

Figure 4.10 Tool tips acquired images show no appreciable wear

When depth of cut was increased from 1 mm to 2.5 mm there was no significant increase in wear despite the rise in temperature. Different colour of produced chips can be seen in Figure 4.11. Under flood coolant the local company used a cutting speed of 170 m/min and 0.25 mm/rev feed rate. However, from these findings it is possible to improve the cutting speed and depth of cut to reduce the machining time.

A0B0C0 A0B0C1 A1B1C0 A1B1C1

Figure 4.11 Chips produced from a number of tests

4.3.3 Conclusion

This research aims to help a local company to find an alternative sustainable cooling method so that they can avoid the problems caused by coolant waste. From a series of tests conducted, MQL cooling proved to be an optimum replacement of the flood coolant. The same machining parameters were used so that there would be no reduction in the number of bolts produced. Tool tips used under MQL cooling have less wear and produce a better surface finish. In addition, the lower power requirements of MQL cooling will reduce production costs. The research shows that MQL is a feasible cooling method for turning process of AISI 4340 steel workpieces.

Chapter 5

PARAMETERS OPTIMISATION FOR DIFFICULT-MATERIALS END MILLING

5.1 Introduction

The results of using different cooling methods on difficult-to-cut materials will be analysed and discussed. The discussion will consider the machining of three difficult to machine materials: Titanium alloy (Ti-6Al-4V), Inconel 718 and Aluminium Metal Matrix Composites (AMMC), to discover whether flood cooling can be replaced by one, or a combination of alternative cooling methods. In addition, the test is also expected to determine the optimum machining parameters for each material. Twenty seven test combinations were conducted for each test material when comparing the performance of the three cooling methods, liquid nitrogen, MQL and flood.

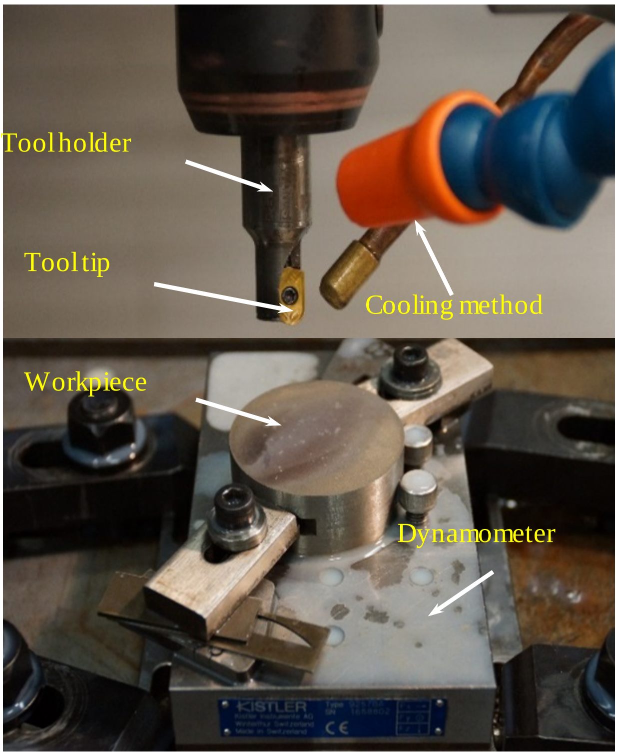


Figure 5.1 Workpiece set up

The effect of input parameters (cooling method, cutting speed and feed rate) was measured by three output parameters (surface roughness, cutting force and required machine power). The output parameters were analysed by the mean S/N ratio for the smaller-is-better (lowest value is the best value for all three) parameters.

5.2 Sustainable End Milling of Titanium Alloy (Ti-6Al-4V)

5.2.1 Experimental results

Table 5.1 Experimental results for surface roughness, cutting force, machine power, and their corresponding S/N ratio Titanium alloy (Ti-6Al-4V)

Experimental No/Condition		Measured Parameters			Calculated S/N Ratio		
		Surface Roughness (µm)	Cutting Force (N)	Machine Power (kW)	Surface Roughness	Cutting Force	Machine Power
1	A0B0C0	0.373	76.7	0.63	8.558	-37.699	4.006
2	A0B0C1	0.922	103.7	0.68	0.705	-40.324	3.343
3	A0B0C2	1.326	137.9	0.74	-2.450	-42.795	2.608
4	A0B1C0	0.260	99.9	0.67	11.693	-40.001	3.471
5	A0B1C1	0.978	121.5	0.74	0.193	-41.701	2.608
6	A0B1C2	1.058	140.7	0.75	-0.518	-42.973	2.492
7	A0B2C0	0.417	106.2	0.72	7.590	-40.526	2.846
8	A0B2C1	0.686	122.5	0.79	3.267	-41.768	2.040
9	A0B2C2	1.941	133.4	0.87	-5.762	-42.512	1.202
10	A1B0C0	0.313	25.1	0.61	10.097	-27.992	4.286
11	A1B0C1	0.704	35.0	0.67	3.017	-30.887	3.471
12	A1B0C2	1.227	41.3	0.71	-1.778	-32.323	2.968
13	A1B1C0	0.151	23.6	0.66	16.400	-27.470	3.602
14	A1B1C1	0.522	32.8	0.73	5.647	-30.323	2.726
15	A1B1C2	1.056	41.0	0.79	-0.471	-32.261	2.040
16	A1B2C0	0.181	24.1	0.71	14.856	-27.661	2.968
17	A1B2C1	0.857	33.3	0.79	1.340	-30.451	2.040
18	A1B2C2	1.631	42.7	0.87	-4.251	-32.622	1.202
19	A2B0C0	0.308	37.9	1.13	10.148	-31.579	-1.069
20	A2B0C1	0.600	45.3	1.19	4.441	-33.127	-1.518
21	A2B0C2	1.270	52.8	1.23	-2.077	-34.459	-1.805
22	A2B1C0	0.192	40.0	1.18	14.318	-32.050	-1.445
23	A2B1C1	1.149	46.6	1.23	-1.209	-33.383	-1.805
24	A2B1C2	0.942	55.5	1.30	0.519	-34.888	-2.286
25	A2B2C0	0.503	40.7	1.24	5.968	-32.198	-1.876
26	A2B2C1	0.999	50.1	1.32	0.006	-34.010	-2.419
27	A2B2C2	1.400	62.5	1.41	-2.921	-35.923	-2.992

Pareto Anova tables were used to analyse the most influential factor among cooling methods, cutting speed and feed rate. Comparisons between the level of factors were made using Design of Experiment method and traditional charts.

5.2.2 Surface roughness

The response graph for the mean S/N ratio, as shown in Figure 5.2, verified the Pareto ANOVA analysis result. It indicated that feed rate (C) had the most significant contribution to the surface roughness. In order to select the optimum combination of parameters B and C, a two-way table was developed. The two-way table showed that B1C0 produced the lowest surface roughness. From Table 5.2, A1 was chosen as the optimum level for cooling method (A).

The findings show that for all cooling methods, lower feed rates (C) have a dominant effect on surface roughness, with a contribution ratio (P = 86.50%), followed by cutting speed (B) (P = 4.12%) and then cooling method (A) (P = 2.88%). The most significant interaction is BxC (P = 2.60%). Optimisation of surface irregularity through the selection of input machining conditions becomes easier, especially the feed rate, since the total contribution of the main effects is approximately 93% compared to 7% total contribution of the interaction effects.

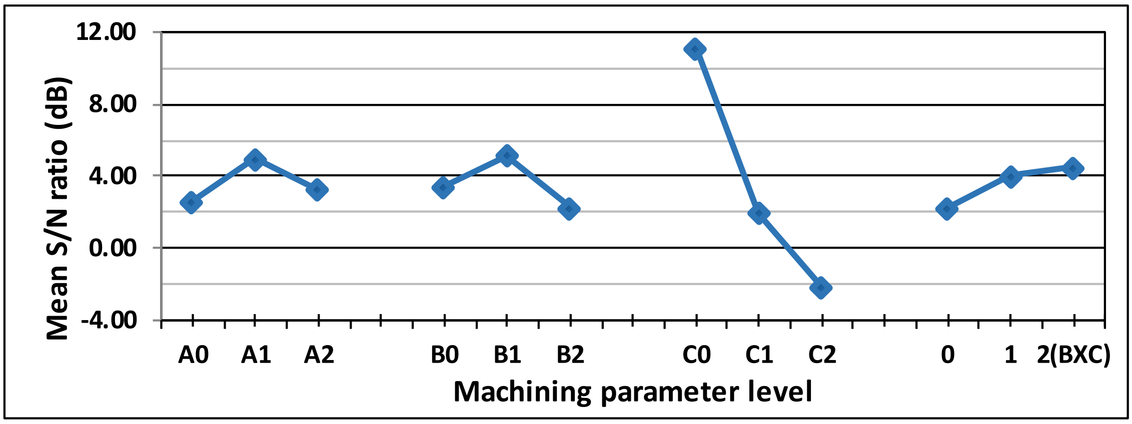
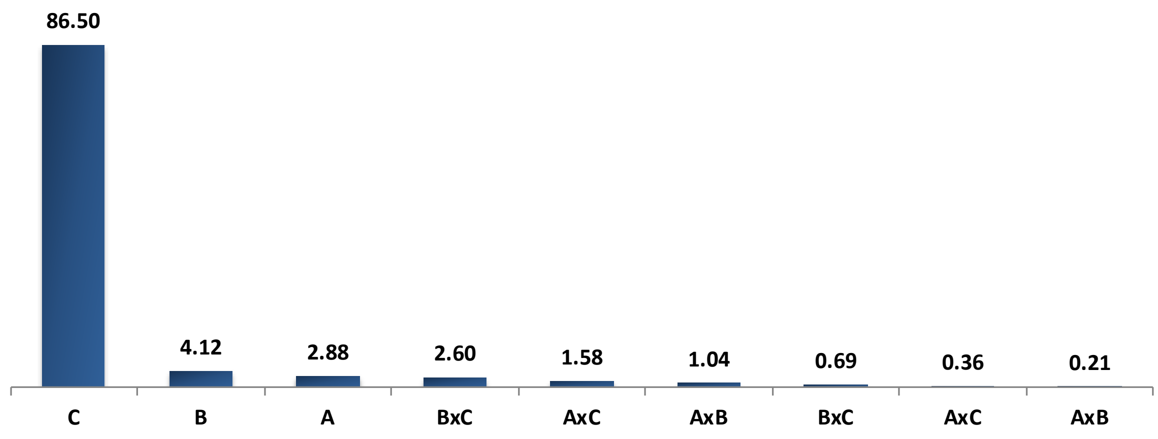


Figure 5.2 Mean S/N ratio for surface roughness

Table 5.2 Pareto ANOVA analysis for surface roughness

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	23.28	30.66	32.39	31.44	99.63	24.58	33.37	32.95	20.50
1	44.86	46.57	25.76	35.83	17.41	41.04	28.10	37.64	36.11
2	29.19	20.09	39.18	30.06	-19.71	31.71	35.86	26.74	40.72
Sum of squares of difference (S)	746.13	1065.84	270.29	54.42	22379.32	408.86	94.22	179.38	673.58
Contribution ratio (%)	2.88	4.12	1.04	0.21	86.50	1.58	0.36	0.69	2.60

Ti-Al-4V
Surface Roughness



Cumulative contribution	**86.50**	**90.62**	**93.50**	**96.11**	**97.69**	**98.73**	**99.43**	**99.79**	**100.00**
Check on significant interaction		BxC two-way table							
Optimum combination of significant factor level		A1B1C0							

Overall, the optimum combination of parameters for obtaining the best surface finish was A1B1C0, i.e., medium level of cooling (MQL), medium cutting speed (80 m/min) and low feed rate (0.1 mm/rev).

S/N ratio from Figure 5.2 shows that surface finish improved if the machining speed is increased from 60 m/min to 80 m/min since lower cutting forces result from the increase of cutting temperature [166]. This result is similar to the highest machining speed endorsed by tool tip manufacturers (30-80 m/min) using flood cooling [51]. However, when the cutting velocity was raised to B2 (100 m/min), there was a significant reduction in surface quality. The poorer surface finish was due to cutting velocity increase, causing the tool interface temperature to increase which promotes the adhesion of tool and workpiece materials.

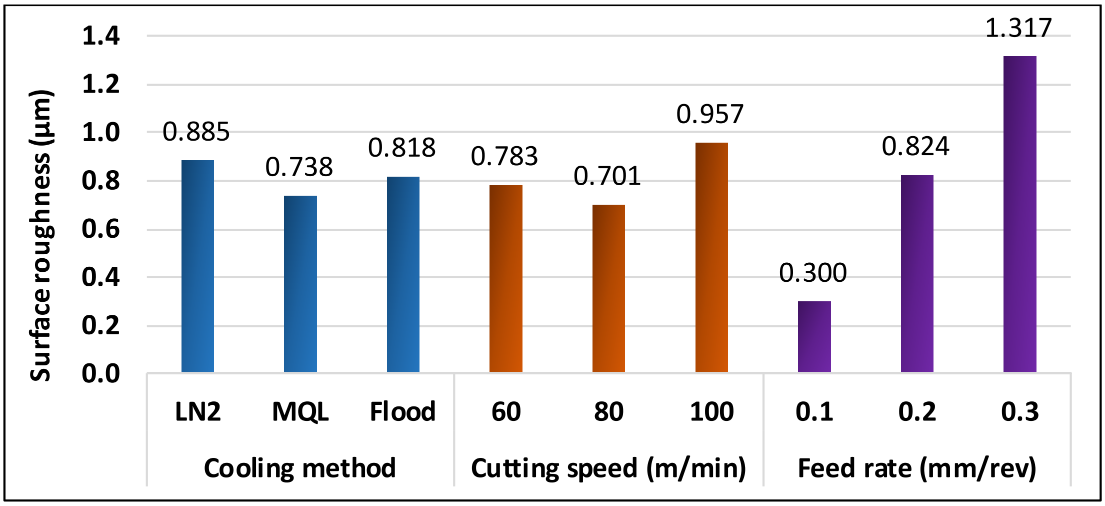


Figure 5.3 Average variation of surface roughness of Titanium alloy

Figure 5.3 confirms that on average, the best surface finish is produced by the MQL cooling. Even though the most influential factor for the surface finish is the feed rate, the role of the cooling method can still be observed to contribute to the surface finish. For most of the tests conducted, MQL provides an excellent surface quality.

Pictures acquired by Olympus Microscope BX51M (Figure 5.4) shows that when using the same cutting speed of 80 m/min (B1), and feed 0.1 mm/rev (C0), machining with MQL (A1) (R_a = 0.151 µm) gave a better effect on the surface finish compared to flood coolant (A2) (R_a = 0.192 µm). The results showed that MQL is able to provide a better lubrication for tool contact with the workpiece.

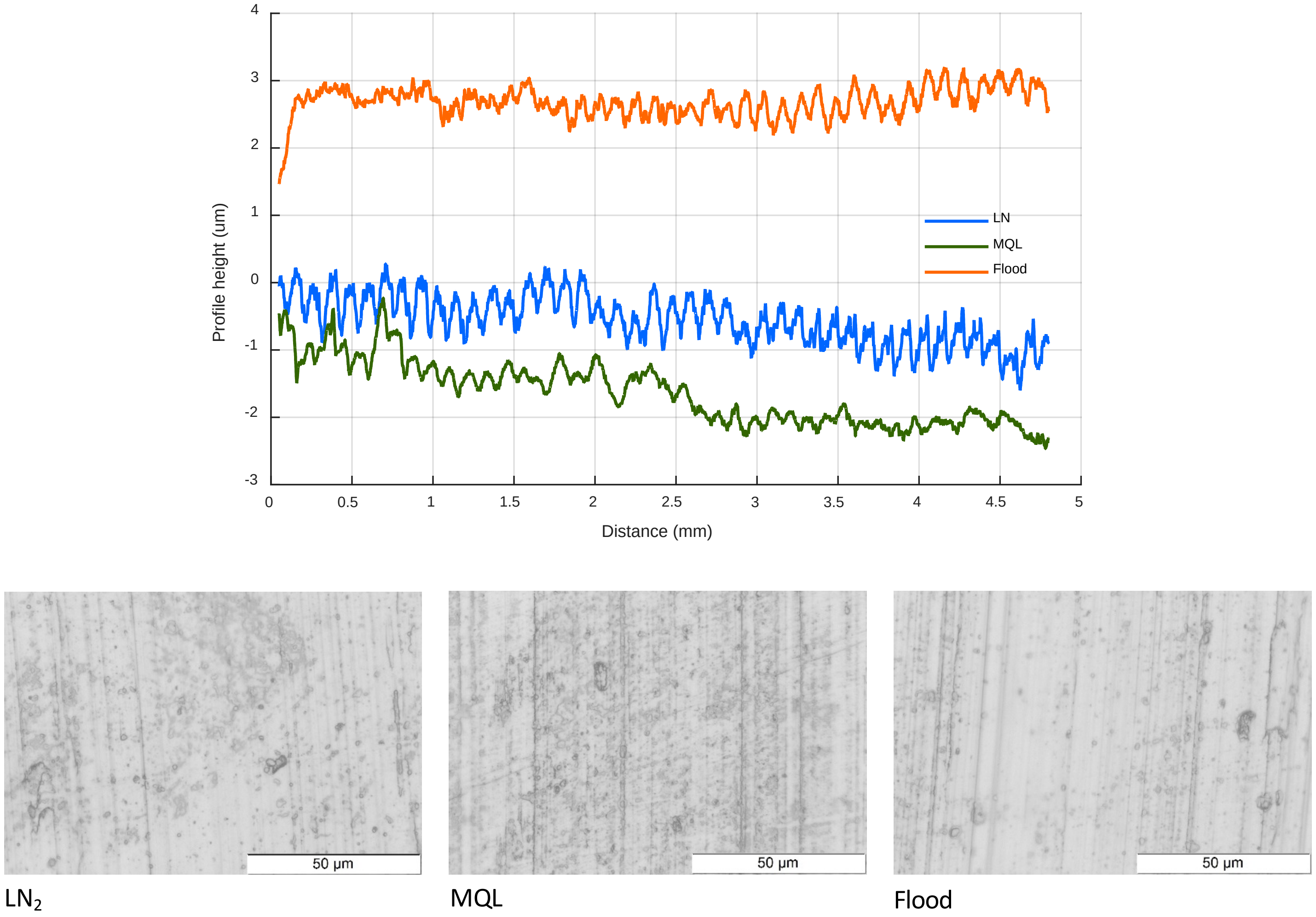


Figure 5.4 Microscope images and surface profiles of B1C0 samples (v = 80 m/min, f = 0.1 mm/rev)

Surface finish produced under flood coolant was only slightly better than that of cryogenic cooling (A0) (R_a = 0.260 μm). The complete surface finish charts for this experiment are presented in Appendix A. Based on its effect on surface finish, MQL cooling method is feasible to replace flood coolant in Titanium alloy machining. With respect to tool wear, all used tooltips were shown to be in good condition since the cutting time for each tip was less than 1 minute. To conclude, the cooling method is significant in how long a tool tip is functional, i.e, it needs a longer cutting time to wear.

5.2.3 Cutting force

Cutting force was measured by stationary Kistler dynamometer. Three forces: Feed force (F_f), Feed normal force (F_{fN}), and Passive force (F_p) were measured to calculate the total force required for this alloy titanium milling process.

$$F_{total} = \sqrt{{F_f}^2 + {F_{fN}}^2 + {F_p}^2} \tag{5.1}$$

The complete charts with F_f, F_{fN}, and F_p values are presented in Appendix B. The response graph for the mean S/N ratio as shown in Figure 5.5 verified the Pareto ANOVA analysis result. The two-way table showed that B0C0 requires the lowest cutting force.

From Table 5.3, A1 was chosen as the optimum level for cooling method (A). The best parameters combination that requires the lowest cutting force was A1B0C0, i.e., medium level of cooling (MQL), low cutting speed (60 m/min) and low feed rate (0.1 mm/rev).

The Pareto ANOVA analysis for the cutting force (Table 5.3) shows that cooling method (A) gave the most significant effect on cutting force with a contribution ratio (P = 88.87%), followed by feed rate (C) (P = 9.90%) and then cutting speed (B) (P = 0.37%). The most significant interaction is AxB (P = 0.34%). Optimisation of cutting force through the selection of input parameters becomes relatively easier, especially the cooling method, since the total contribution of the main effects is approximately 99%, compared to 1% total contribution of the interaction effects.

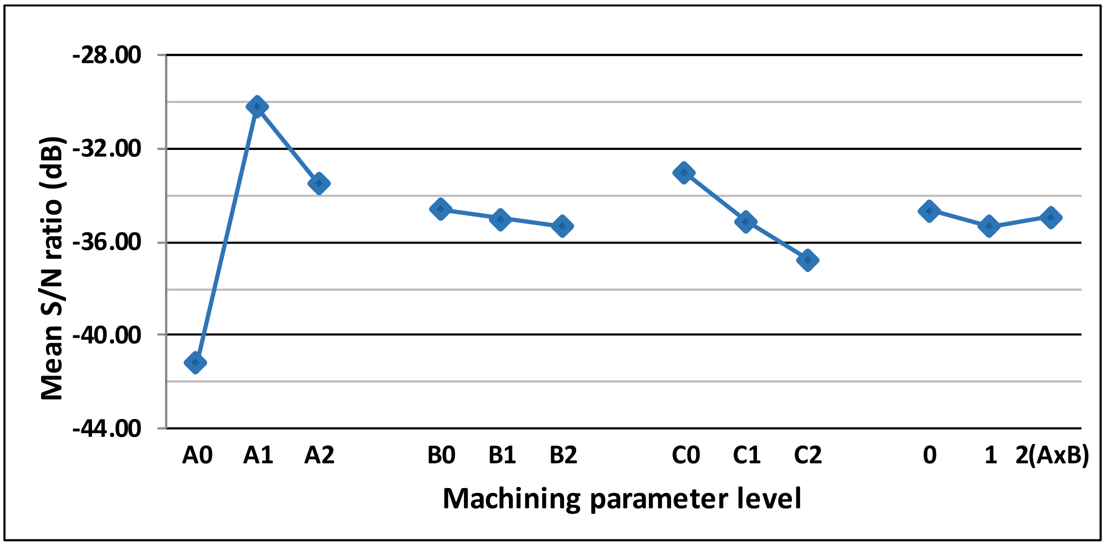
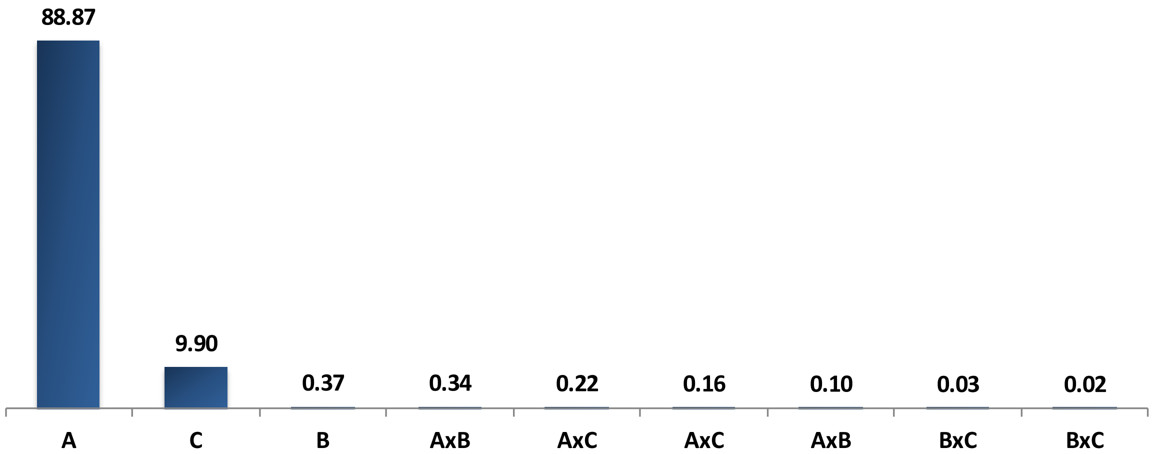


Figure 5.5 Mean S/N ratio for cutting force

In this test, the lowest machining temperature starts from cryogenic cooling, followed by flood cooling and the last MQL. Figure 5.6 shows that reducing the temperature of the workpiece increases the cutting force. Cutting speed and feed rate had similar trends; the cutting force increases when these parameters increase.

In addition to improving the surface finish, Figure 5.6 shows that MQL also gives the best influence on the cutting force. MQL significantly lowered the cutting force compared to that of flood, and much lower when compared to that of cryogenic cooling. This result was specifically due to the primary function of MQL, which is lubricating and not dissipating the machining heat. The workpiece temperature remains high, making it more plastic and reducing the effort for cutting. MQL application reduces the frictional forces between the tool and the workpiece. MQL is able to provide better lubrication due to the consistent bond of lubricant with the surface of the workpiece [123].

Table 5.3 Pareto ANOVA analysis for cutting force

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-370.30	-311.19	-311.87	-313.00	-297.17	-315.95	-315.16	-313.62	-313.74
1	-271.99	-315.05	-318.01	-314.57	-315.97	-312.19	-316.83	-314.92	-314.84
2	-301.62	-317.67	-314.02	-316.33	-330.76	-315.77	-311.92	-315.37	-315.33
Sum of squares of difference (S)	15259.62	63.83	58.13	16.60	1699.71	27.03	37.28	4.94	3.99
Contribution ratio (%)	88.87	0.37	0.34	0.10	9.90	0.16	0.22	0.03	0.02
Ti-Al-4V Cutting Force									
Cumulative contribution	88.87	98.77	99.14	99.48	99.69	99.85	99.95	99.98	100.00
Check on significant interaction		AxB two-way table							
Optimum combination of significant factor level		A1B1C0							

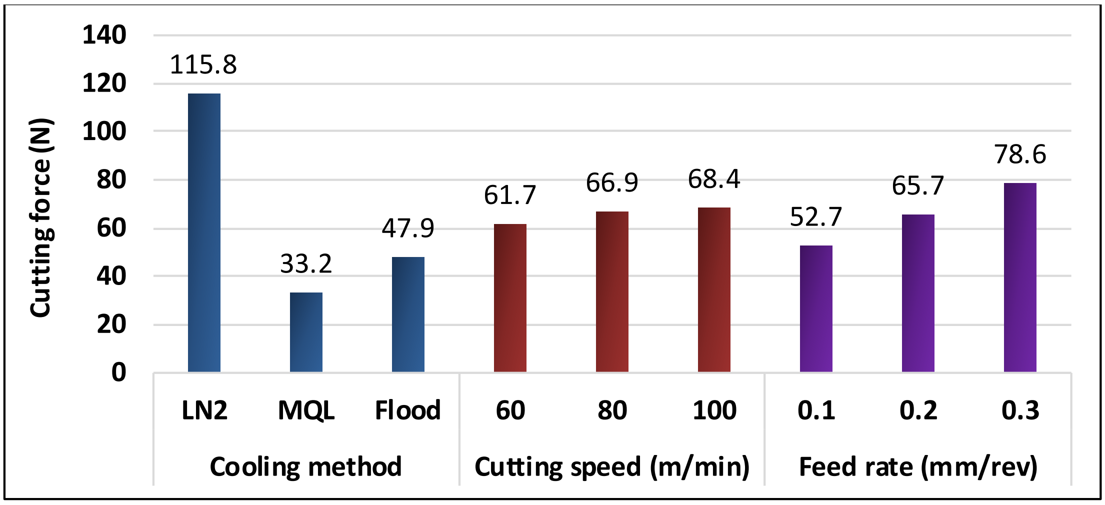


Figure 5.6 Average variation of cutting force for Titanium alloy

It has been found that when using cryogenic cooling that the tool requires significantly greater force to cut the workpiece, and is far greater compared to the other two cooling methods, as their low temperatures do not allow the material to soften, and requires more force to shear the workpiece. In addition, liquid nitrogen also increases the hardness of titanium alloy due to the formation of nitrides [167].

Figure 5.5 and Table 5.3 show that the effect of cutting speed in terms of cutting force can be ignored. This result is consistent with Ernst and Merchant who disregarded cutting speed in calculating cutting force [168].

5.2.4 Machine power requirement

From Table 5.4, A1 was chosen as the optimum level for cooling method. The parameter combination that requires the lowest machine power was A1B0C0, i.e., medium level of cooling (MQL), low cutting speed (60 m/min) and low feed rate (0.1 mm/rev). The two-way table indicated that B0C0 requires the lowest power.

The Pareto ANOVA analysis for machine power requirement (Table 5.4) shows that cooling method (A) gave the most significant effect on cutting force with a contribution ratio (P = 89.74%), followed by cutting speed (B) (P = 4.90%) and then feed rate (C) (P = 4.84%). The most significant interaction is AxB (P = 0.15%). Optimisation of cutting force through the selection of input parameters becomes relatively uncomplicated, especially the cooling method, since the total contribution of the main effects is approximately 99%, compared to 1% of the total contribution of the interaction effects of the parameter.

From Figure 5.7 it can be seen that MQL gave the best effect on required machine power, though it is closely followed by cryogenic cooling, and the traditional flood required the greatest machine power.

The response graph in Figure 5.7 verified the result from Pareto ANOVA, that cooling method has the most significant effect on required machine power (89.74%). Machining speed and feed rate demonstrated a similar trend, the increase of cutting velocity and feed rate requires higher machining power. However, this time the effect of the cutting velocity (4.90%) on machine power is slightly higher than that of the feed rate (4.84%).

For cryogenic cooling, according to Knowlen, commercial production of 1 kg of liquid nitrogen requires energy of approximately 0.5 kWh [163]. The energy requirement to produce liquid nitrogen that evaporates during the machining process needs to be taken into account to calculate the total energy used for cryogenic cooling.

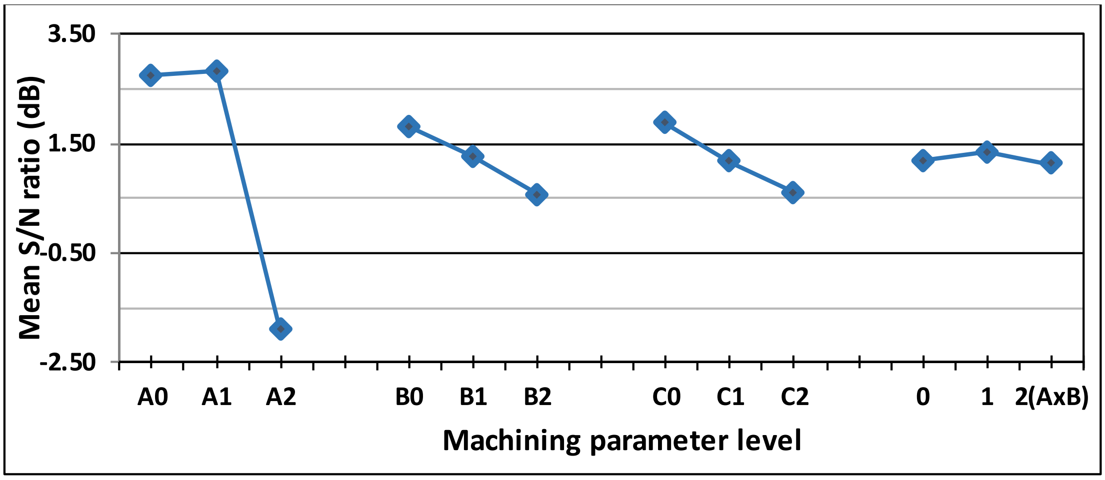
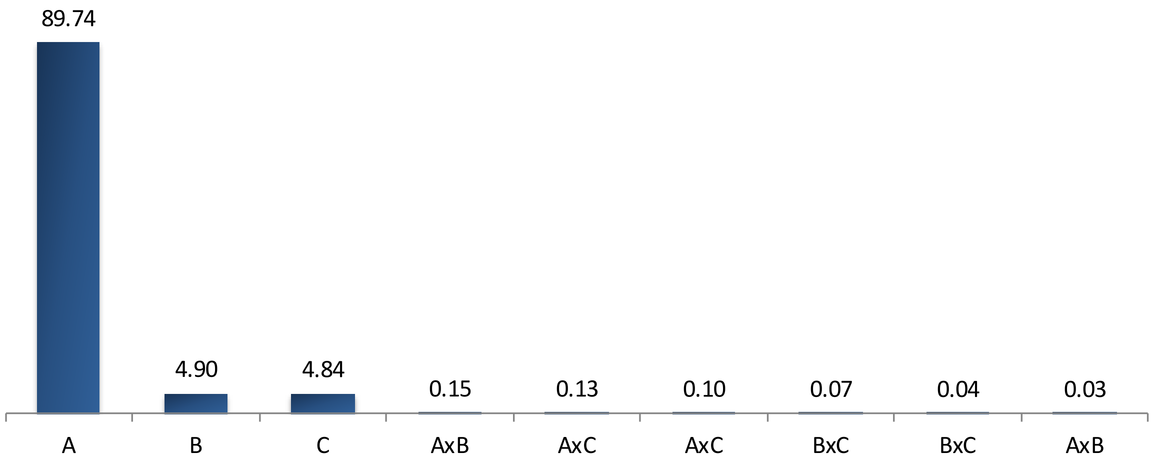


Figure 5.7 Mean S/N ratio for machine power

Table 5.4 Pareto ANOVA analysis for machine power

Sum at factor level	Factor and interaction								
	A	**B**	**AxB**	**AxB**	**C**	**AxC**	**AxC**	**BxC**	**BxC**
0	24.62	16.29	10.63	11.04	16.79	10.79	11.48	11.13	10.17
1	25.30	11.40	12.01	10.39	10.49	11.76	9.81	10.34	11.48
2	-17.21	5.01	10.06	11.28	5.43	10.15	11.42	11.24	11.06
Sum of squares of difference (S)	3558.11	191.87	6.01	1.27	194.37	3.96	5.35	1.45	2.70
Contribution ratio (%)	89.74	4.84	0.15	0.03	4.90	0.10	0.13	0.04	0.07
Ti-Al-4V Machine Power									
Cumulative contribution	**89.74**	**94.64**	**99.48**	**99.63**	**99.76**	**99.86**	**99.93**	**99.97**	**100.00**
Check on significant interaction			AxB two-way table						
Optimum combination of significant factor level			A1B0C0						

Examination of Figure 5.8 also shows that MQL cooling requires less energy compared to the cryogenic and the traditional coolant. Feed rate and cutting velocity show a similar trend. The power requirement increases when feed rate and cutting velocity increase. Lower power requirements of MQL cooling (58% of flood power) will reduce the machining cost. Therefore, MQL cooling is more sustainable compared to cryogenic cooling in terms of energy requirement.

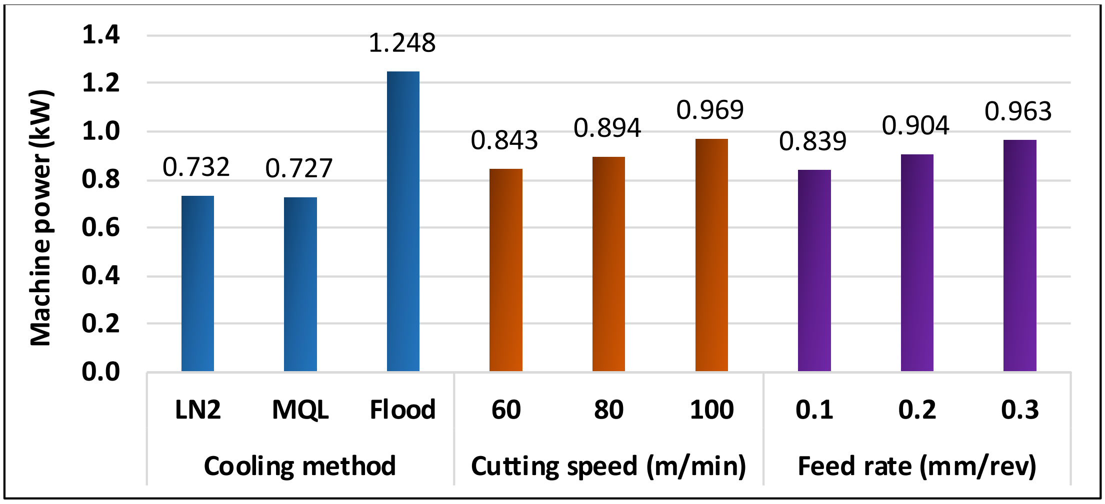


Figure 5.8 Average variation of machine power of Titanium alloy

Figure 5.8 also shows that the increase of cutting speed and feed rate is directly proportional to the increase of power requirements. The graph also shows that cryogenic cooling and MQL cooling require nearly similar machine power for any cutting speed and feed rate, while the flood cooling requires much greater power. The power required for the pump for coolant circulation plays a major role in the high power requirements of flood cooling.

5.3 Sustainable End Milling of Inconel 718

5.3.1 Experimental result

Table 5.5 Experimental results for surface roughness, cutting force, machine power, and their corresponding S/N ratios for Inconel 718

Experimental No/Condition		Measured Parameters			Calculated S/N Ratio		
		Surface Roughness (µm)	Cutting Force (N)	Machine Power (kW)	Surface Roughness	Cutting Force	Machine Power
1	A0B0C0	0.427	55.1	0.67	7.398	-34.828	3.479
2	A0B0C1	0.655	88.4	0.70	3.680	-38.927	3.098
3	A0B0C2	0.615	124.6	0.73	4.227	-41.911	2.734
4	A0B1C0	0.524	132.7	0.76	5.608	-42.459	2.384
5	A0B1C1	0.564	116.0	0.75	4.978	-41.293	2.499
6	A0B1C2	0.976	129.7	0.79	0.210	-42.255	2.047
7	A0B2C0	0.208	145.9	0.82	13.642	-43.279	1.724
8	A0B2C1	0.410	133.0	0.83	7.744	-42.474	1.618
9	A0B2C2	0.763	148.7	0.88	2.343	-43.445	1.110
10	A1B0C0	0.388	48.1	0.65	8.216	-33.638	3.742
11	A1B0C1	0.431	56.4	0.69	7.268	-35.019	3.223
12	A1B0C2	0.795	62.2	0.72	1.978	-35.878	2.853
13	A1B1C0	0.691	53.8	0.73	3.210	-34.613	2.734
14	A1B1C1	0.533	54.5	0.76	5.459	-34.724	2.384
15	A1B1C2	0.650	81.8	0.84	3.739	-38.255	1.514
16	A1B2C0	0.232	41.8	0.77	12.678	-32.426	2.270
17	A1B2C1	0.311	60.1	0.84	10.154	-35.571	1.514
18	A1B2C2	0.320	79.1	0.92	9.887	-37.967	0.724
19	A2B0C0	0.253	61.5	1.17	11.948	-35.772	-1.364
20	A2B0C1	0.578	70.5	1.21	4.766	-36.965	-1.656
21	A2B0C2	0.557	72.6	1.23	5.088	-37.223	-1.798
22	A2B1C0	0.274	60.1	1.23	11.234	-35.573	-1.798
23	A2B1C1	0.776	75.7	1.30	2.202	-37.577	-2.279
24	A2B1C2	0.896	124.6	1.42	0.954	-41.908	-3.046
25	A2B2C0	0.327	59.4	1.28	9.678	-35.481	-2.144
26	A2B2C1	0.470	68.2	1.35	6.551	-36.676	-2.607
27	A2B2C2	0.488	120.7	1.48	6.225	-41.631	-3.405

5.3.2 Surface roughness

The Pareto ANOVA analysis Table 5.6 shows that for surface roughness, even though parameter C (feed rate) had the most significant contribution, parameter B (cutting speed) also has significant effect on response. A two-way table was developed to find the optimum combination of parameters C and B. According to the two-way table, A2C0 combination produced the best surface finish. Figure 5.9 shows that B2 was the optimum level for cutting speed. Overall, the optimum parameter combination for obtaining the best surface finish was A2B2C0, i.e., the highest level of cooling (flood), the highest cutting speed (80 m/min) and the lowest feed rate (0.1 mm/rev).

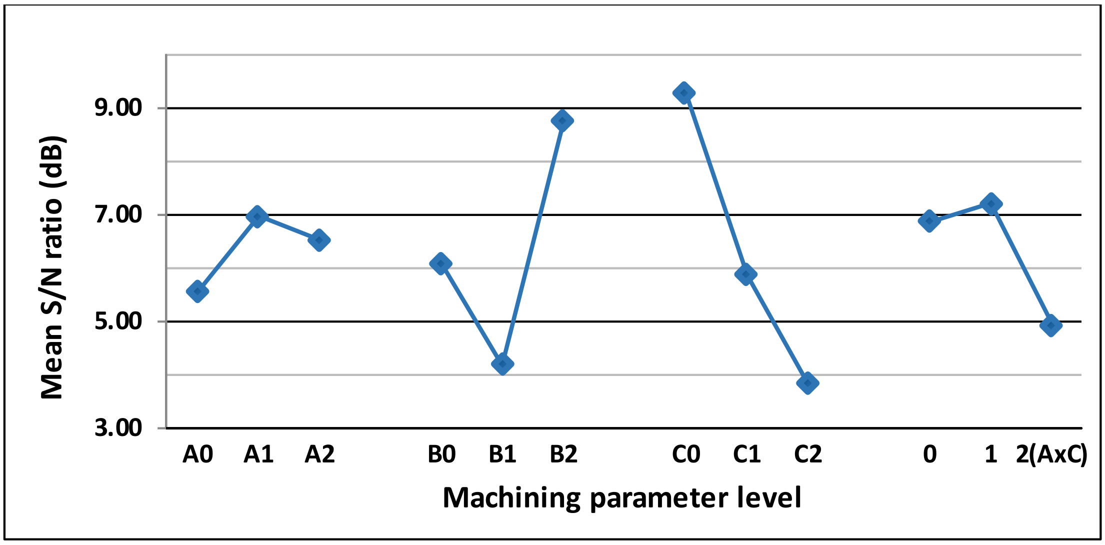


Figure 5.9 Mean S/N ratio for surface roughness

Figure 5.10 confirms that on average, the lowest feed rate 0.1 mm/rev gave the best surface finish which is a normal result of the machining process.

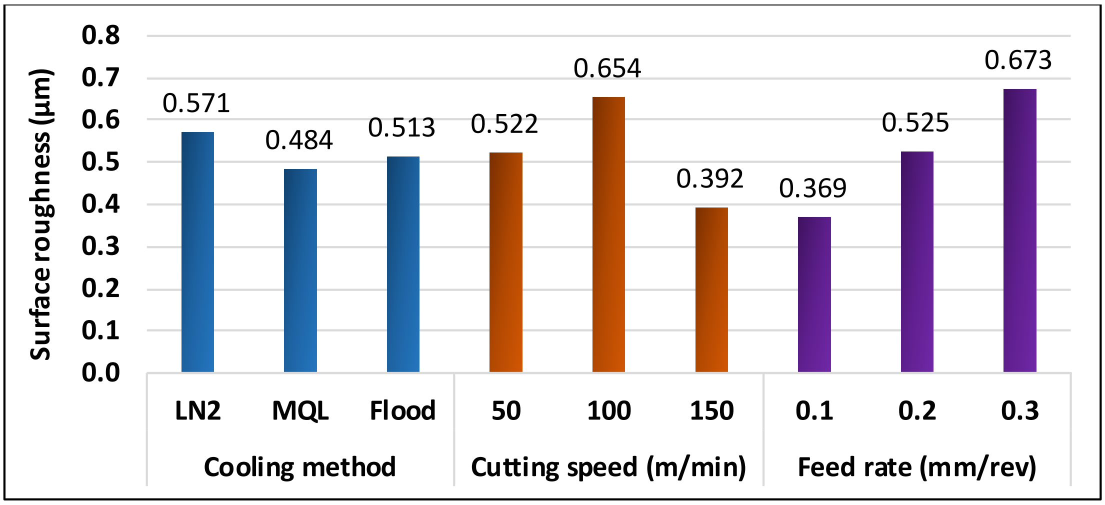


Figure 5.10 Average variation of surface roughness of Inconel 718

Table 5.6 Pareto ANOVA analysis for surface roughness

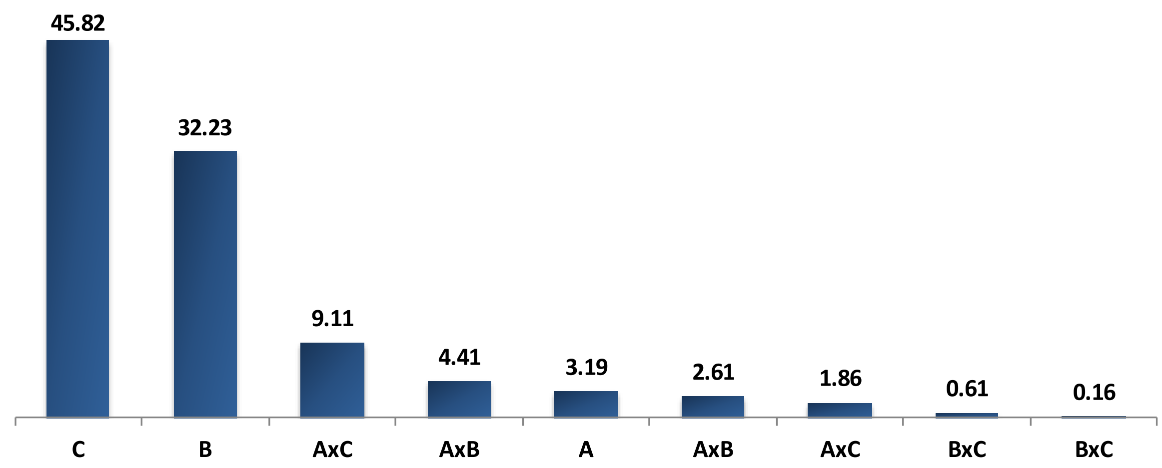
Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	49.83	54.57	62.41	50.17	83.61	55.77	61.79	56.91	58.66
1	62.59	37.59	50.71	65.32	52.80	52.77	64.87	54.22	56.61
2	58.65	78.90	57.94	55.58	34.65	62.52	44.40	59.93	55.79
Sum of squares of difference (S)	256.06	2586.42	209.23	353.58	3676.19	149.59	730.61	48.96	13.03
Contribution ratio (%)	3.19	32.23	2.61	4.41	45.82	1.86	9.11	0.61	0.16
Inconel 718 Surface Roughness									
Cumulative contribution	45.82	78.05	87.16	91.56	94.76	97.36	99.23	99.84	100.00
Check on significant interaction		AxC two-way table							
Optimum combination of significant factor level		A2B2C0							

Figure 5.9 and Figure 5.10 show the lowest surface roughness produced by MQL cooling. For the cutting speed, the increase from B0 to B1 gave a worse surface finish, but the best surface finish was produced when it is increased to B2 (the highest speed).

5.3.3 Cutting force

The Pareto ANOVA analysis Table 5.7 shows that parameter A (cooling method) also the most significant factors for cutting force. However parameter C (feed rate) and parameter B (cutting speed) has a significant effect. The response graph for mean S/N ratio Figure 5.11 verified the result. Based on the two-way table, A1B0 combination required the lowest cutting force.

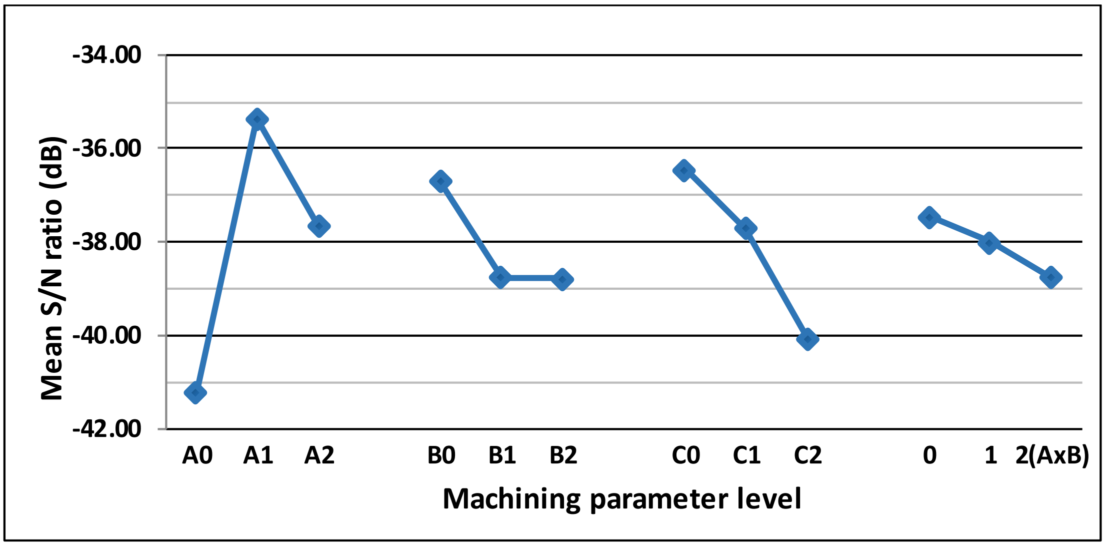


Figure 5.11 Mean S/N ratio for cutting force

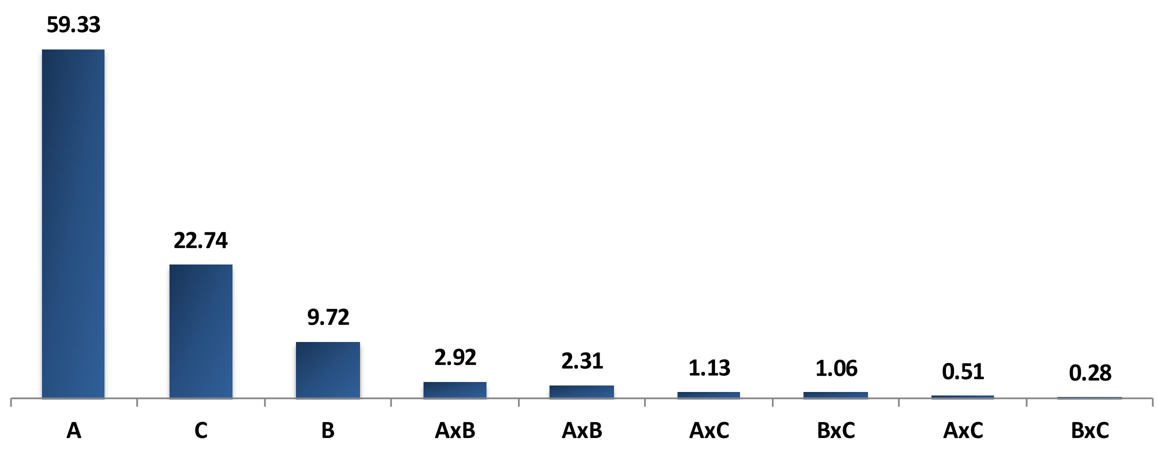
From Figure 5.11 C0 was chosen as the optimum level for feed rate. Finally, the best combination that requires the lowest cutting force was A1B0C0, i.e., medium level of cooling (MQL), the lowest cutting speed (40 m/min) and the lowest feed rate (0.1 mm/rev).

MQL is the least efficient method of dissipating the temperature of the workpiece, while LN_2 and flood reduce the temperature significantly. Based on the cutting parameters shown in Figure 5.12 MQL has the lowest cutting force.

Table 5.7 Pareto ANOVA analysis for cutting force

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-370.94	-330.23	-336.75	-337.11	-328.13	-343.95	-346.71	-341.44	-340.94
1	-318.16	-348.72	-344.39	-342.00	-339.29	-344.20	-341.68	-346.66	-344.58
2	-338.87	-349.01	-346.82	-348.86	-360.54	-339.82	-339.57	-339.86	-342.44
Sum of squares of difference (S)	4242.83	695.15	165.48	208.86	1625.85	36.32	80.60	76.09	20.07
Contribution ratio (%)	59.33	9.72	2.31	2.92	22.74	0.51	1.13	1.06	0.28

Inconel 718
Cutting Force



Cumulative contribution	88.87	98.77	99.14	99.48	99.69	99.85	99.95	99.98	100.00
Check on significant interaction		AxB two-way table							
Optimum combination of significant factor level		A1B0C0							

These results are found to be consistent with Liao *et al.* [67] who found that the higher the temperature the lower the cutting force requirements are. Cutting speed and feed rate have the similar trend, higher cutting speed and feed rate need higher cutting force.

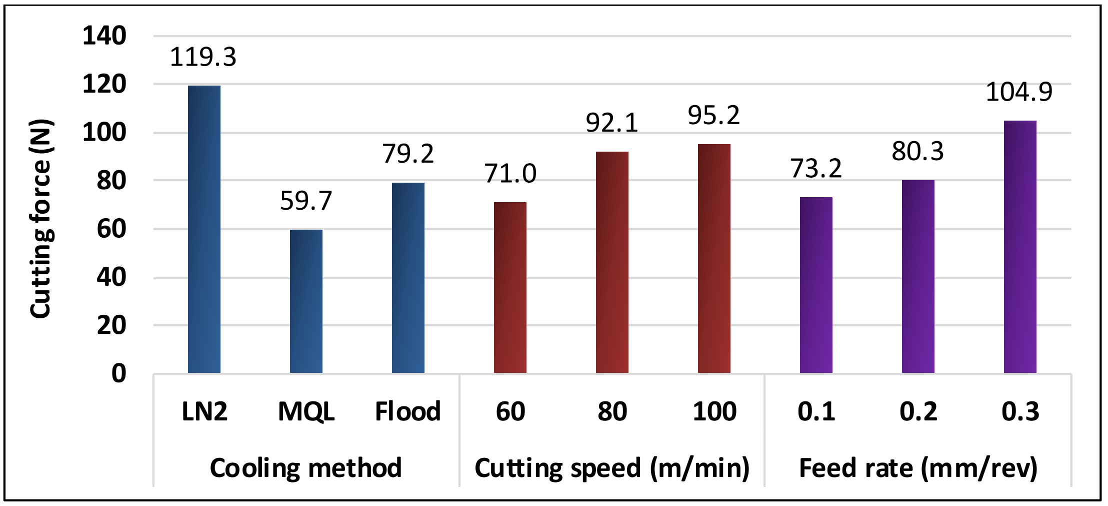


Figure 5.12 Average variation of cutting force of Inconel 718

5.3.4 Machine power

For machine power requirement, parameter A (cooling method) even has a more significant effect, while parameter C (feed rate) has the least effect. Based on Table 5.8 and Figure 5.13 the best parameters combination that requires the lowest machine power was A1B0C0, i.e., medium level of cooling (MQL), low cutting speed (60 m/min) and low feed rate (0.1 mm/rev).

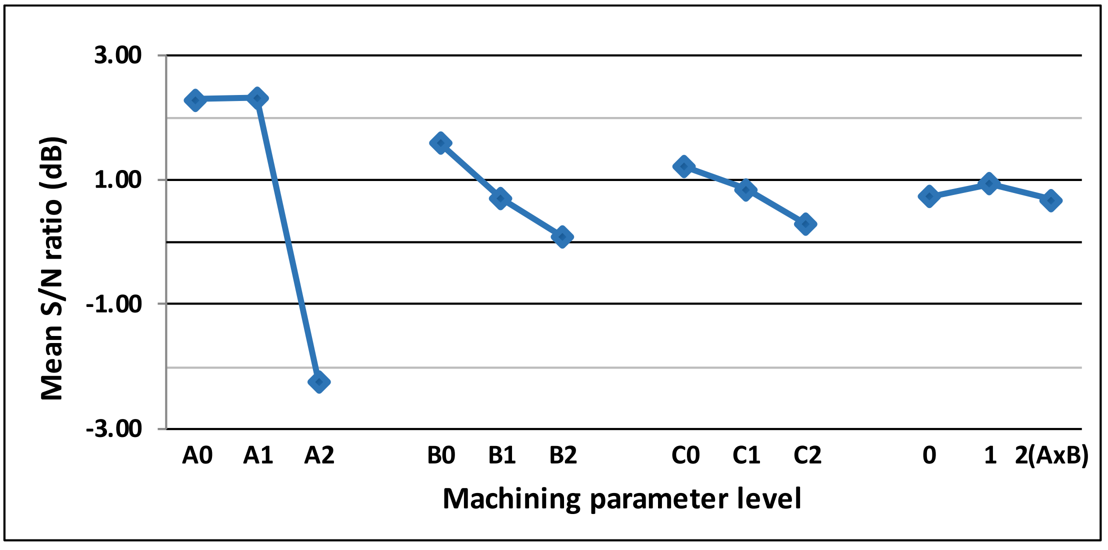
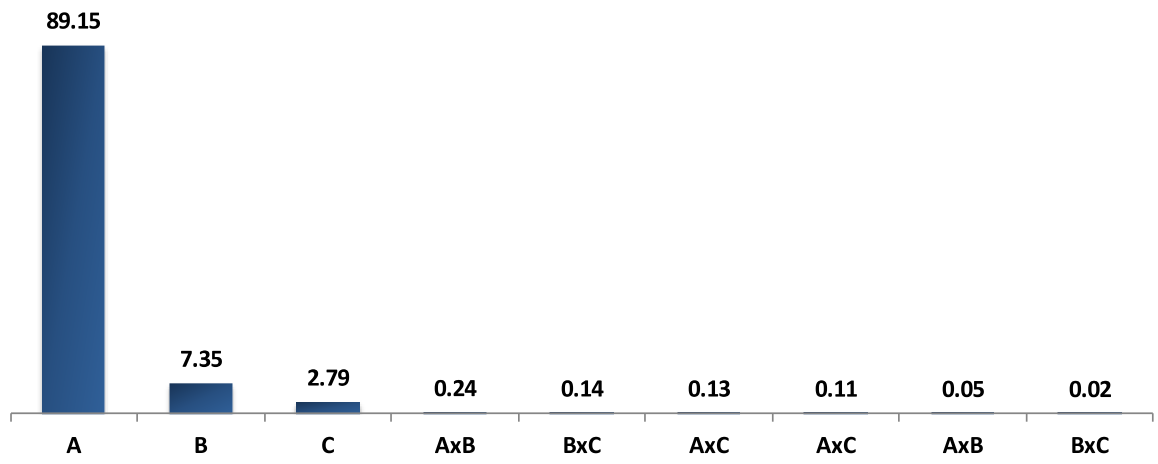


Figure 5.13 Mean S/N ratio for machine power

Table 5.8 Pareto ANOVA analysis for machine power

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	20.63	14.25	6.63	7.72	10.96	6.07	6.39	6.83	6.82
1	20.89	6.37	8.53	6.56	7.73	7.65	6.94	6.35	6.97
2	-20.16	0.74	6.20	7.08	2.67	7.64	8.03	8.18	7.57
Sum of squares of difference (S)	3349.32	276.10	9.19	2.04	104.79	4.94	4.17	5.38	0.94
Contribution ratio (%)	89.15	7.35	0.24	0.05	2.79	0.13	0.11	0.14	0.02

Inconel 718 Machine Power



Cumulative contribution	89.15	96.50	99.29	99.53	99.68	99.81	99.92	99.98	100.00
Check on significant interaction	AxB two-way table								
Optimum combination of significant factor level	A1B0C0								

Figure 5.14 shows an important fact that, on average, MQL cooling needs similar energy to cryogenic. Flood requires the greatest power. Cutting speed and feed rate show a similar trend, and the power requirement increases when cutting feed and feed rate increase.

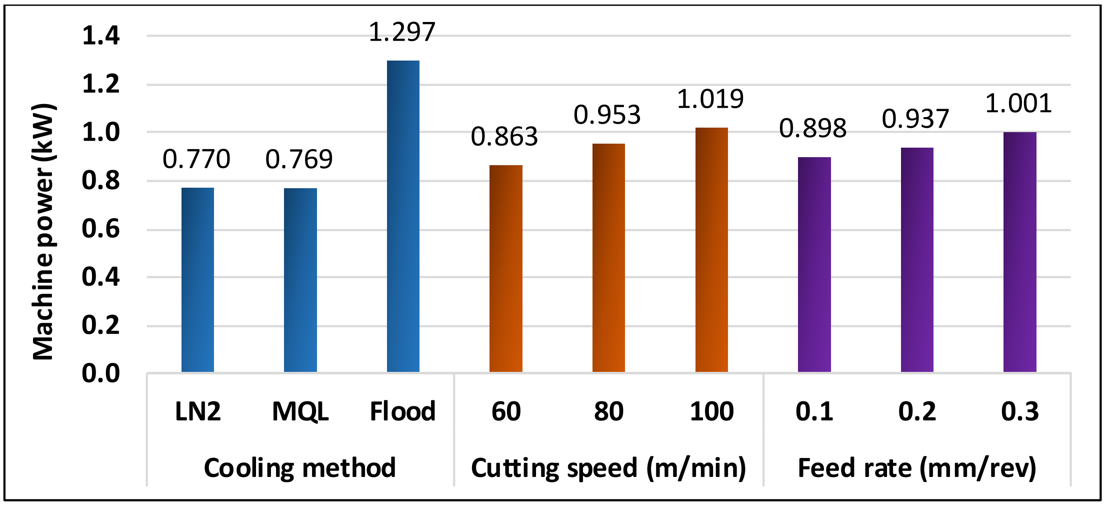


Figure 5.14 Average variation of machine power based on cutting parameters

The results from three output parameters based on Pareto ANOVA analysis (Table 5.6, Table 5.7, and Table 5.8), surface roughness, cutting force and machine power shows that the cooling method was the most dominant factor in the milling process of Inconel. The cooling method contribution in reducing machine power was the highest (89.15%), followed by cutting force (59.33%) and surface roughness (45.82%).

The machine power requirement is one of the important factors that supports sustainable machining. Since the required power of LN_2 and MQL were significantly lower, only 59% of that of flood (Figure 5.14). In term of energy requirement, both alternative cooling are more sustainable than flood cooling.

For surface roughness (Figure 5.9) and cutting force (Figure 5.11), MQL cooling method gave the best result, while the LN_2 performance for both categories was worse than that of flood. Overall, the MQL is the best method of cooling on Inconel milling process.

5.4 Sustainable End Milling of Aluminium Metal Matrix Composites (AMMC)

5.4.1 Experimental result

Table 5.9 Experimental results for surface roughness, cutting force, machine power, and their corresponding S/N ratios for AMMC

Experimental No/Condition		Measured Parameters			Calculated S/N Ratio		
		Surface Roughness (μm)	Cutting Force (N)	Machine Power (kW)	Surface Roughness	Cutting Force	Machine Power
1	A0B0C0	0.139	83.1	0.60	17.118	-38.390	4.437
2	A0B0C1	1.058	84.4	0.66	-0.492	-38.526	3.609
3	A0B0C2	2.044	97.7	0.68	-6.211	-39.797	3.350
4	A0B1C0	0.166	88.4	0.71	15.614	-38.928	2.975
5	A0B1C1	0.199	99.7	0.75	14.023	-39.973	2.499
6	A0B1C2	1.317	107.0	0.85	-2.392	-40.584	1.412
7	A0B2C0	0.158	97.3	0.83	16.026	-39.762	1.618
8	A0B2C1	0.365	108.5	0.91	8.754	-40.709	0.819
9	A0B2C2	1.503	110.9	0.90	-3.537	-40.899	0.915
10	A1B0C0	0.137	16.3	0.59	17.286	-24.240	4.583
11	A1B0C1	0.703	22.7	0.63	3.061	-27.111	4.013
12	A1B0C2	1.852	29.6	0.68	-5.354	-29.432	3.350
13	A1B1C0	0.157	16.2	0.71	16.063	-24.203	2.975
14	A1B1C1	0.405	23.3	0.78	7.850	-27.364	2.158
15	A1B1C2	1.571	30.4	0.77	-3.922	-29.662	2.270
16	A1B2C0	0.167	16.3	0.84	15.544	-24.220	1.514
17	A1B2C1	0.557	22.1	0.87	5.081	-26.892	1.210
18	A1B2C2	2.414	27.7	0.94	-7.654	-28.859	0.537
19	A2B0C0	0.163	17.8	1.10	15.738	-25.029	-0.828
20	A2B0C1	0.746	26.5	1.15	2.544	-28.461	-1.214
21	A2B0C2	1.798	35.5	1.20	-5.094	-31.013	-1.584
22	A2B1C0	0.102	15.8	1.20	19.856	-23.981	-1.584
23	A2B1C1	0.863	23.6	1.29	1.280	-27.457	-2.212
24	A2B1C2	1.811	30.8	1.38	-5.157	-29.784	-2.798
25	A2B2C0	0.129	14.6	1.32	17.765	-23.291	-2.411
26	A2B2C1	0.343	19.5	1.40	9.294	-25.805	-2.923
27	A2B2C2	1.697	24.8	1.37	-4.592	-27.903	-2.734

5.4.2 Surface roughness

Based on Table 5.10 and verified by Figure 5.15, parameter C (feed rate) has the most significant contribution. Results of the two-way table shows that A0B1 provide the lowest surface roughness. Figure 5.15 also shows that C0 was the optimum level for the feed rate (C), so the combination of parameters to produce the best surface finish was A0B1C0, i.e., the lowest cooling level (cryogenic), medium cutting speed (100 m/min) and the lowest feed rate (0.1 mm/rev).

Table 5.10 Pareto ANOVA analysis, for milling process of AMMC, shows that for surface roughness, feed rate has the most significant influence with 93.89% contribution. Moreover, the best finish was achieved by the lowest feed rate. This result shows that an optimisation process with a low feed rate will decrease the rate of production.

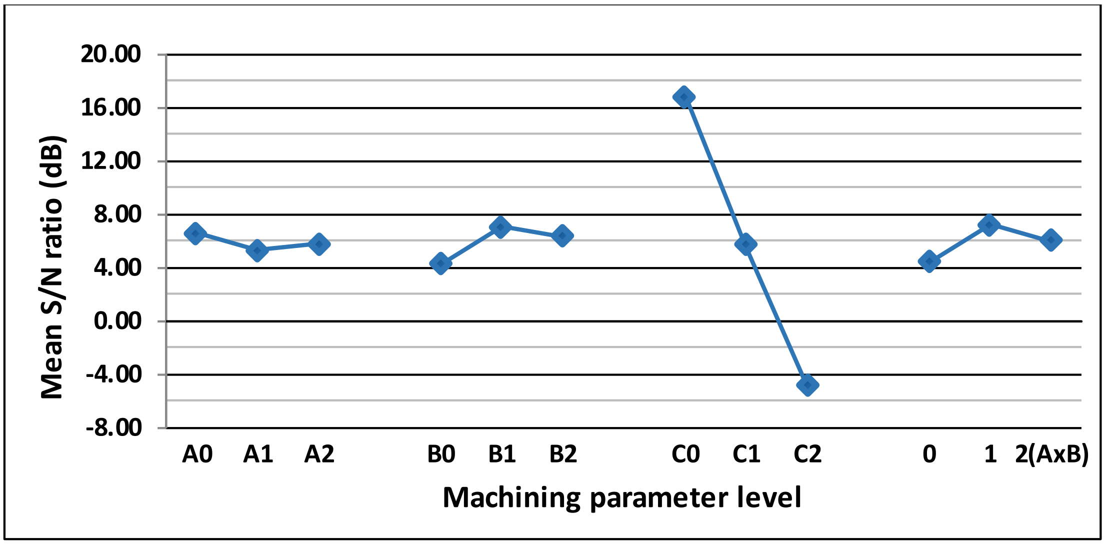
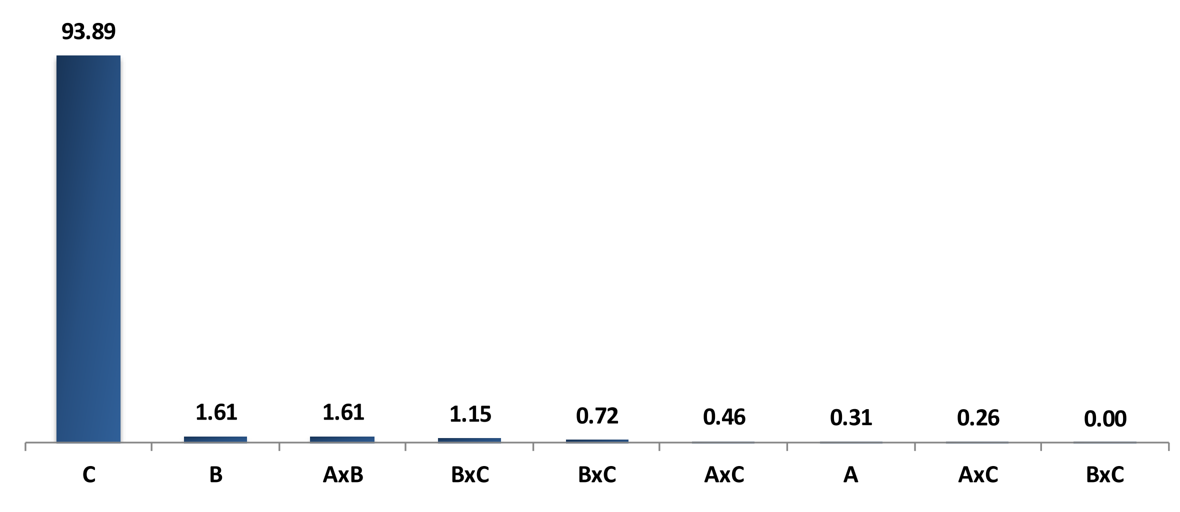


Figure 5.15 Mean S/N ratio for surface roughness

Figure 5.16 also verified that on average, cryogenic cooling provides the best surface finish, and feed rate has the highest contribution to the value of surface finish. The lowest feed rate gave the best surface finish, and the highest feed rate produced the worst surface finish.

Table 5.10 Pareto ANOVA analysis for surface roughness

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	58.90	38.59	39.36	52.87	151.01	44.95	49.91	61.80	57.51
1	47.95	63.21	64.70	53.40	51.39	56.33	58.71	40.86	42.98
2	51.63	56.68	54.42	52.21	-43.91	57.21	49.87	55.83	58.00
Sum of squares of difference (S)	186.23	975.95	974.57	2.14	57001.64	280.82	155.73	698.06	437.23
Contribution ratio (%)	0.31	1.61	1.61	0.00	93.89	0.46	0.26	1.15	0.72
AMMC Surface Roughness									
Cumulative contribution	93.89	95.50	97.10	98.25	98.97	99.43	99.74	100.00	100.00
Check on significant interaction			AxB two-way table						
Optimum combination of significant factor level			A0B1C0						

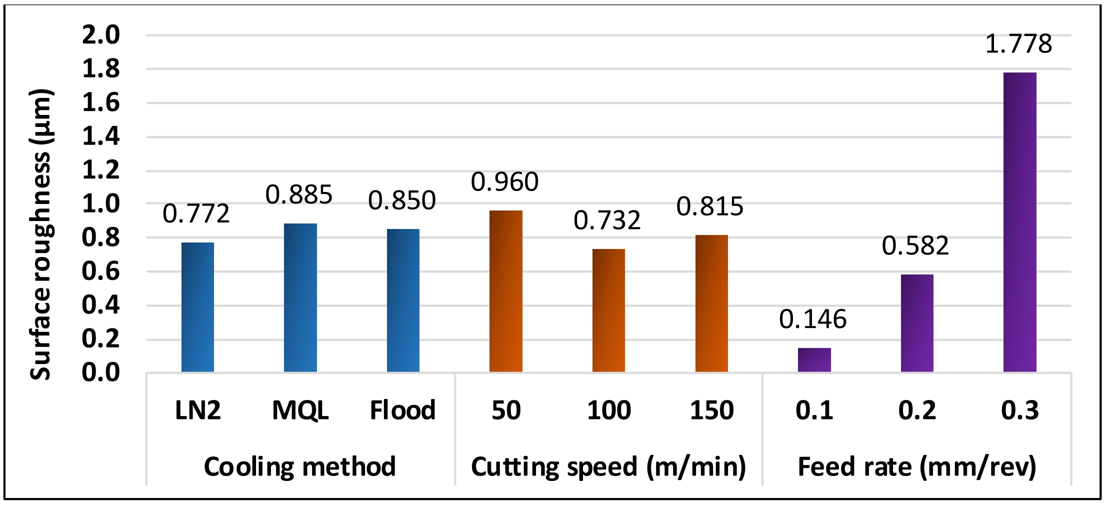


Figure 5.16 Average variation of surface roughness of AMMC

5.4.3 Cutting force

For cutting force, Table 5.11 shows that the parameter A (cooling method) was the most significant factor and the lowest cutting force was generated by A2C0. From Figure 5.17 the highest cutting speed B2 slightly outperformed B0 and B1. The combination of cutting parameters that generated the lowest force was A2B2C0, i.e., the highest level of cooling (flood), the highest cutting speed (150 m/min) and the lowest feed rate (0.1 mm/rev).

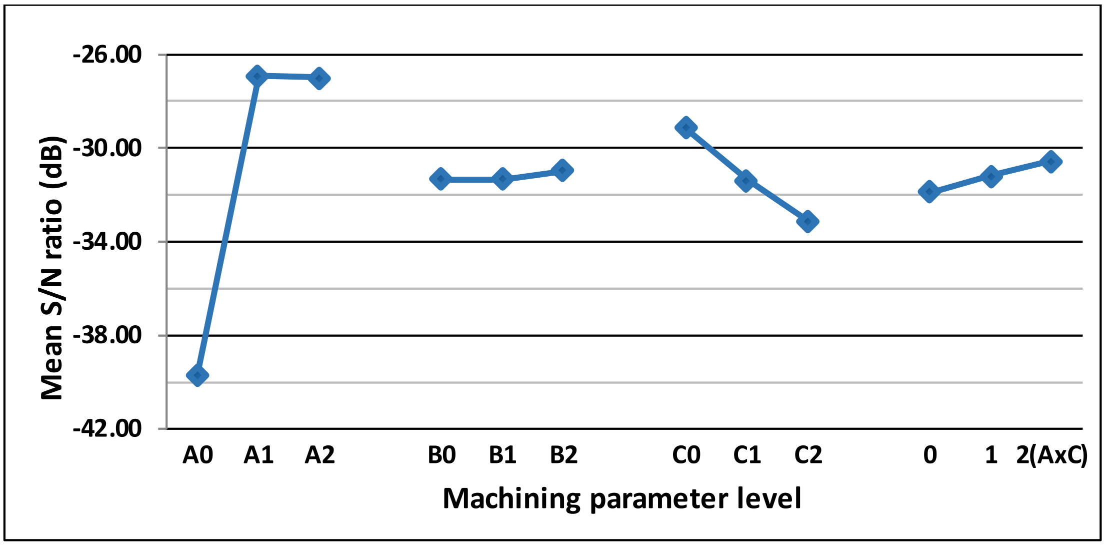
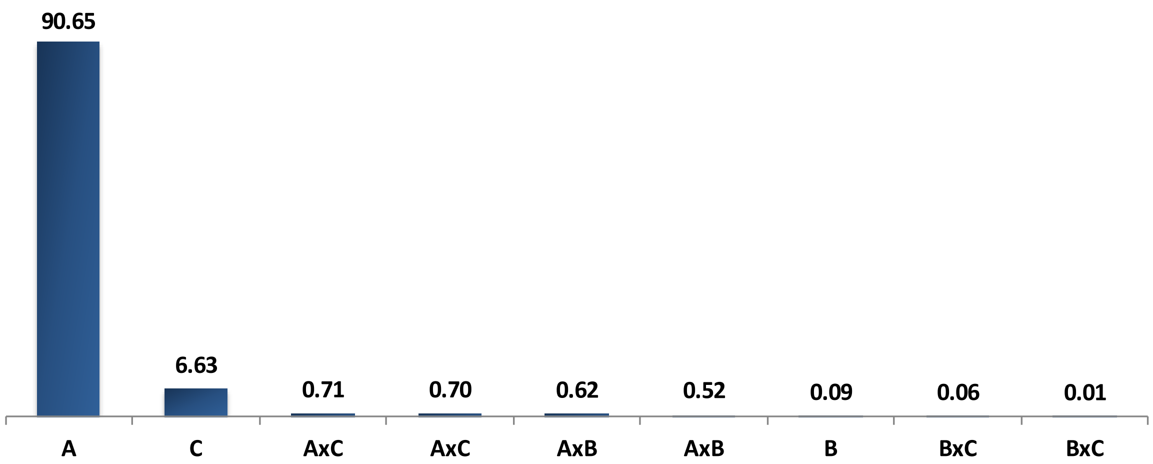


Figure 5.17 Mean S/N ratio for cutting force

Table 5.11 Pareto ANOVA analysis for cutting force

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-357.63	-282.06	-277.97	-275.00	-262.11	-286.82	-287.21	-281.16	-280.18
1	-242.05	-282.00	-277.33	-284.02	-282.36	-280.64	-279.53	-278.94	-281.47
2	-242.79	-278.41	-287.17	-283.44	-298.00	-275.01	-275.73	-282.37	-280.82
Sum of squares of difference (S)	26550.06	26.30	181.67	152.88	1942.85	209.23	205.28	18.23	2.48
Contribution ratio (%)	90.65	0.09	0.62	0.52	6.63	0.71	0.70	0.06	0.01

AMMC Cutting Force



Cumulative contribution	**90.65**	**97.28**	**98.00**	**98.70**	**99.32**	**99.84**	**99.93**	**99.99**	**100.00**
Check on significant interaction		AxC two-way table							
Optimum combination of significant factor level		A2B2C0							

It can be observed from Figure 5.18, that on average, the cutting force needed for MQL cooling was slightly lower than that of flood. Cryogenic required significantly greater (more than four times) force compared to the other two. This result shows that due to an extremely low cryogenic temperature, a milling tool requires greater force to shear the workpiece.

The trends of cutting speed and feed rate were similar, and the required cutting force was directly proportional to the cutting speed and feed rate. However, the increase of cutting force due to the increase of feed rate was more significant than that of cutting speed.

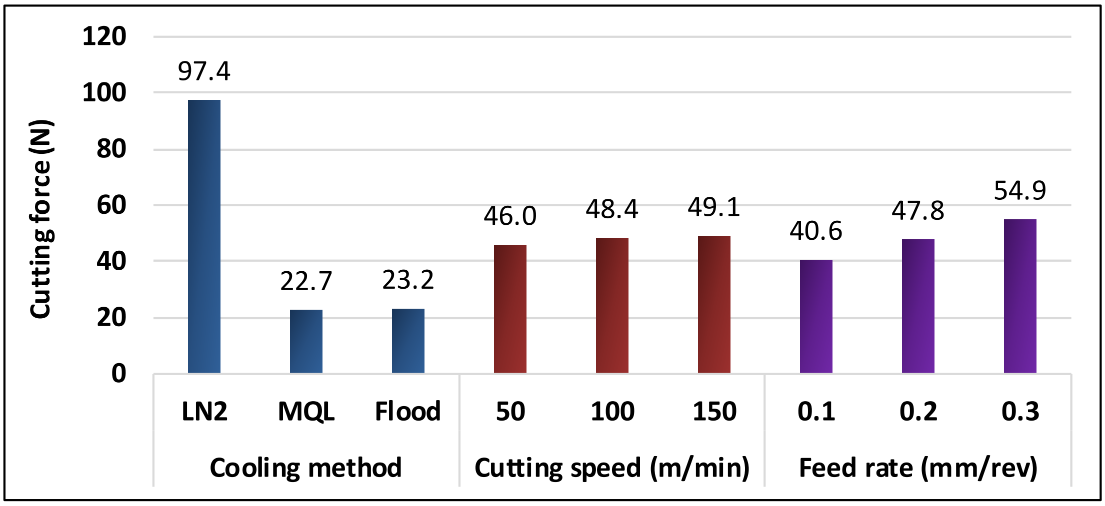


Figure 5.18 Average variation of cutting force of AMMC

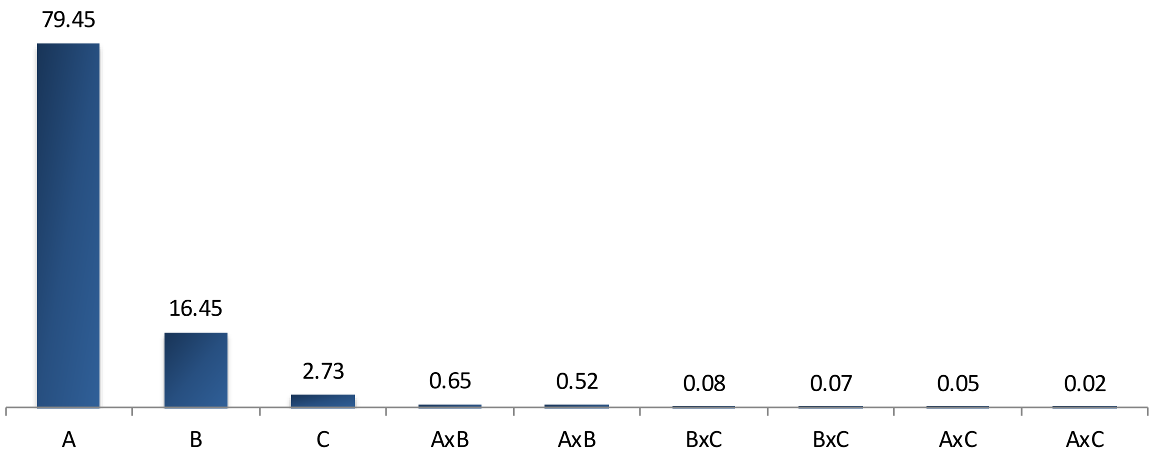
5.4.4 Machine power

Parameter A (cooling method) was also the most dominant factor for the machine power requirements (Table 5.12). However, the role of cutting speed for the machine power was higher compare to cutting force. A1B0 was found as the best combination for a lower power requirement. From Figure 5.19, C0 was the optimum level for feed rate, so that the combination of the best parameters that require the lowest power was A1B0C0, i.e., a medium level of cooling (MQL), the lowest cutting speed (50 m/min) and the lowest feed rate (0.1 mm/rev).

Table 5.12 Pareto ANOVA analysis for machine power

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	21.57	19.65	8.00	10.67	13.21	8.77	9.23	8.12	9.29
1	22.55	7.63	10.70	6.46	7.89	8.82	8.20	9.43	7.95
2	-18.35	-1.52	7.07	8.64	4.65	8.17	8.34	8.22	8.52
Sum of squares of difference (S)	3267.23	676.42	21.35	26.59	112.10	0.79	1.89	3.19	2.72
Contribution ratio (%)	79.45	16.45	0.52	0.65	2.73	0.02	0.05	0.08	0.07

AMMC Machine Power



Cumulative contribution	**79.45**	**95.90**	**98.63**	**99.27**	**99.79**	**99.87**	**99.93**	**99.98**	**100.00**
Check on significant interaction		AxB two-way table							
Optimum combination of significant factor level		A1B0C0							

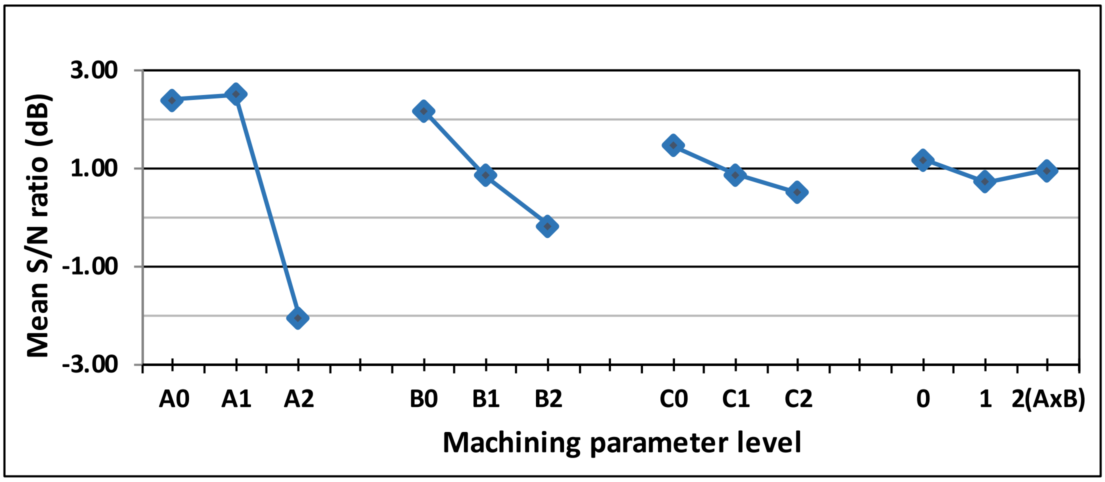


Figure 5.19 Mean S/N ratio for machine power

Figure 5.20 shows that the MQL power requirement was similar to that of cryogenic, while flood required much greater power. Cutting speed and feed rate show a similar trend; the required power was directly proportional to the increase of cutting speed or feed rate.

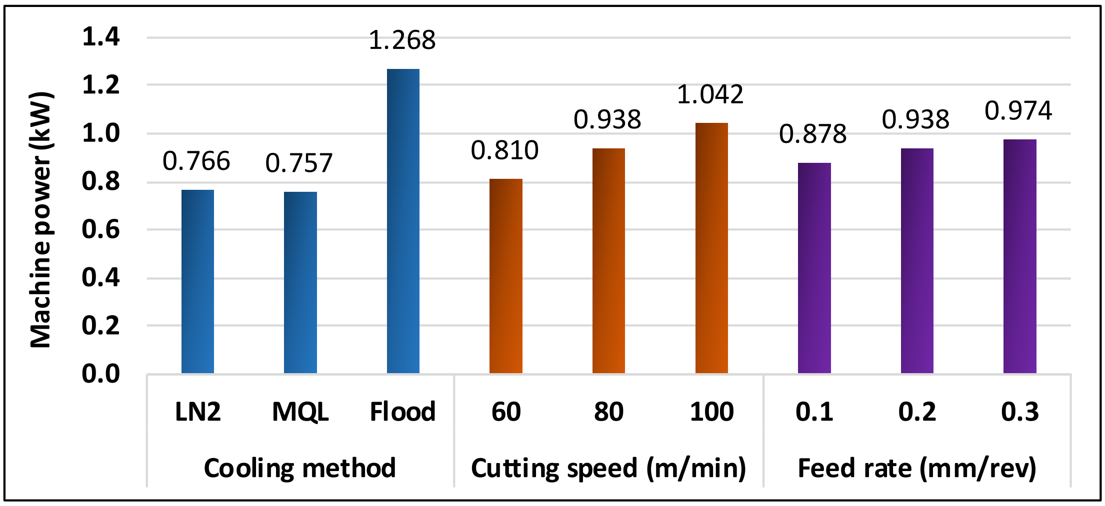
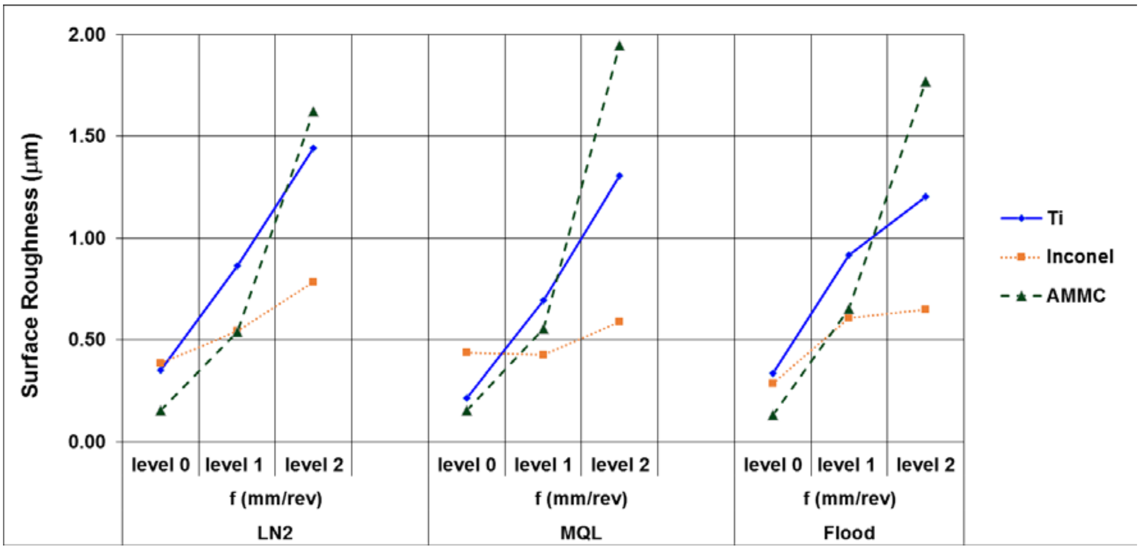


Figure 5.20 Average variation of machine power based on cutting parameters

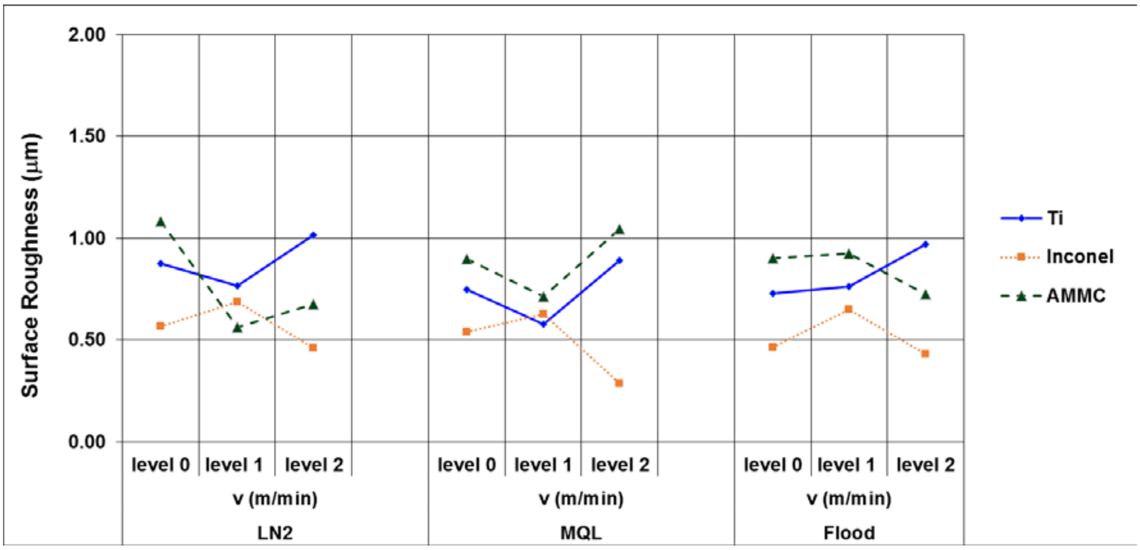
The cooling method was the most dominant factor for the cutting force and machine power requirement, 90.65% and 79.45% respectively (Table 5.11 and Table 5.12). For surface roughness, cryogenic cooling produced the best surface finish followed by flood (Figure 5.16). MQL gave the worst surface finish. However, MQL required the lowest cutting force, closely followed by flood (Figure 5.18). LN_2 need the highest cutting force. The required power of LN_2 and MQL were significantly lower than that of flood (Figure 5.20).

5.5 Conclusions

Figure 5.21 indicates that for the surface roughness, the three cooling methods show similar performances for all test materials. The surface roughness range for Inconel is found to be the narrowest followed by Titanium alloy, while AMMC has the widest range. This confirms earlier findings which reported that it is very difficult to get a good surface finish for AMMC [38, 39].



(a)



(b)

Figure 5.21 Surface roughness based on (a) feed rate and (b) cutting speed

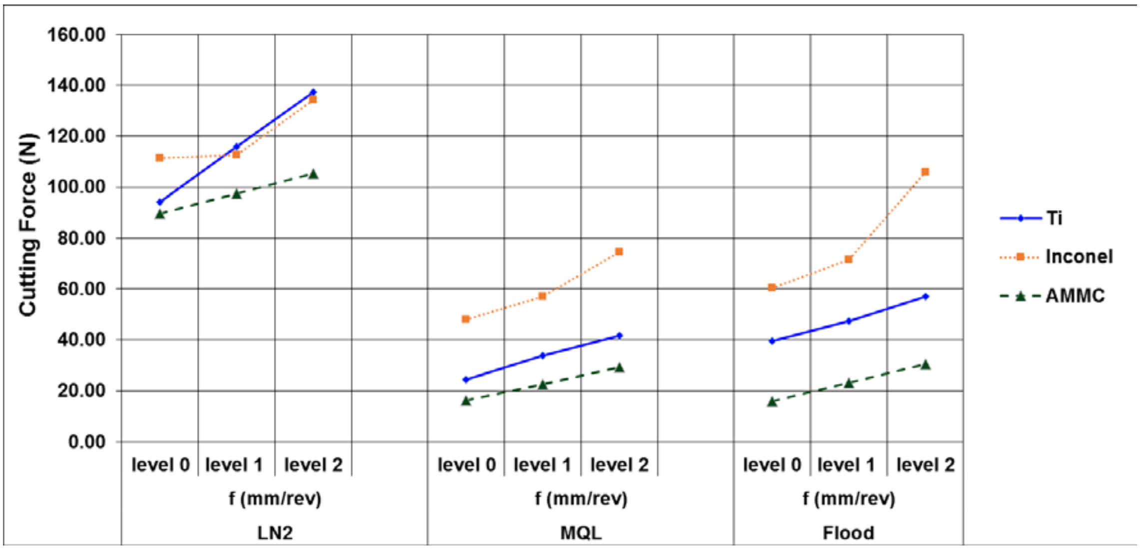
For all cooling methods and all materials the increase in surface roughness is directly proportional to the increase of the feed rate, following the conventional wisdom of machining.

The worst surface roughness for Inconel was produced at medium cutting speeds for any cooling methods. In contrast, for Titanium alloy and AMMC, the medium cutting speeds provide the best surface finish given by LN_2 and MQL. For flood, the best surface roughness of Titanium alloy was obtained at the lowest cutting speed, while the best surface roughness of AMMC was obtained at the highest cutting speed.

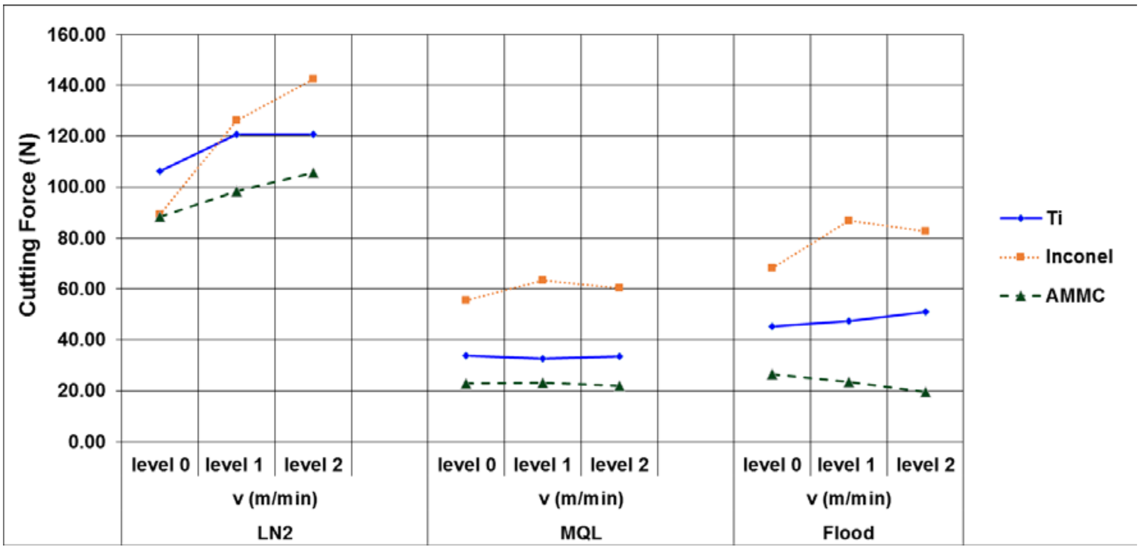
From Figure 5.22 it is observed that LN_2 required a significantly larger cutting force for all materials. It is highly possible that low cutting temperatures caused the workpiece to harden and become more difficult to cut. However, it is quite surprising that Titanium alloy needed more force than Inconel for medium and high feed rate. This case shows that the cooling effect of LN_2 and the chemical reaction of nitrogen with Titanium alloy all play a role in the increase of the cutting force [167, 169]. For both other cooling methods, the Inconel cutting force was higher than the Titanium alloy for all feed rate levels.

For MQL and flood, Inconel requires the greatest power, which makes sense, because Inconel is the hardest material among the three. AMMC needed the lowest cutting force for all cooling methods and for all levels of feed rate and cutting speed.

For Inconel and Titanium, MQL requires a slightly smaller cutting force than that of flood. Especially for AMMC, a similar cutting force was required for both MQL and flood. LN_2 requires the highest cutting force. Inconel is also found to require the greatest cutting force for both MQL and flood application. For LN_2 application, the cutting force for Inconel grew by the increasing of the cutting speed, while for MQL and flood the greatest cutting force was required by medium cutting speed.



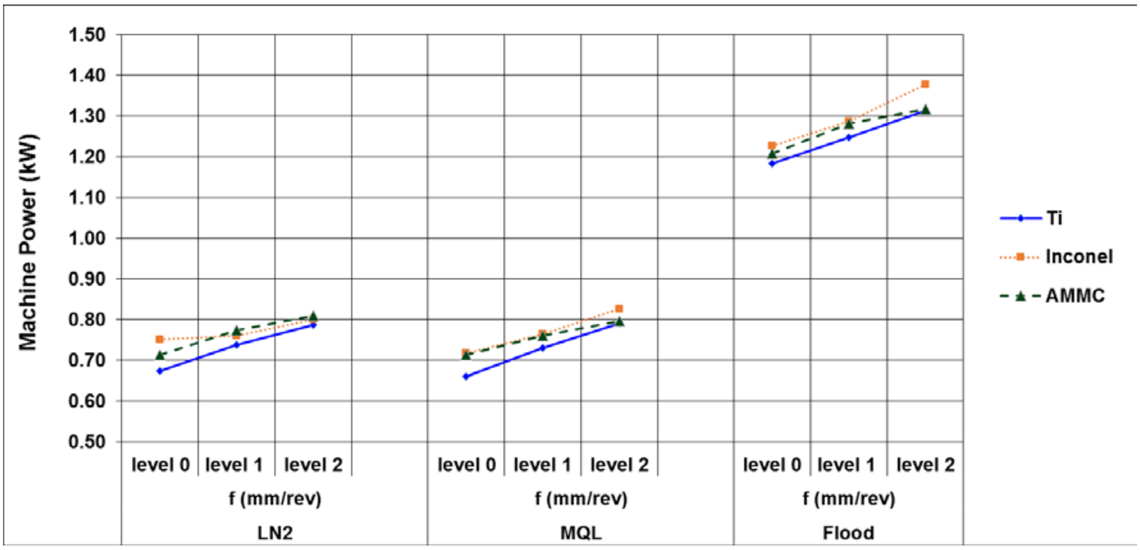
(a)



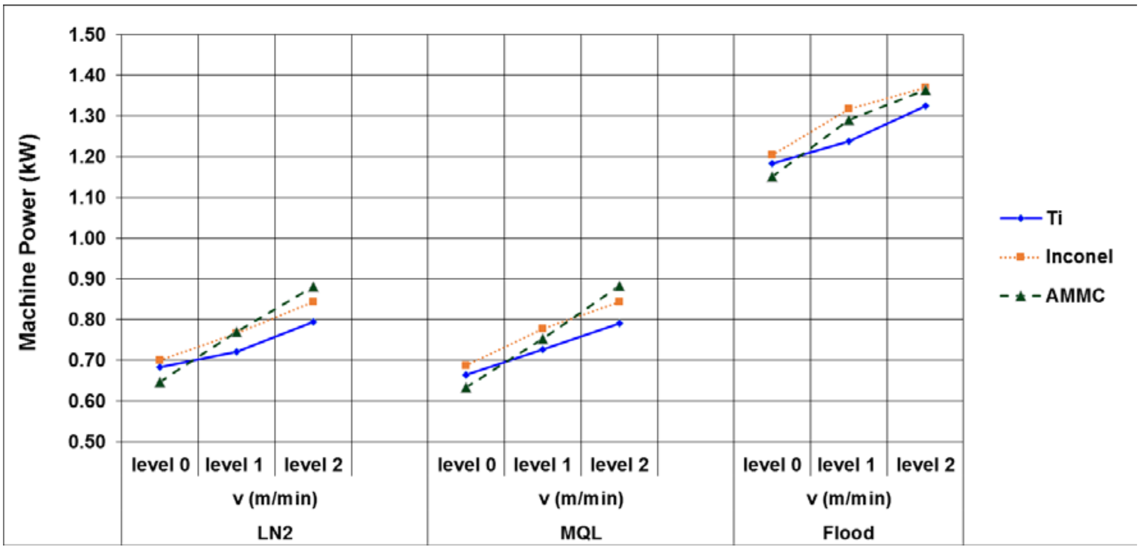
(b)

Figure 5.22 Cutting force based on (a) feed rate and (b) cutting speed

The required machine power for flood is much higher than LN_2 and MQL (Figure 5.23). This difference is mostly due to the power required by the pump to circulate the coolant (approximately 0.4 kW). Machine power for LN_2 and MQL ranges from 0.6 kW - 0.9 kW, whereas for flood it ranges from 1.1 kW - 1.4 kW. There is still a difference of about 0.1 kW when the pump power (0.4 kW) is not included into the calculation. Therefore LN_2 and MQL can be used as the replacement for flood coolant when reducing power is the main priority.



(a)



(b)

Figure 5.23 Machine power requirement based on (a) feed rate and (b) cutting speed

Chapter 6

COOLING METHODS PERFORMANCE ON TOOL LIFE

6.1 Introduction

During the machining process, tool wear is accelerated by the high machining temperature due to the cutting action and the tool friction. Typically, the conventional application of coolant to the cutting processes can decrease the rate of tool wear. Coolant is widely used throughout the world of metal cutting since it has been proven to prolong the tool life by lowering the temperature of the tool interface, while lubricating the contact area of the chips across the top rake face.

As previously discussed, various environmental problems associated with coolant usage make its application in the machining process costly. This is, therefore, one of the drivers that encourage the metal cutting industry to examine ways to reduce the use of coolant as much as possible. For difficult-to-cut materials, tool wear is a more acute challenge, especially if coolant was to be dispensed with. By adjusting machining parameters, such as lowering cutting speed or feed, it is possible to obtain a reasonable tool life. However, a decrease in cutting speed or feed is not entirely satisfactory as it makes the machining process less economical, making it necessary to find a more effective cooling method.

The challenges mentioned above can be solved by finding an alternative cooling method that has near or equivalent ability to conventional coolant to maintain tool life for a reasonable period. In this chapter, the performance of two alternative cooling methods (liquid nitrogen and Minimum Quantity Lubrication), will be compared with conventional coolant in maintaining tool life.

6.2 Test Details

In this experiment 45 tests were conducted with three types of difficult-to-cut materials, i.e., Titanium alloy, Inconel 718 and AMMC, using CoroMill R390-11 T3 31M PM S40T (coated Tungsten Carbide) milling tool tips, which were replaced after each test. Three cooling methods: liquid nitrogen, MQL and flood were used to maintain the rate of tool wear. The machining parameters used for the tests are shown in Table 6.1. A single endmill cutter tool, with a 12 mm diameter was used to produce a slot with 1 mm depth.

Table 6.1 Machining parameters for cooling methods performance tests

Level	Cooling methods	Cutting speed (m/min)	Feed (mm/rev)	Titanium alloy test time (s)	Inconel 718 test time (s)	AMMC test time (s)
1				60	5	60
2				120	10	120
3	LN_2	150	0.1	180	15	180
4				240	20	240
5				300	25	300
1				60	5	60
2				120	10	120
3	MQL	150	0.1	180	15	180
4				240	20	240
5				300	25	300
1				60	5	60
2				120	10	120
3	Flood	150	0.1	180	15	180
4				240	20	240
5				300	25	300

6.3 Result and Discussion

Olympus Microscope BX51M with Olympus Stream Image Analysis Software was used to examine the tool surface and to measure the tool wear of each test. Figure 6.1, Figure 6.2 and Figure 6.3 show the rate of tool wear for each test material cooled with LN_2, MQL or flood.

The figures display the growth of tool wear for 5 level machining processes of each test material. For Titanium alloy and AMMC, machining levels are increased every 60 seconds, while for Inconel it is every 5 seconds. These figures are displayed to show the overall tool wear measurement results, as well as to observe the formation of wear from one level to the next.

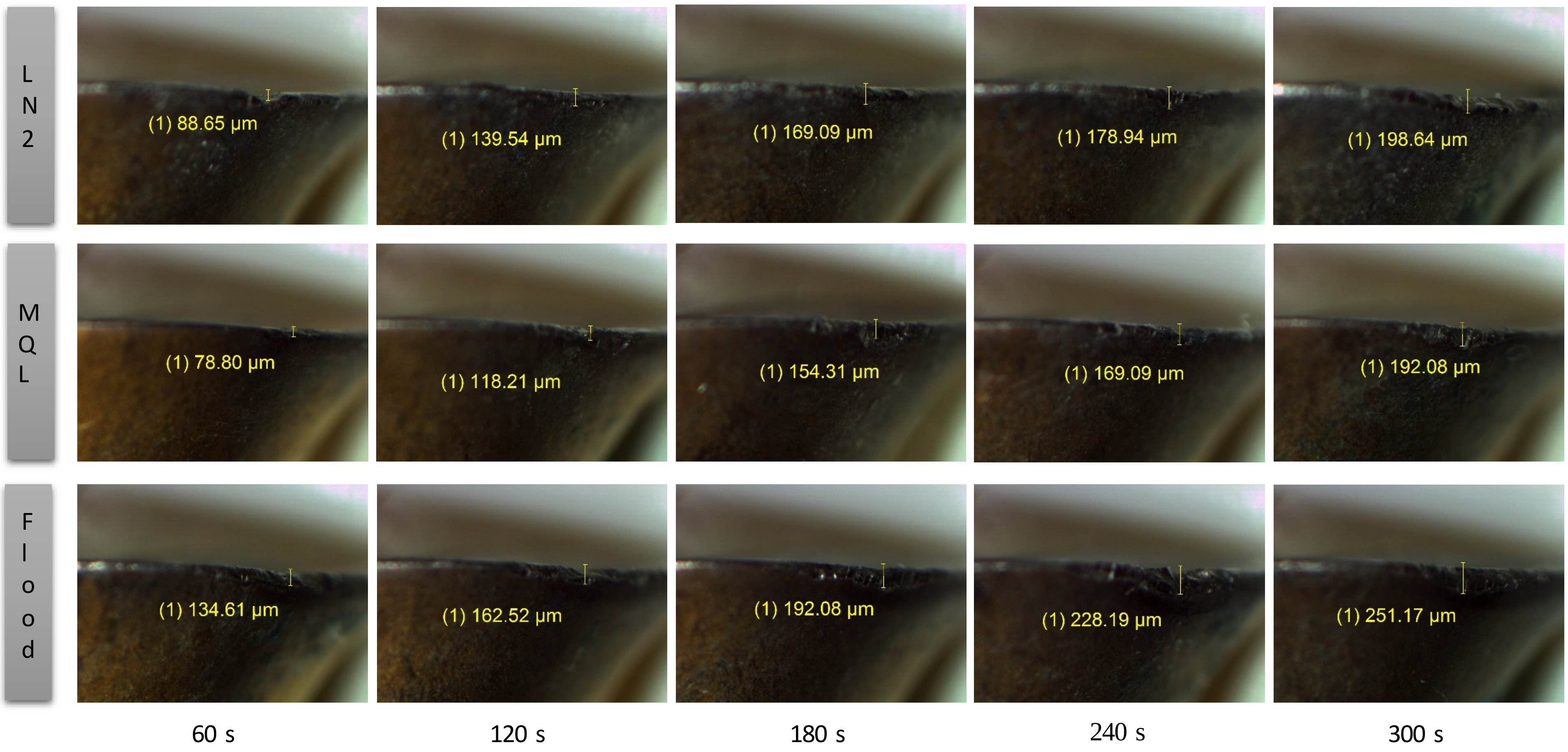


Figure 6.1 Measured flank wear after machining Titanium alloy samples

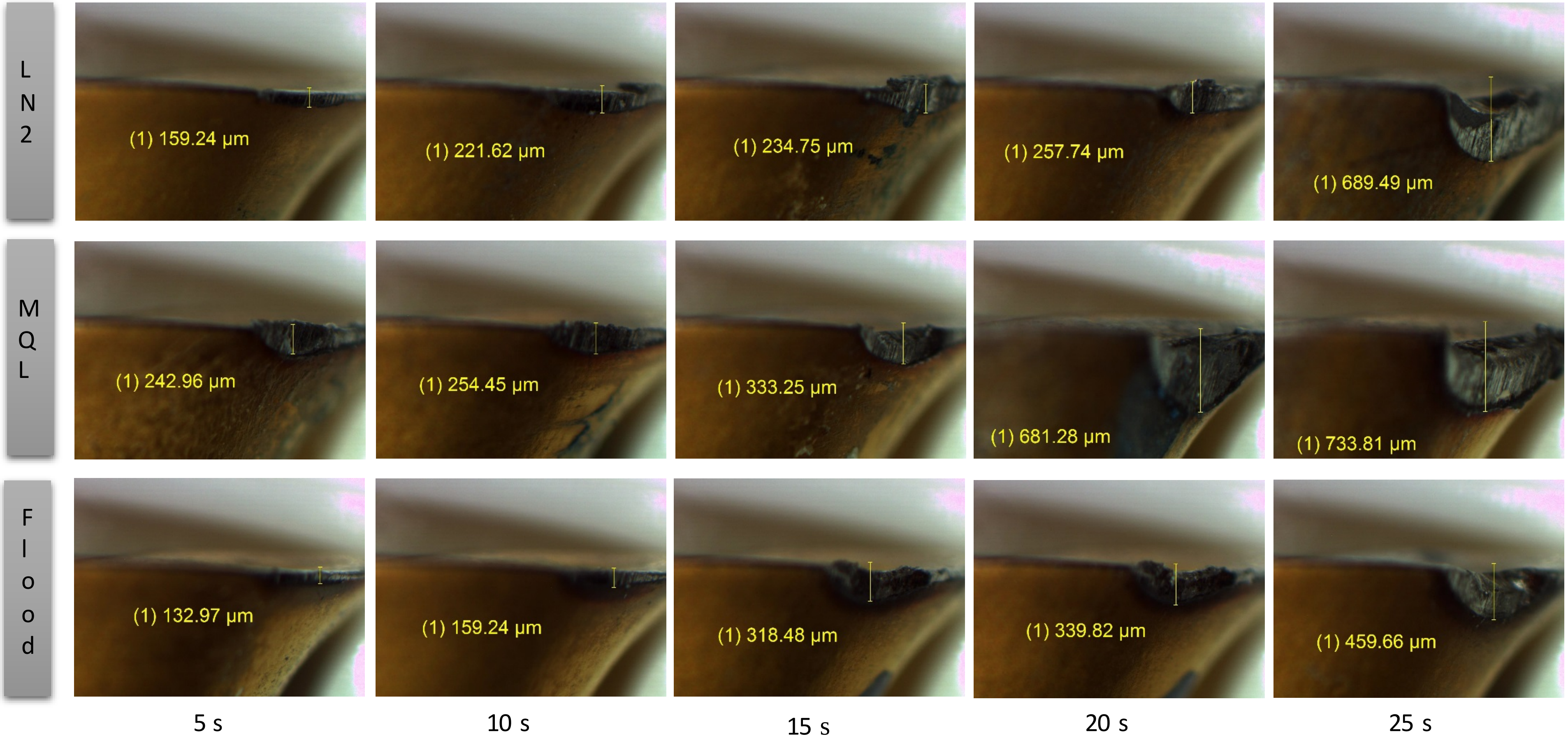


Figure 6.2 Measured flank wear after machining Inconel 718 samples

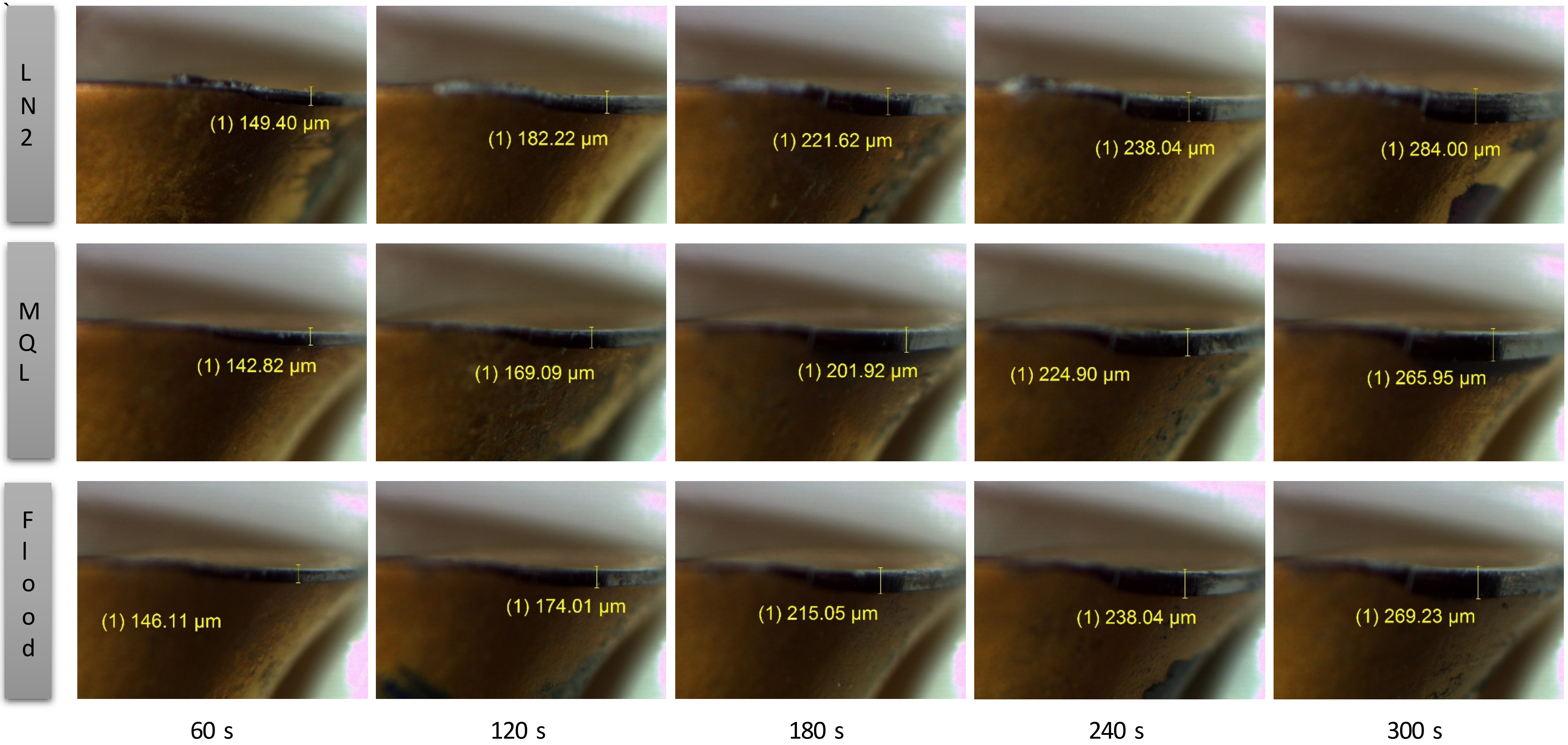


Figure 6.3 Measured flank wear after machining AMMC samples

6.3.1 Tool Wear

As shown in Figure 6.4, compared to LN_2 and flood, MQL was able to provide the best lubrication for Titanium alloy and AMMC since it provides a slightly better tool wear. However, for Inconel cutting, MQL was found to have the worst tool wear.

LN_2 performance was also better than flood for machining Titanium alloy, although flood was better for machining AMMC. Therefore, for machining Titanium alloy and AMMC, MQL and LN_2 have been found to be a suitable alternative in replacing flood if only tool life is considered.

For Inconel, LN_2 can be used as an alternative, since the increase in tool wear is more stable than that of flood. Under MQL application, the tool wears were higher at any level for this material. The MQL lubrication effect does not seem enough to keep the tool from rapid wearing.

For all cooling methods, Inconel machining causes the fastest tool wear. The high speed makes the MQL quantity insufficient to lubricate or cool the machining process. When cutting Inconel, LN_2 and flood are not as effective as when cooling Titanium alloy, the tool wear reaches 200 µm in a very short time (after 10 seconds). This indicates that the cutting speed of 150 m/min is too high for machining Inconel.

The tool wear for AMMC is relatively similar for all cooling methods, whereas MQL gives slightly better results than the other two methods. It was found that the tool wear experienced by AMMC was faster than the Titanium alloy. This is very likely due to the fact that AMMC has reinforcement materials, which makes it more difficult to cut compared to Titanium alloy [73].

By taking the tool wear as a consideration, MQL can be used to replace flood on the cutting process of Titanium alloy and AMMC. LN_2 can also be used instead of flood for Titanium alloy cutting. However, for AMMC cutting, flood is slightly better compared to LN_2.

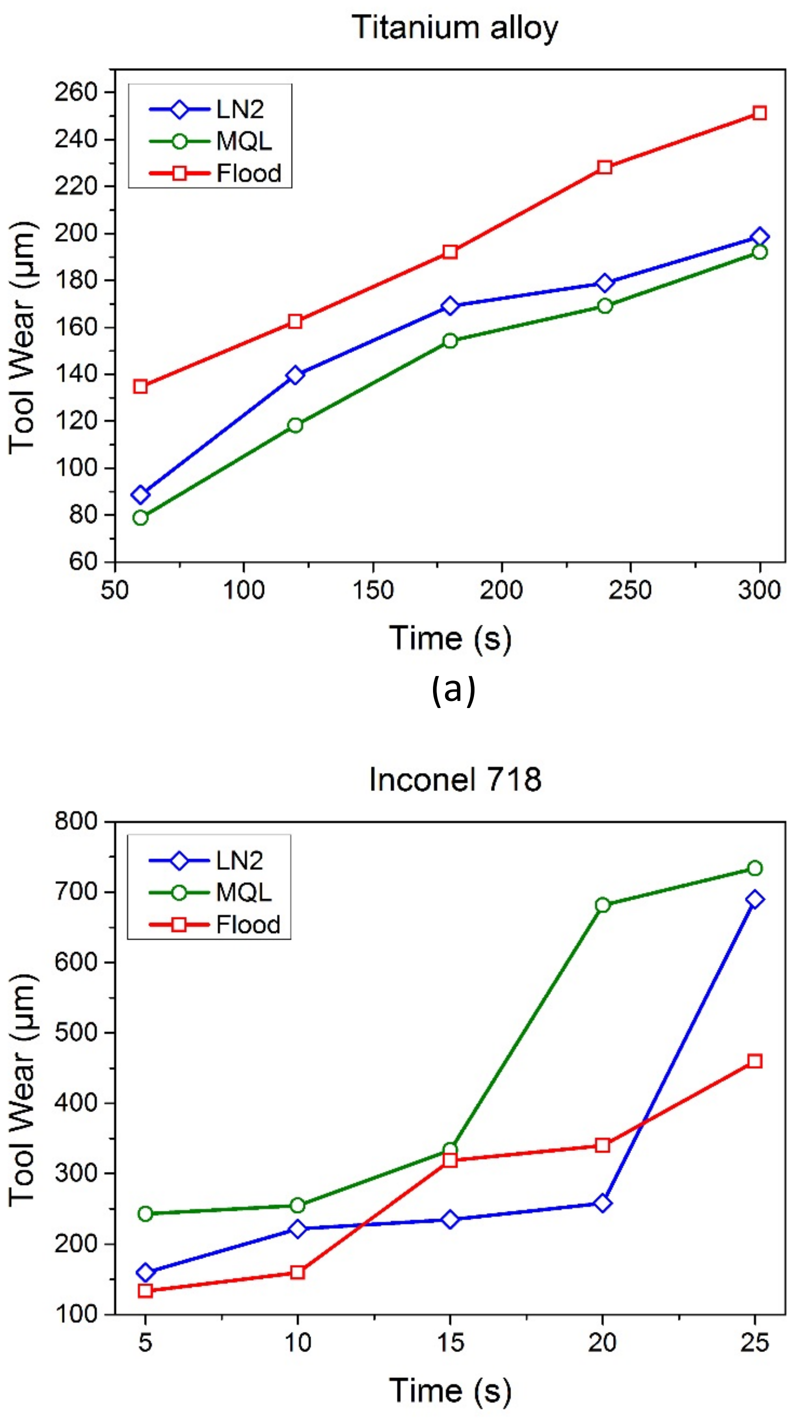
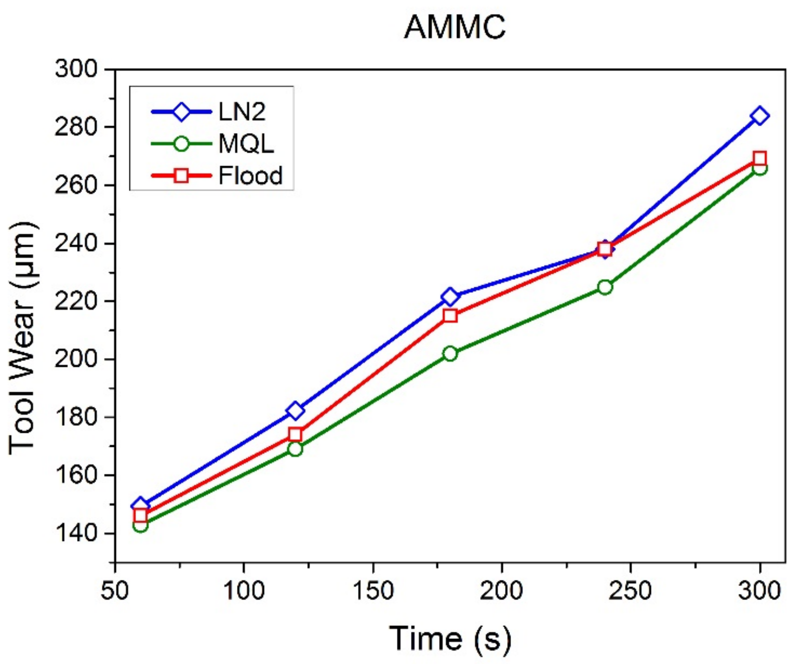


Figure 6.4 Tool wear based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued on the next page)



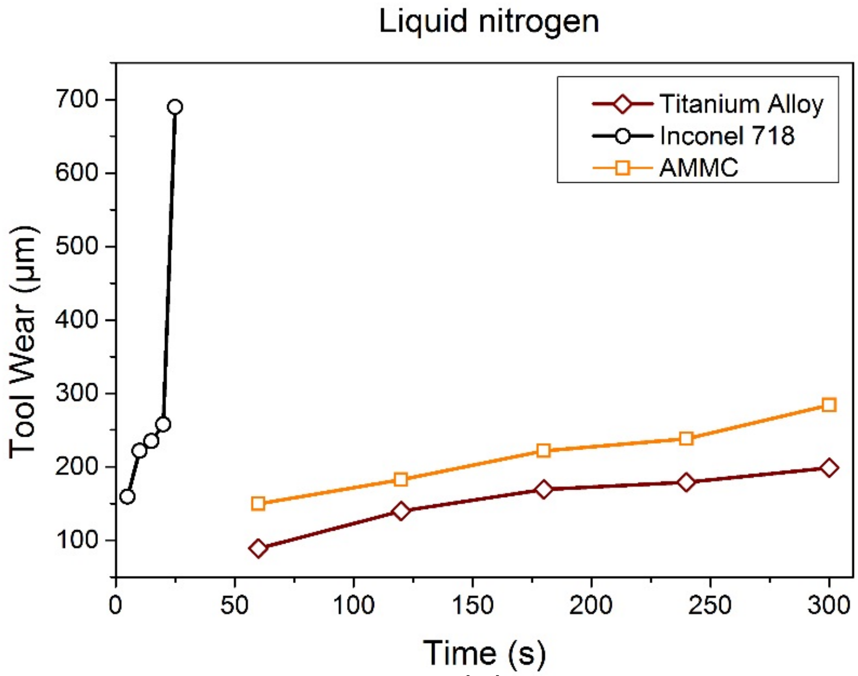
(c)

Figure 6.4 Tool wear based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued from the previous page)

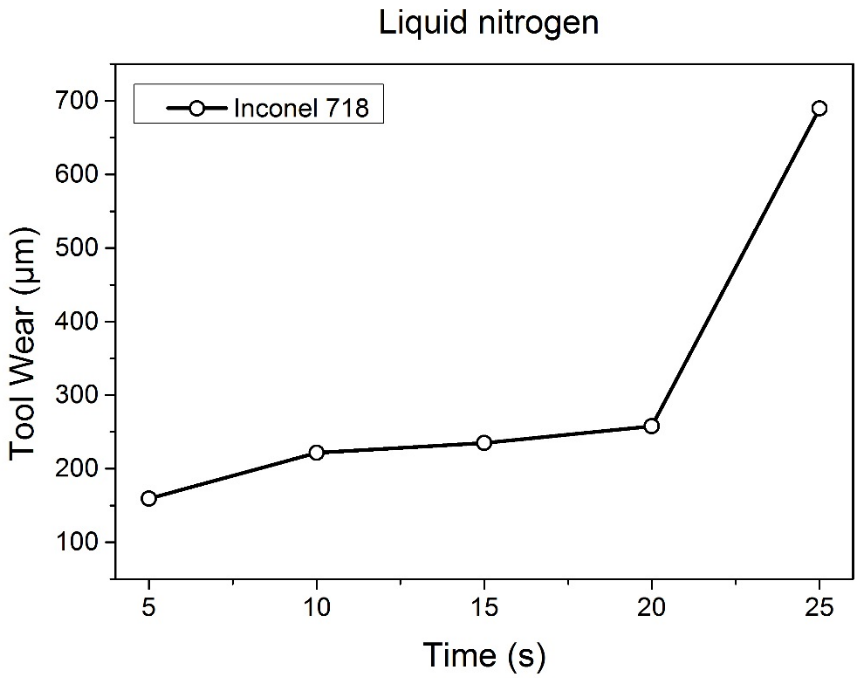
Figure 6.5 to Figure 6.7 show the performance of the cooling methods in reducing tool wear. To show the rate of tool wear more clearly for Inconel machining, a separate chart is given in part b of each figure.

Figure 6.5a shows the performance of liquid nitrogen cooling on all three test materials. It can be seen that the rate of tool wear for Inconel machining was much faster than that of Titanium alloy and AMMC machining. In comparison, within 5 minutes, tool wear for Titanium and AMMC were 198 μm and 284 μm respectively. Whereas for Inconel, tool wear reached 254 μm in just 20 seconds, and even rose drastically to 689 μm after 25 seconds. The rate of tool wear for Inconel machining can be seen separately in Figure 6.5b.

The rate of tool wear for machining Titanium Alloy and AMMC has the same tendency, both gradually increased over time. Liquid nitrogen provides slightly less tool wear for Titanium Alloy (88 μm to 198 μm) compared to AMMC (149 μm to 284 μm).



(a)



(b)

Figure 6.5 Tool wear for liquid nitrogen (a) all materials (b) Inconel 718

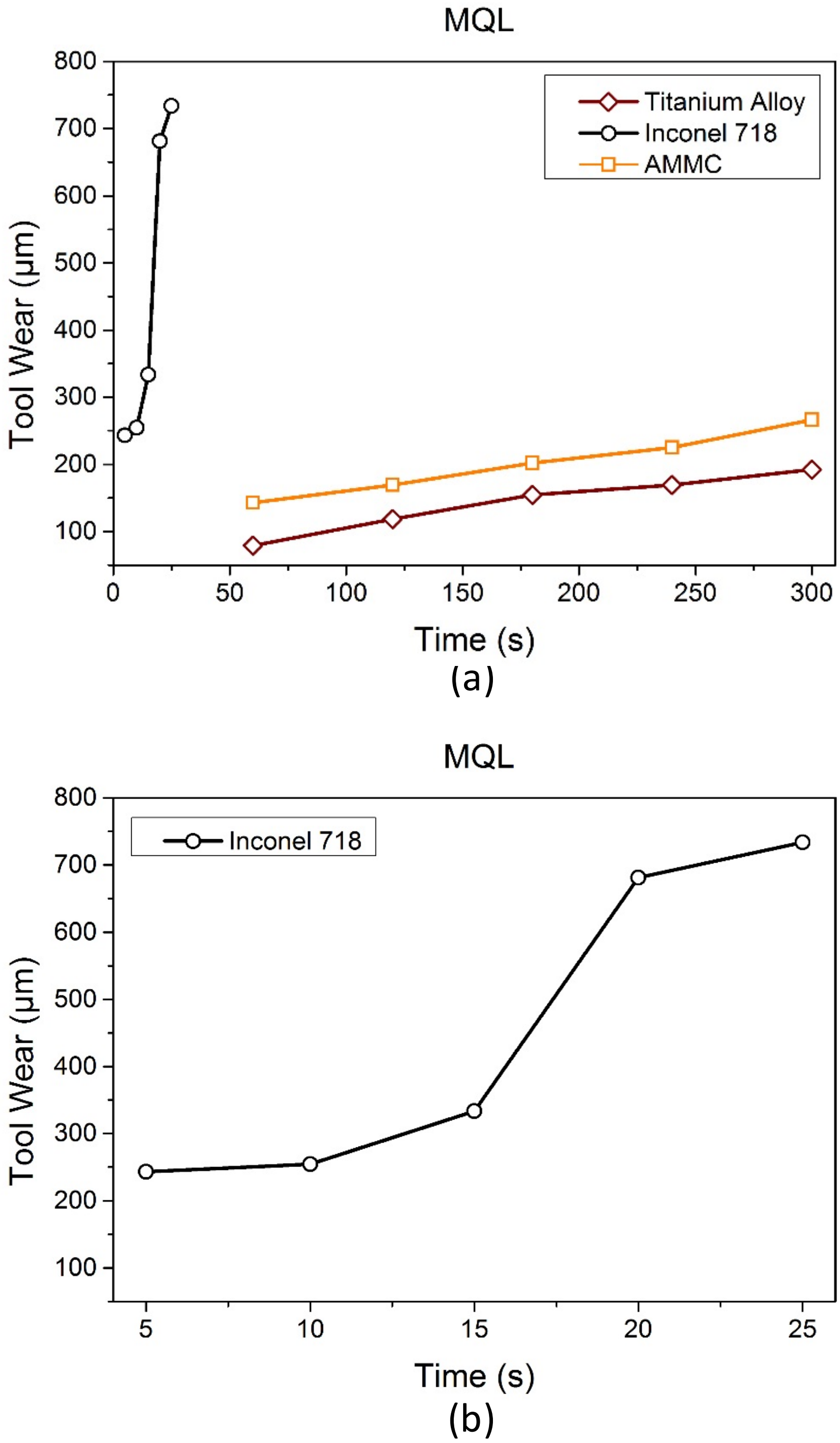


Figure 6.6 Tool wear for MQL (a) all materials (b) Inconel 718

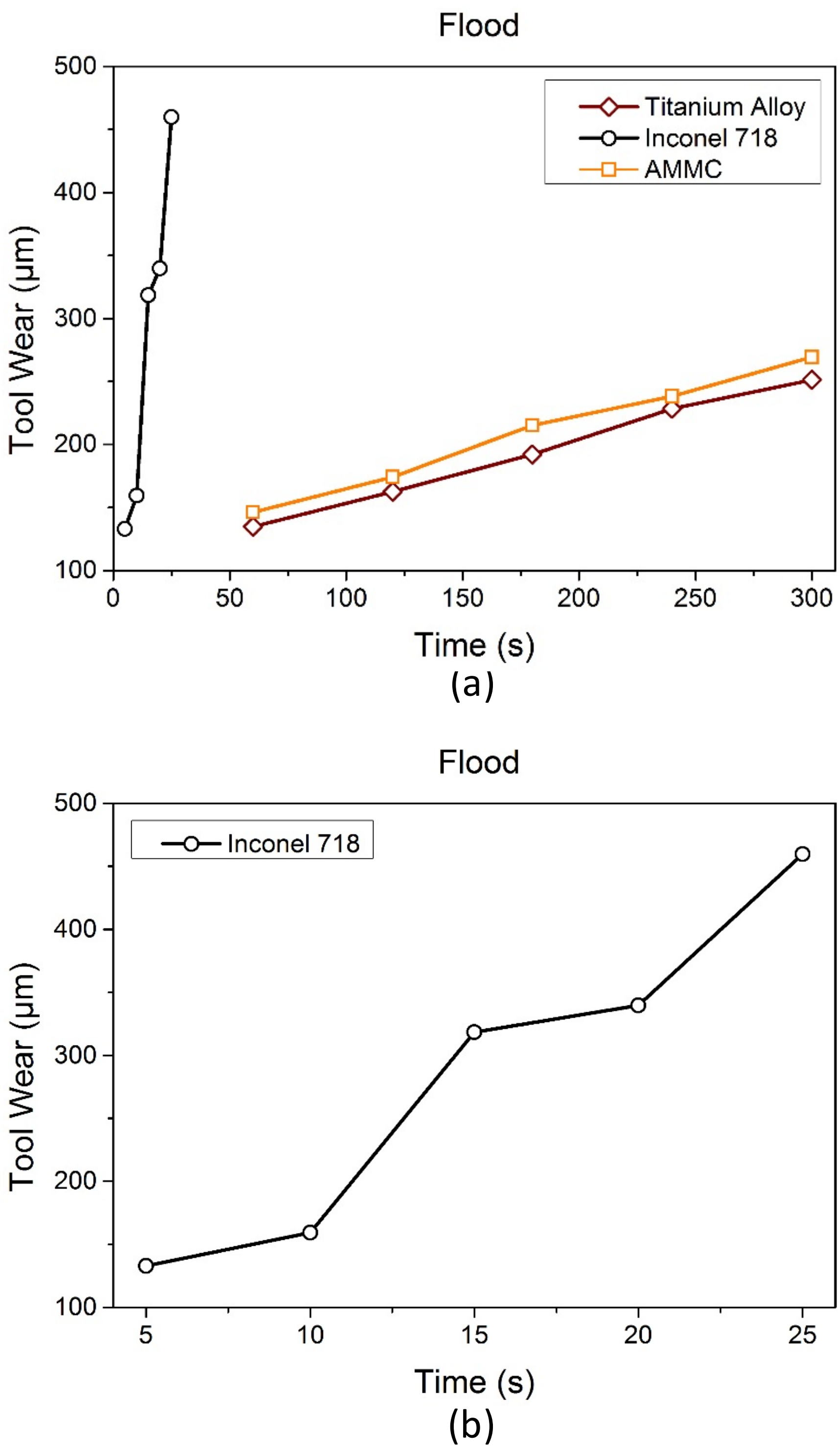


Figure 6.7 Tool wear for flood (a) all materials (b) Inconel 718

For MQL applications in Figure 6.6, the rate of tool wear for Inconel machining also remains higher than the two other materials. The rate of inconel machining tool wear with MQL increased dramatically to 681 µm at 20 seconds, and 733 µm at 25 seconds, worse than LN_2. In the machining of Titanium Alloy and AMMC, the MQL application gave similar results to those shown by LN_2. However, the MQL wear rate was slightly below LN_2 of 78 µm to 192 µm for Titanium alloy, and 142 µm to 265 µm for AMMC.

Figure 6.7 shows that flood gave the lowest tool wear rate for Inconel machining compared to the previous two cooling methods. Tool wear for flood applications started from 132 µm (5 seconds) and reached 459 µm after 25 seconds. From this result it can be seen that flood is the best cooling method for Inconel in terms of tool wear, even though the tool wear reached 459 µm in just 25 seconds. Flood gave the fastest wear rate for Titanium Alloy, with the highest wear rate of 251 µm. For AMMC, tool wear rate for flood was slightly lower than LN_2.

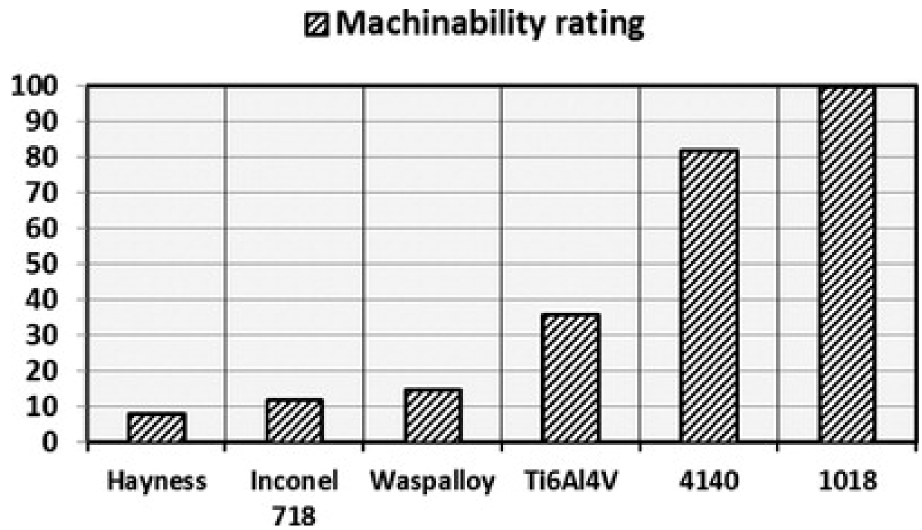


Figure 6.8 Machinability rating of some engineering materials [170, 171]

From the material point of view, it can be seen that Inconel machining caused the highest tool wear for all cooling methods and for any level. Tool wears of Inconel cutting for 25 seconds were higher than that of Titanium alloy or AMMC cutting for 5 minutes. The main reason for these results is, with 46 HRC, Inconel is classified as one of the very hard materials [172]. These results can also be associated to the machinability rating of the Inconel 718, which is significantly lower than that of the Titanium alloy (Figure 6.8).

Tools experience the lowest wear when cutting Titanium alloys with all cooling methods at any level. Therefore, MQL was the most effective cooling method for Titanium alloy and AMMC, but worst for Inconel.

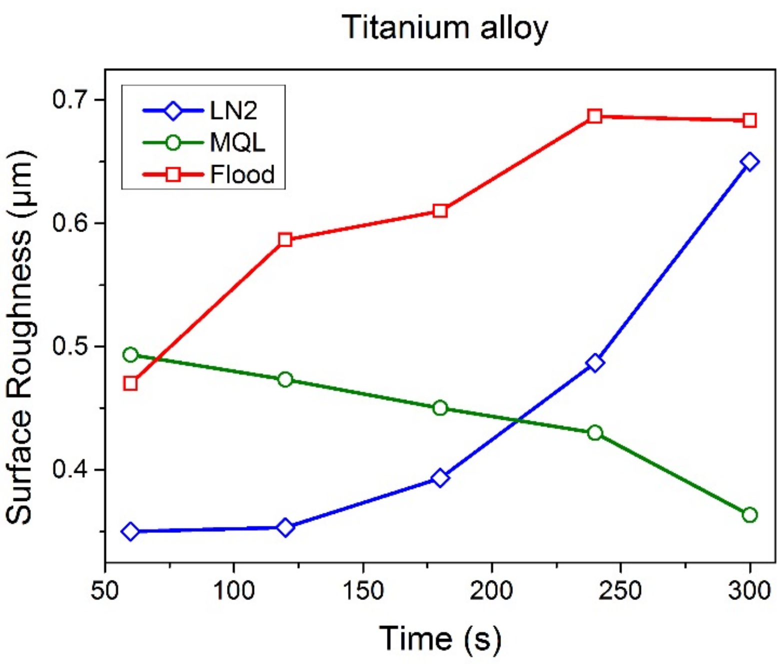
6.3.2 Surface Roughness

Figure 6.9 provides information on the surface roughness values of Titanium Alloy, Inconel 718, and AMCC based on workpiece materials. For Titanium alloy, MQL was found to be the most effective cooling method since its surface roughness steadily decreased over time (started from 0.47 µm). Liquid nitrogen actually gave a good finish for Titanium at the beginning (started from 0.35 µm); however, after 3 minutes machining, the surface roughness value produced by MQL overtake that of liquid nitrogen. Higher workpiece temperature and better lubrication were the most likely reasons of the improving of MQL results.

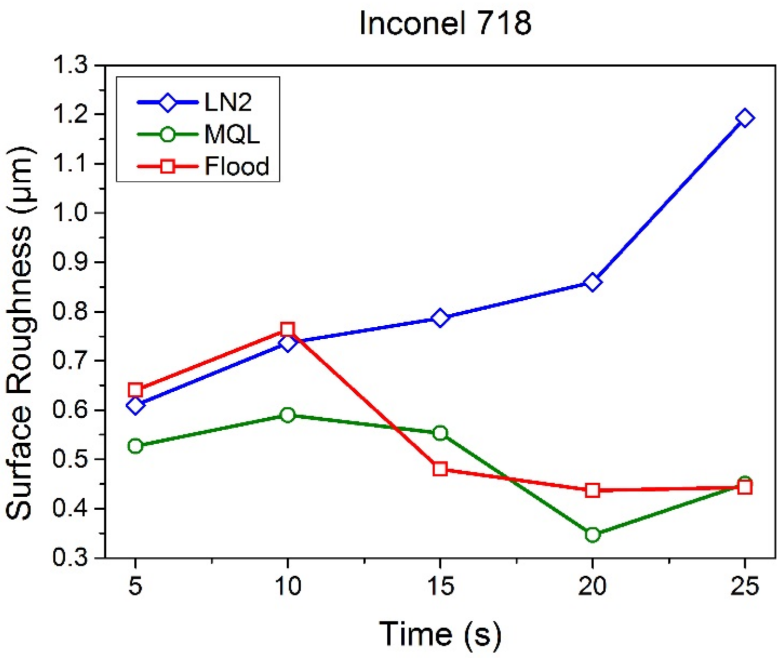
MQL was also found as effective cooling for Inconel, followed by flood. This result shows that for Inconel, lubrication is important for a good finish. The LN_2 cooling effect seems incapable of reducing the surface roughness that reached 1.2 µm within 25 minutes, much higher compared to surface roughness for MQL and flood, with 0.45 µm and 0.44 µm, respectively.

Flood was the most reliable cooling for AMMC since it can keep the surface roughness value of 0.31 µm after 5 minutes. Surface roughness for MQL increased significantly after 3 minutes and reached 0.68 µm at the end. It seems AMMC needs the constant volume of flood coolant more than lubrication effect of MQL, especially when the machining temperature increased.

This study revealed that MQL was the most reliable cooling for Titanium alloy and Inconel. However, MQL was the worst cooling method for AMMC, especially after 3 minutes machining. Flood cooling produced the worst surface finish for Titanium alloy, but it is the most effective cooling for AMMC.

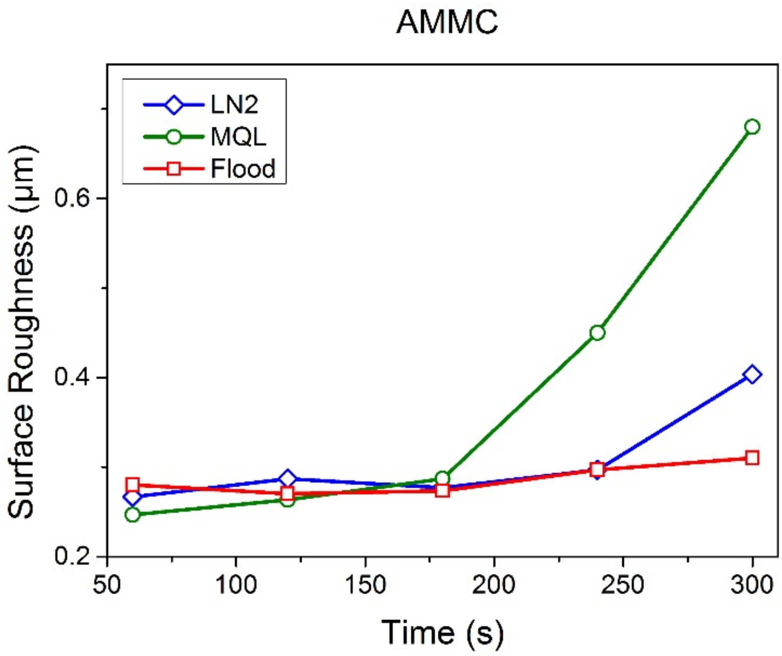


(a)



(b)

Figure 6.9 Surface roughness based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued on the next page)

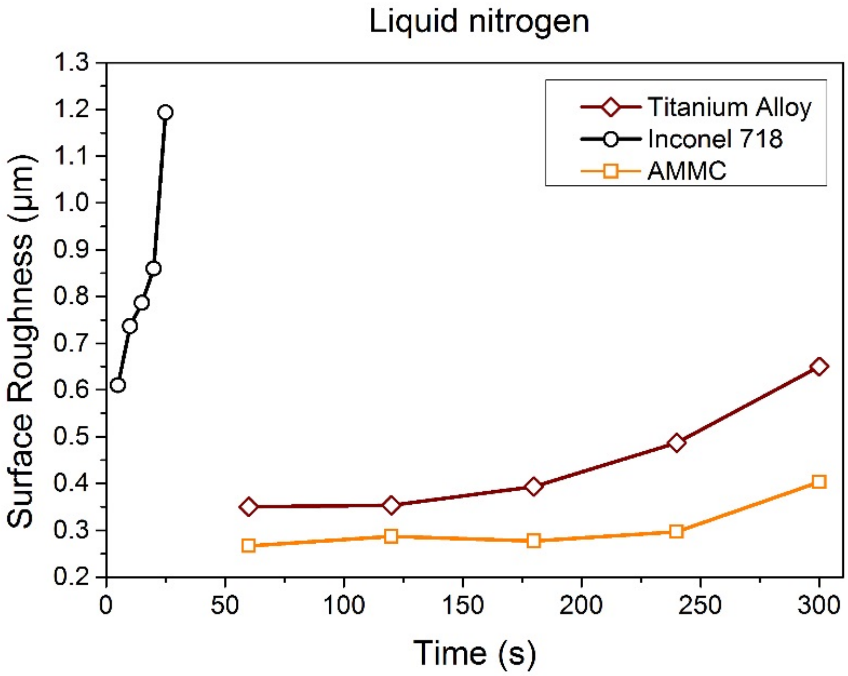


(c)

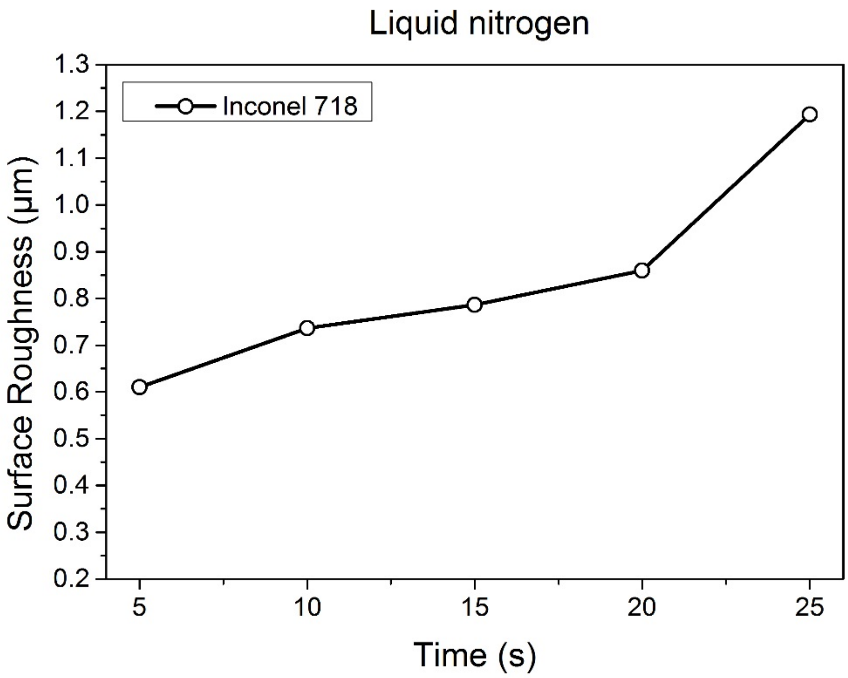
Figure 6.9 Surface roughness based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued from the previous page)

Figure 6.10 to Figure 6.12 show the performance of the cooling methods on surface finish for each test material. From Figure 6.10 it can be clearly seen that under liquid nitrogen, AMMC has the best surface finish. Starting with 0.26 µm at level 1 there was a slight fluctuation, ending with the value of 0.4 µm at level 5. Titanium Alloy followed with the surface roughness of 0.35 µm at level 1, and then slowly increased to 0.65 µm at level 5. Liquid nitrogen gave the worst surface roughness for Inconel, starting with 0.61 µm at level 1 and then rising drastically to 1.2 µm at level 5.

MQL cooling at the beginning produced an excellent finish for AMMC compared to Titanium alloy and Inconel (Figure 6.11). Then it shows a downward trend for AMMC, while there is an improving trend for both Titanium alloy and Inconel. Surface roughness of Titanium alloy steadily reduced over time, showing that a slightly worn tool gave a better finish for this material [173]. Further investigation is needed to determine when the surface roughness will start to increase as a result of tool wear.

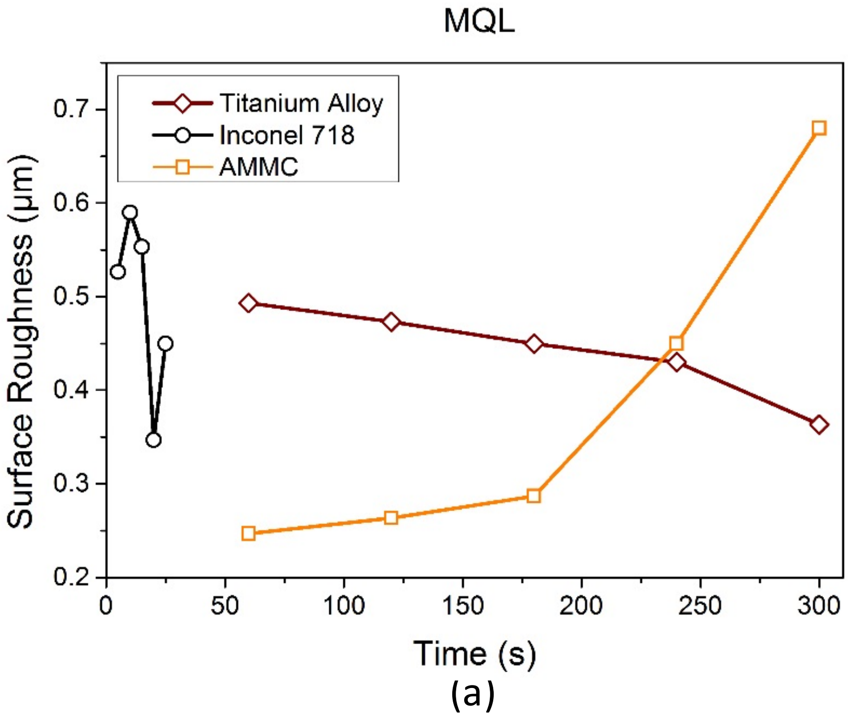


(a)



(b)

Figure 6.10 Surface roughness for liquid nitrogen (a) all materials (b) Inconel 718



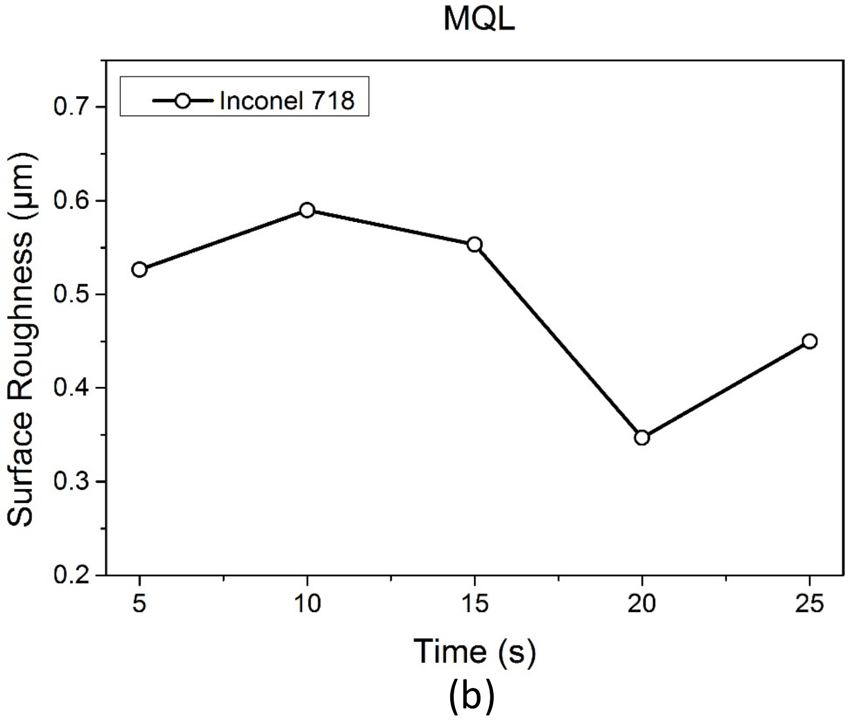
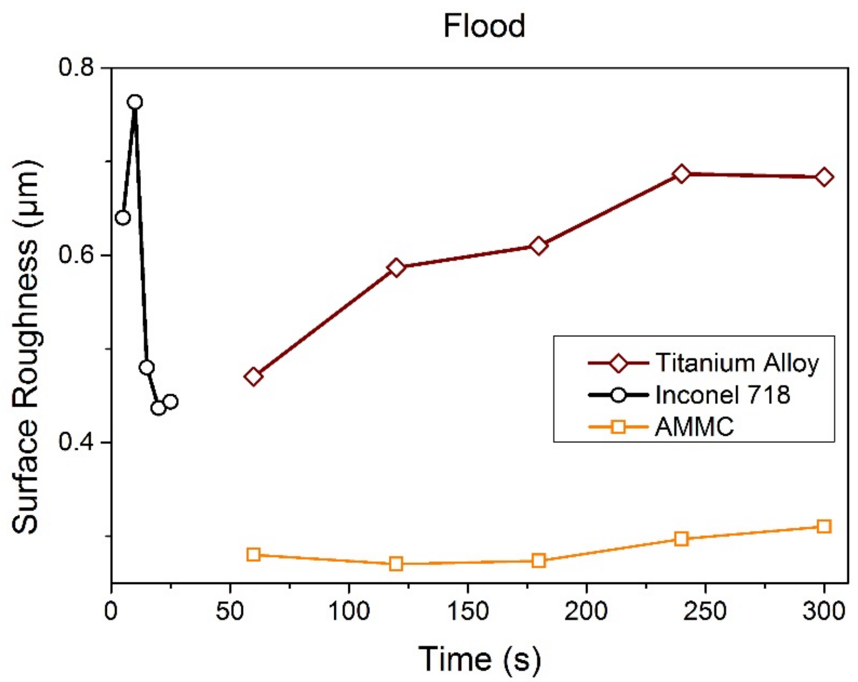
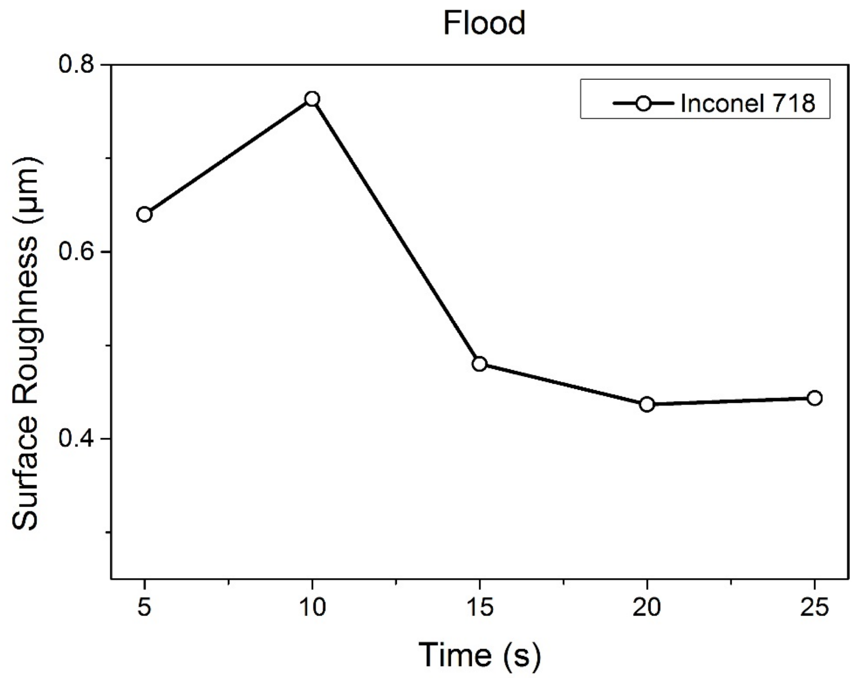


Figure 6.11 Surface roughness for MQL (a) all materials (b) Inconel 718



(a)



(b)

Figure 6.12 Surface roughness for flood (a) all materials (b) Inconel 718

For Inconel, surface roughness produced by LN_2 was increasing rapidly, while for MQL and flood, improvement occurred after the second level. These results illustrate that Inconel machining requires lubrication effects more (provided by MQL and flood), compared to the cooling effects of LN_2.

For AMMC, flood gave the best surface finish (0.28 μm steadily raised to 0.31 μm), followed by liquid nitrogen. Under MQL cooling, the surface finish raised after the third level and became the highest at the fifth level (0.68 μm). This shows that AMMC machining needs a lower temperature more than lubrication effects.

The surface roughness of Titanium alloy under LN_2 and flood increased proportionally to time. Flood cooling produced the worst surface finish for Titanium alloy, while MQL cooling produced a better finish with the passage of time. These results indicate that the MQL lubrication effect plays an important role in producing a good surface finish for Titanium alloy.

6.3.3 Machine power requirement

From the power requirement (Figure 6.13), MQL required the lowest power for Titanium alloy machining, which was less than 0.9 kW at level 5. The power requirement for cryogenic cooling was slightly higher, fluctuating around 0.9 kW for all level. For AMMC, the three cooling methods have the same trend, the power requirement increases gradually over time. Similarly, for Titanium alloy, LN_2 requires a slightly higher power than MQL, which requires the lowest power. Flood requires much higher power, 1.32 kW at level 1 and 1.41 kW at level 5 compared to MQL, 0.83 kW and 0.92 kW for the same levels.

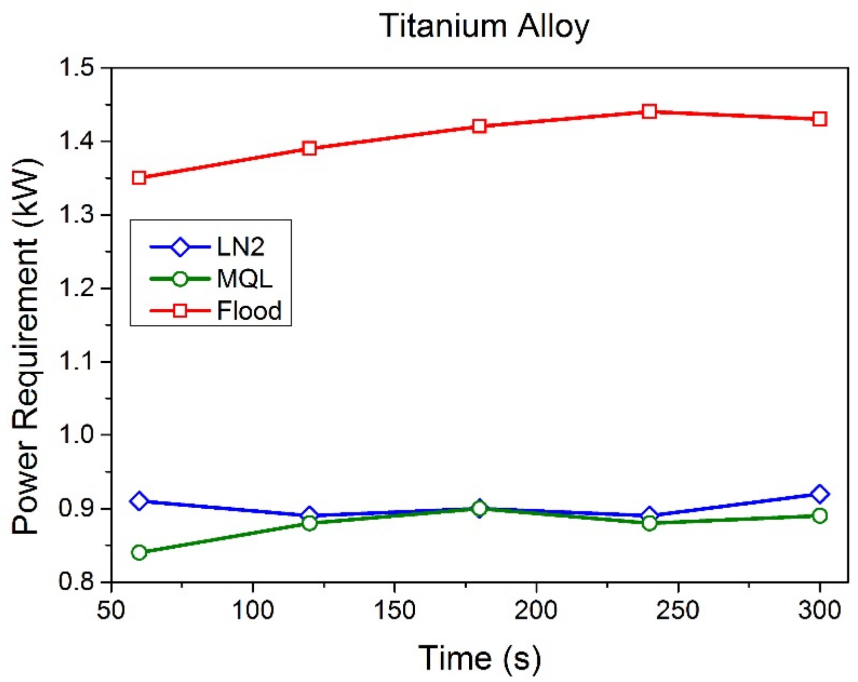
As for Inconel 718, MQL and LN_2 required the same power at level 5, which is 1.1 kW. Flood required significantly higher power, compared to that of the other two cooling methods. At level 1 flood power requirement was 1.35 kW and then increased steadily to 1.4 kW at level 5. It is obvious that for all test materials, the required powers for both MQL and LN_2 were similar and much lower than that of flood. Therefore, in terms of test materials, both LN_2 and MQL can be used as alternative cooling methods to reduce machine power requirements.

The power requirement for AMMC cutting for liquid nitrogen increased over time. This was most likely caused by the tool wear, which also occurred gradually due to the contact with the reinforcement particles contained in the AMMC [72, 73]. MQL power requirements were slightly lower than liquid nitrogen with the same trend, indicating that the increased power due to the tool wear was slightly compensated by the lubrication effects provided by MQL. The power requirements for flood cooling applications on AMMC cutting were similar to that of Titanium alloys, ranging from 1.32 kW at level 1 to 1.41 kW at level 5.

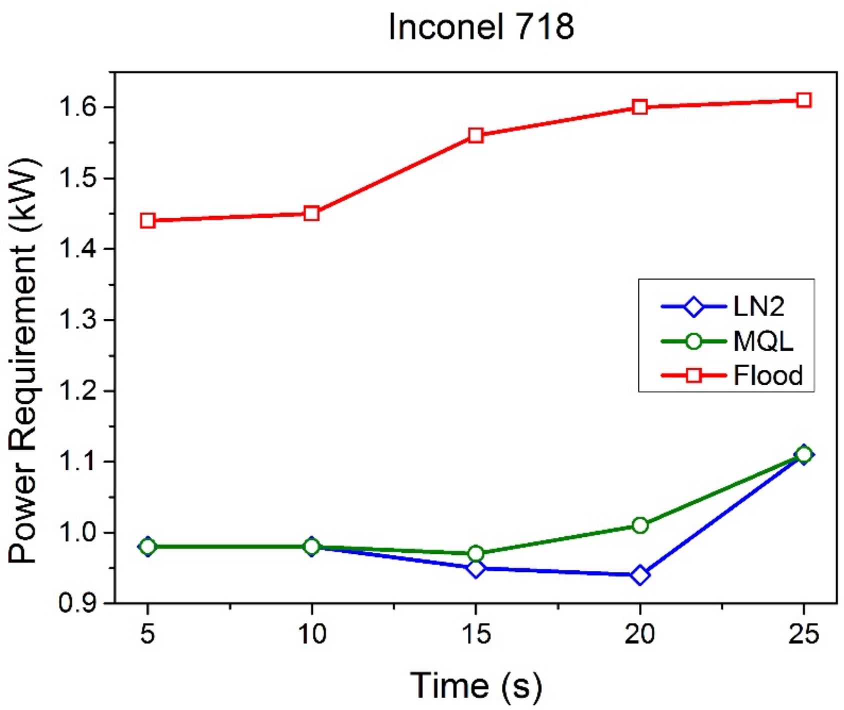
Inconel required the highest power for liquid nitrogen applications (Figure 6.14). The power requirement peaks after 20 seconds. This drastic increase (in excess of 1.1 kW) was due to the rise of the bluntness of the tool tip. The power requirement for AMMC increased over time. This is most likely caused by gradual wear of the tool due to abrasive effect of AMMC particle reinforcement [174, 175]. For Titanium alloy, power requirements fluctuate around 0.9 kW.

For MQL applications, Inconel also required the highest power compared to the other two materials (Figure 6.15). The drastic increase even occurs earlier (after 15 seconds), indicating that MQL lubrication is ineffective in decreasing the power requirement to cut Inconel. AMMC power requirements also increased over time.

Power requirements for Inconel were instantly increased after 10 seconds, and reached 1.61 kW when the flood was used as a coolant (Figure 6.16). AMMC power requirements trend for flood application were similar to liquid nitrogen and MQL applications, 1.32 kW in the first minute and 1.41 on the 5th minute. The required power of the Titanium alloy under flood cooling was slightly above that of AMMC for each level.

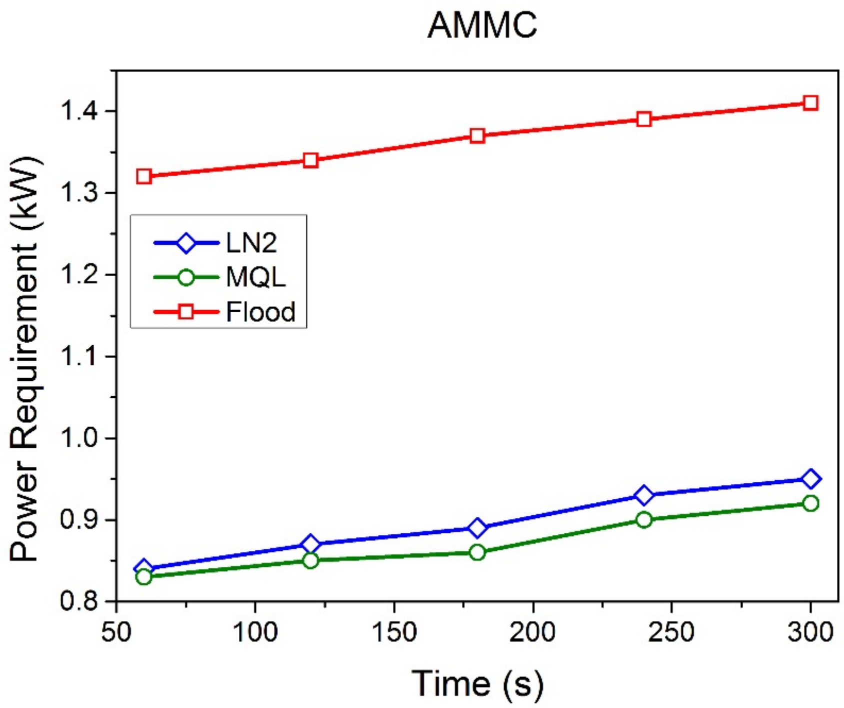


(a)



(b)

Figure 6.13 Power requirement based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued on the next page)



(c)

Figure 6.13 Power requirement based on workpiece materials (a) Titanium Alloy (b) Inconel 718 (c) AMMC (continued from the previous page)

From Figure 6.14 - Figure 6.16, it is apparent that Inconel requires much greater power than that of Titanium alloy and AMMC. Flood needs the greatest power among the three cooling methods, mostly caused by the pump power for circulating the coolant. The range of required power for Inconel was between 0.9 – 1.1 kW when LN_2 and MQL were applied, for flood it was 1.4 – 1.6 kW. The average power requirements for Titanium alloy and AMMC were similar under LN_2 and MQL. Titanium alloy power requirement was slightly above AMMC when flood was applied as a coolant.

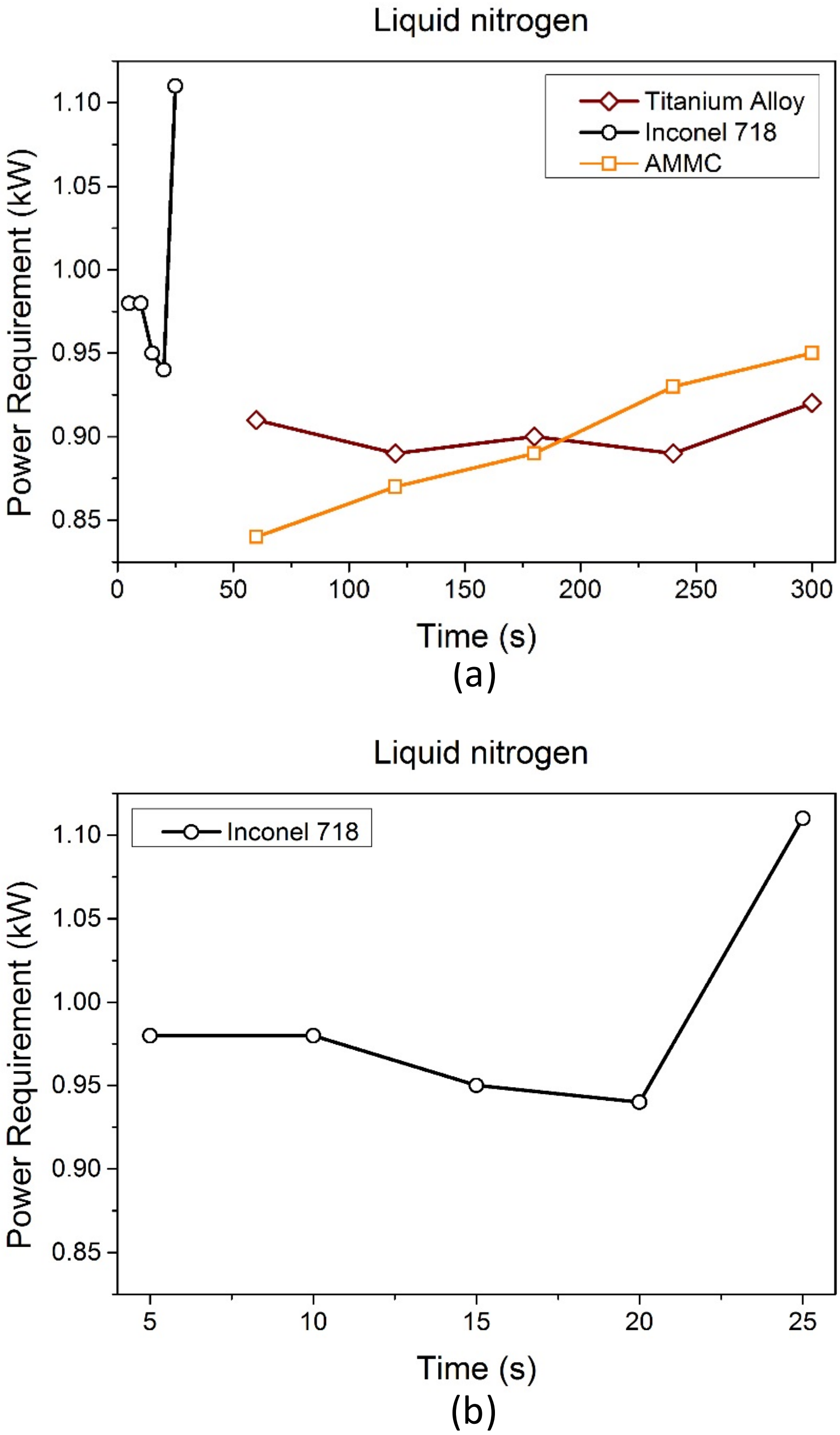


Figure 6.14 Power requirement for liquid nitrogen (a) all materials (b) Inconel 718

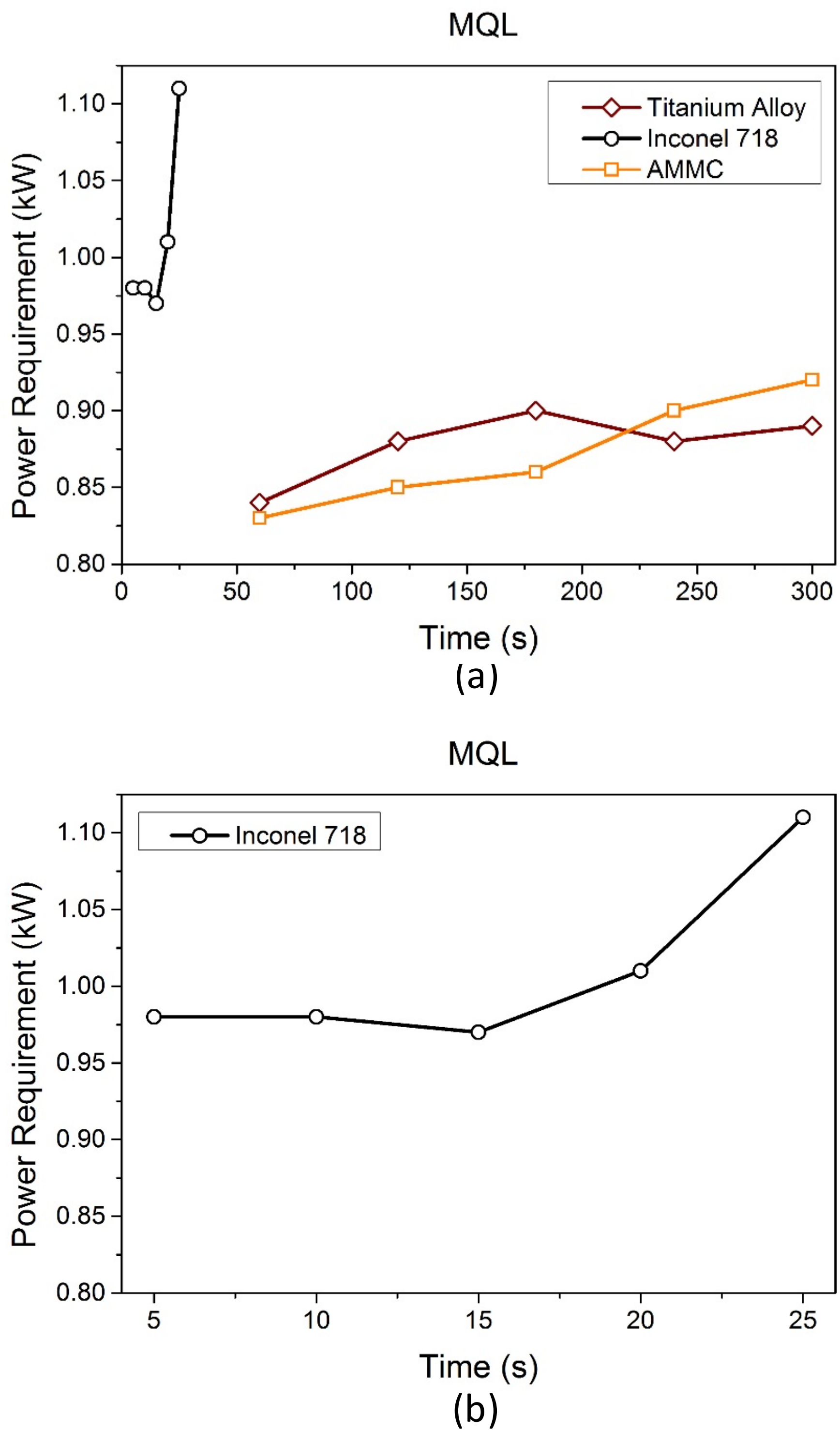


Figure 6.15 Power requirement for MQL (a) all materials (b) Inconel 718

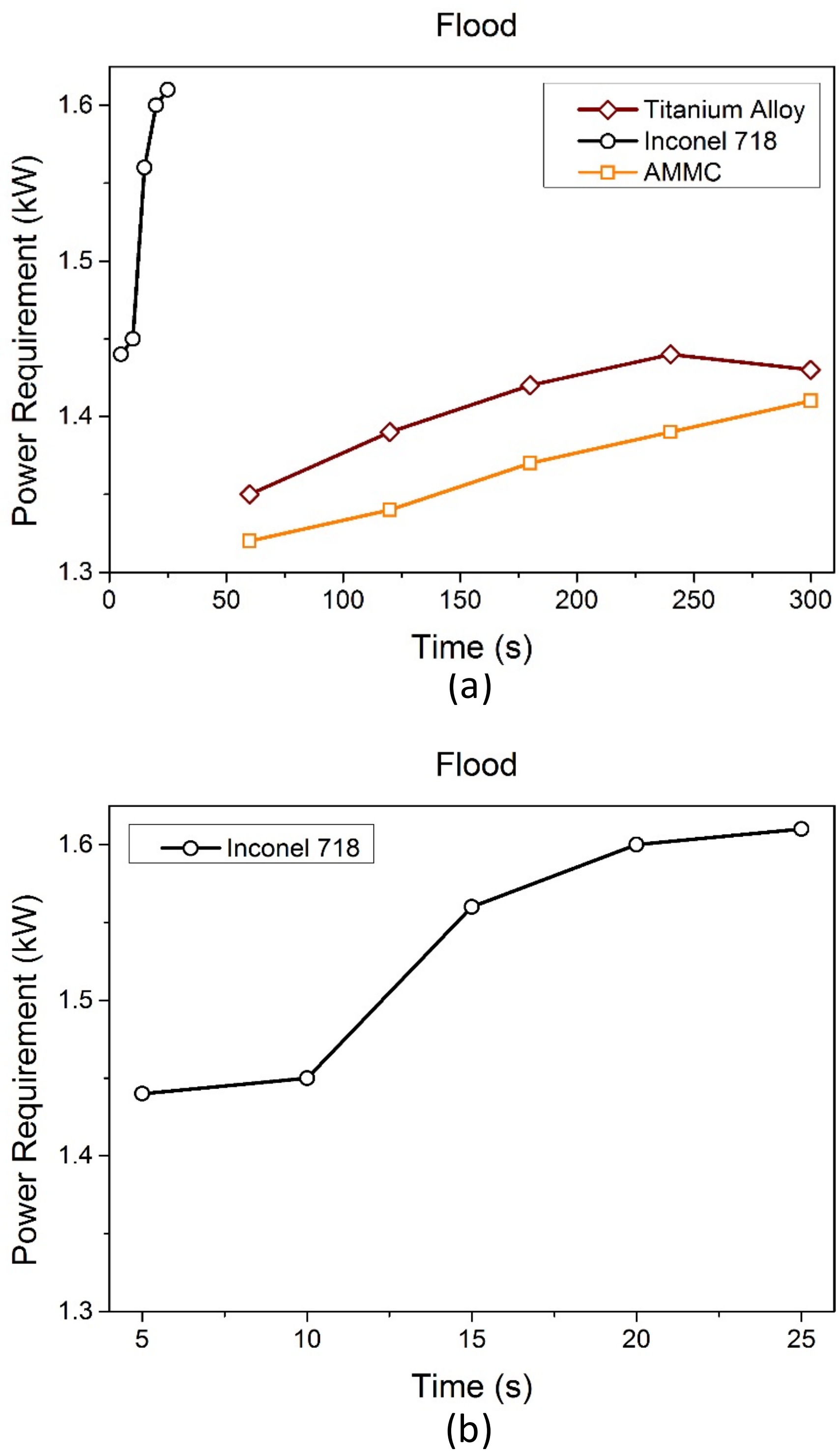


Figure 6.16 Power requirement for flood (a) all materials (b) Inconel 718

6.3.4 Tool wear prediction model for Titanium alloy

Multivariable regression analysis was conducted to compare the performance of the three cooling methods and to develop a mathematical model. Since the cooling methods data are categorical, the flood was used as a reference and the other two cooling methods were used as dummy parameters (Table 6.2). Machining time (t) which is a crucial factor for the tool life, was used as a dependent variable in this model as the test level. The regression process was performed with SPSS to generate the dependent variables coefficients as shown in Table 6.3.

Table 6.2 Titanium alloy categorical data with flood as reference

Cooling Method	Time (s)	LN_2 Dummy	MQL Dummy	Tool Wear (µm)
1 (LN_2)	60	1	0	88.65
1 (LN_2)	120	1	0	139.54
1 (LN_2)	180	1	0	169.09
1 (LN_2)	240	1	0	178.94
1 (LN_2)	300	1	0	198.64
2 (MQL)	60	0	1	78.80
2 (MQL)	120	0	1	118.21
2 (MQL)	180	0	1	154.31
2 (MQL)	240	0	1	169.09
2 (MQL)	300	0	1	192.08
3 (Flood)	60	0	0	134.61
3 (Flood)	120	0	0	162.52
3 (Flood)	180	0	0	192.08
3 (Flood)	240	0	0	228.19
3 (Flood)	300	0	0	251.17

Table 6.3 Coefficients of tool wear for Titanium alloy

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	110.153	6.584		16.729	0.000
Time	0.464	0.028	0.861	16.384	0.000
LN_2 Dummy	-38.742	5.889	-0.399	-6.578	0.000
MQL Dummy	-51.216	5.889	-0.528	-8.696	0.000

From Table 6.3 above, an equation to predict the tool wear to be produced by each cooling method can be established. With the R squared (goodness of fit of a model) value of 0.970, this indicates that the model can be used effectively to predict the tool wear. This model is a good model to be accepted.

$$Tw_F = 0.464t + 110.153\ (\mu m) \tag{6.1}$$

$$Tw_N = 0.464t + 110.153 - 38.742\ (\mu m) = 0.464t + 71.411\ (\mu m) \tag{6.2}$$

$$Tw_M = 0.464t + 110.153 - 51.216\ (\mu m) = 0.464t + 58.937\ (\mu m) \tag{6.3}$$

Where:

Tw_F = Tool wear under flood (µm),

Tw_N = Tool wear under liquid nitrogen (µm),

Tw_M = Tool wear under MQL (µm), and

t = cutting time (s)

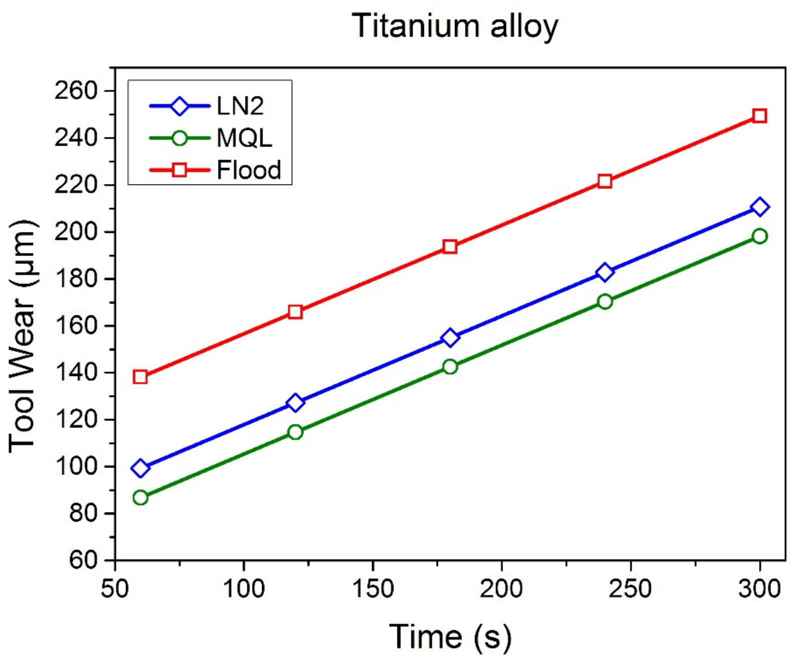


Figure 6.17 Cooling methods predicted performance on tool wear for Titanium alloy

Figure 6.18 shows the comparison of the actual tool wear with tool wear produced from the model for Titanium alloy machining. It is clearly seen that for the three cooling methods, the predicted values produced by the model are very close to the actual machining values.

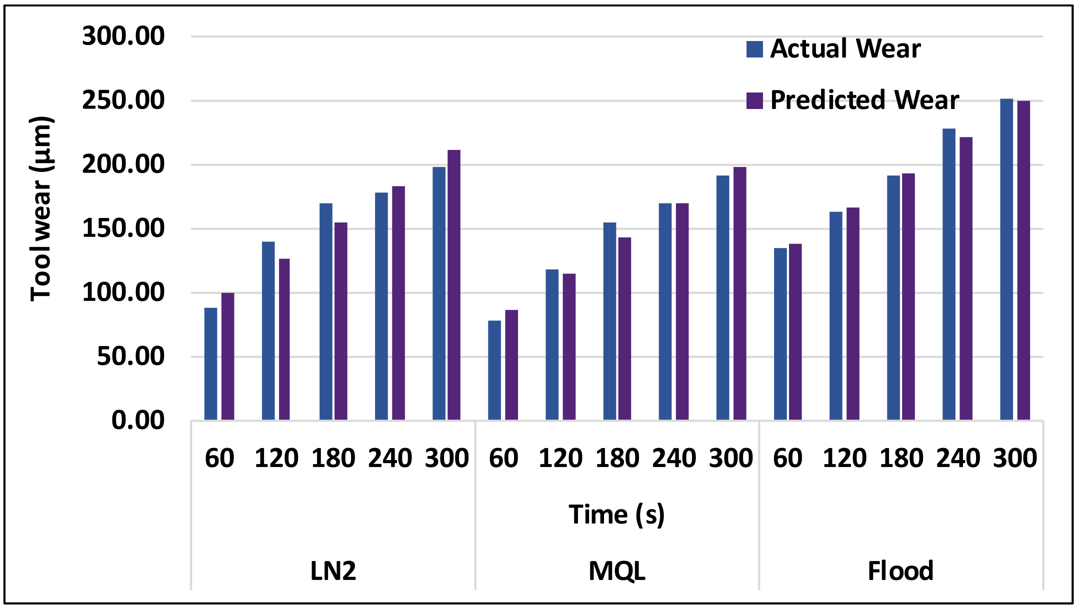


Figure 6.18 Actual and predicted tool wear comparison for Titanium alloy

6.3.5 Tool wear prediction model for Inconel 718

Similar to Titanium alloy, tool wear multivariable regression analysis was also conducted for Inconel 718. The flood data was used as a reference, and the other two cooling methods were used as dummy parameters (Table 6.4). The dependent variable coefficients generated by SPSS are shown in Table 6.5.

Table 6.4 Inconel 718 categorical data with flood as reference

Cooling Method	Time (s)	LN_2 Dummy	MQL Dummy	Tool Wear (µm)
1 (LN_2)	5	1	0	159.24
1 (LN_2)	10	1	0	221.62
1 (LN_2)	15	1	0	234.75
1 (LN_2)	20	1	0	257.74
1 (LN_2)	25	1	0	689.49
2 (MQL)	5	0	1	242.96
2 (MQL)	10	0	1	254.45
2 (MQL)	15	0	1	333.25

2 (MQL)	20	0	1	681.25
2 (MQL)	25	0	1	733.81
3 (Flood)	5	0	0	132.97
3 (Flood)	10	0	0	159.24
3 (Flood)	15	0	0	318.48
3 (Flood)	20	0	0	339.82
3 (Flood)	25	0	0	459.66

Table 6.5 Coefficients of tool wear for Inconel 718

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-51.874	71.839		-0.722	0.485
Time	22.261	3.710	0.811	6.001	0.000
LN_2 Dummy	30.534	64.255	0.074	0.475	0.644
MQL Dummy	167.110	64.255	0.406	2.601	0.025

From Table 6.5 above, equations to predict the tool wear value for each cooling method can be established. With the R squared value of 0.799 the model is acceptable to be used.

$$Tw_F = 22.261t - 51.874\ (\mu m) \tag{6.4}$$

$$Tw_N = 22.261t - 51.874 + 30.534\ (\mu m) = 22.261t - 21.34\ (\mu m) \tag{6.5}$$

$$Tw_M = 22.261t - 51.874 + 167.110\ (\mu m) = 22.261t + 115.236\ (\mu m) \tag{6.6}$$

From the above equations, MQL shows the lowest performance in machining Inconel 718. Flood cooling performs better in maintaining tool life, even though for all cooling methods severe wear occurs after 25 seconds (level 5). From this result, machining Inconel at a high cutting speed is not recommended.

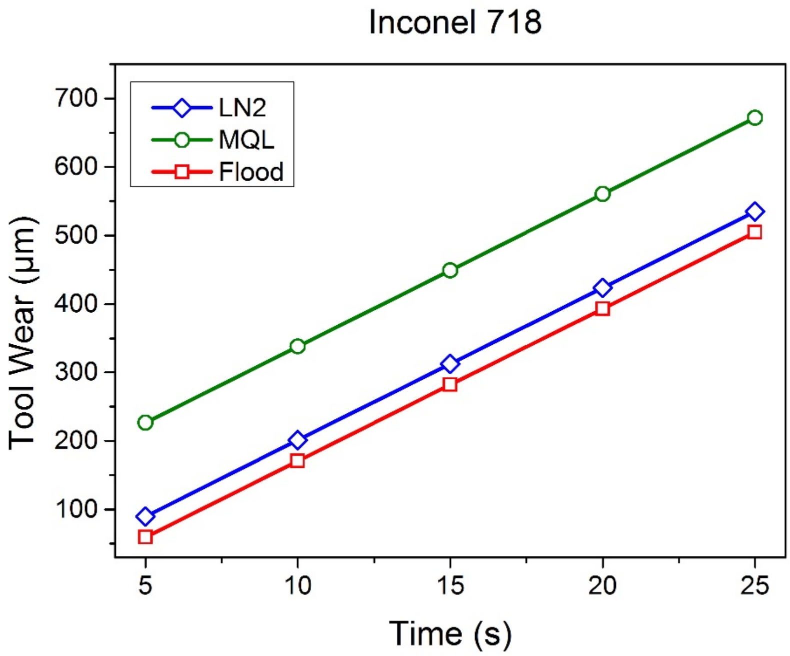


Figure 6.19 Cooling methods predicted performance on tool wear for Inconel 718

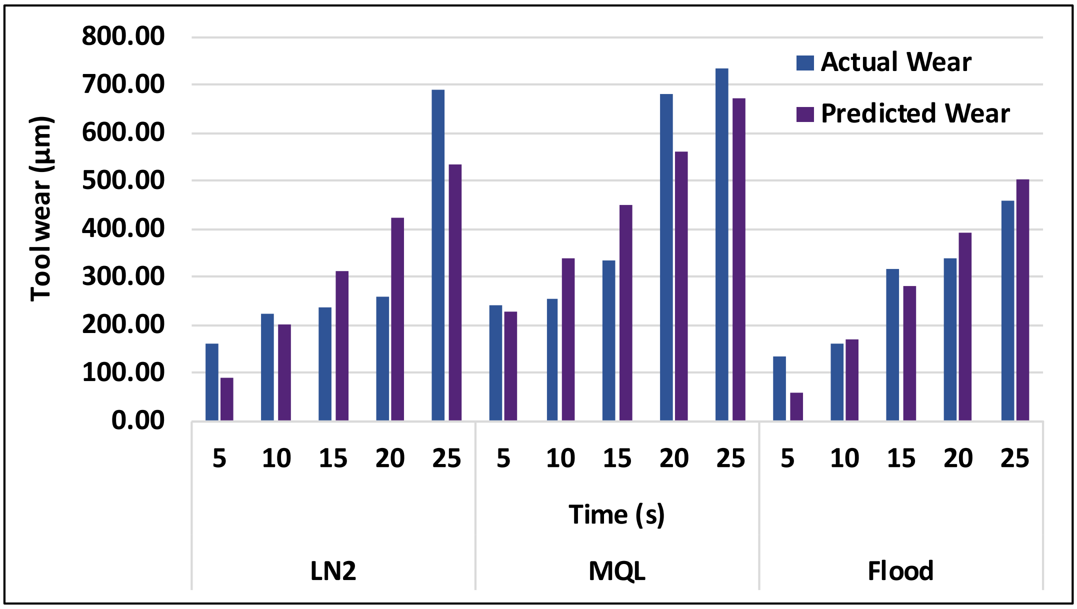


Figure 6.20 Actual and predicted tool wear comparison for Inconel 718

The comparison of the actual machining tool wear with the model data for the Inconel machining is shown in Figure 6.20. The significant differences are found in LN_2 and MQL results. Although this model is not as good as the model produced for Titanium alloy, with R squared 0.799, this model is sufficient to predict the rate of the wear rate for Inconel machining.

6.3.6 Tool wear prediction model for AMMC

Table 6.6 shows data for multivariable regression analysis conducted for tool wear on AMMC. The flood data was used as a reference and the other two cooling methods were used as dummy parameters. Table 6.7 shows the dependent variables coefficients generated by SPSS.

Table 6.6 AMMC categorical data with flood as reference

Cooling Method	Time (s)	LN_2 Dummy	MQL Dummy	Tool Wear (µm)
1 (LN_2)	60	1	0	149.40
1 (LN_2)	120	1	0	182.22
1 (LN_2)	180	1	0	221.62
1 (LN_2)	240	1	0	238.04
1 (LN_2)	300	1	0	284.00
2 (MQL)	60	0	1	142.82
2 (MQL)	120	0	1	169.09
2 (MQL)	180	0	1	201.92
2 (MQL)	240	0	1	224.90
2 (MQL)	300	0	1	265.95
3 (Flood)	60	0	0	146.11
3 (Flood)	120	0	0	174.01
3 (Flood)	180	0	0	215.05
3 (Flood)	240	0	0	238.04
3 (Flood)	300	0	0	269.23

Equations to generate tool wear value can be arranged from coefficients in Table 6.7. Since R squared value of the model is 0.990, it is a good model to be used.

Table 6.7 Coefficients of tool wear for AMMC

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	114.752	3.722		30.828	0.000
Time	0.521	0.160	0.987	32.510	0.000
LN_2 Dummy	6.568	3.329	0.069	1.973	0.074
MQL Dummy	-7.552	3.329	-0.079	-2.268	0.044

$$Tw_F = 0.521t + 114.752 \ (\mu m) \tag{6.7}$$

$$Tw_N = 0.521t + 114.752 + 6.568 \ (\mu m) = 0.521t + 121.32 \ (\mu m) \tag{6.8}$$

$$Tw_M = 0.521t + 114.752 - 7.552 \ (\mu m) = 0.521t + 107.2 \ (\mu m) \tag{6.9}$$

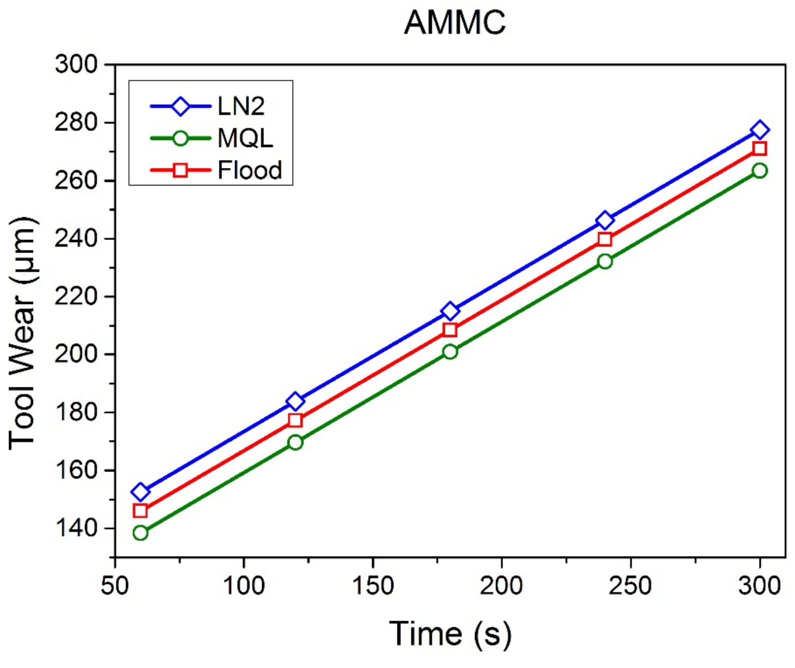


Figure 6.21 Cooling methods predicted performance on tool wear for AMMC

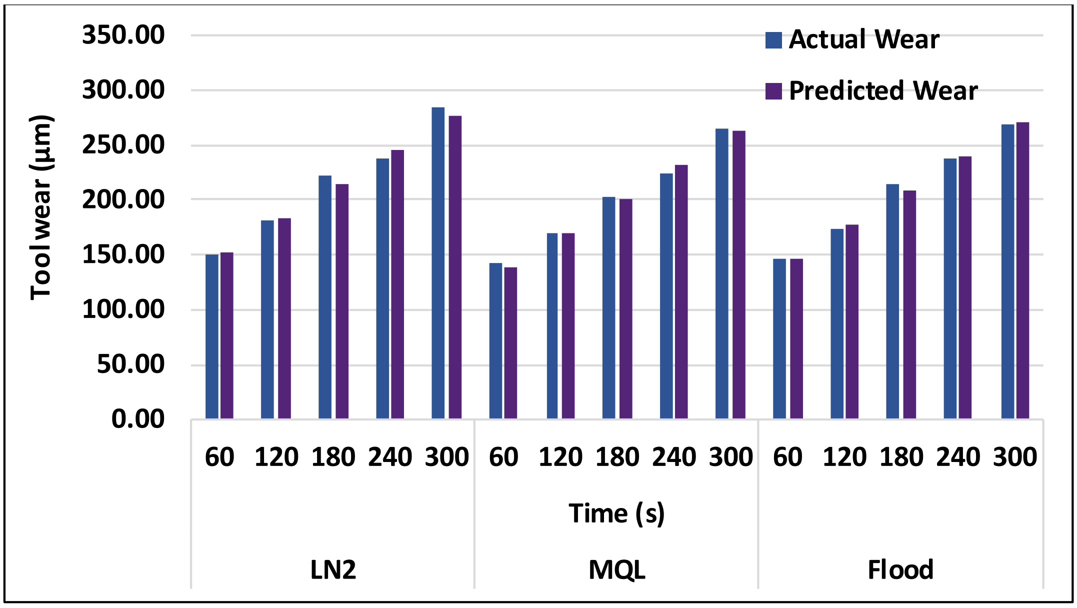


Figure 6.22 Actual and predicted tool wear comparison for AMMC

The comparison of the actual tool wear from the machining process, with the predicted tool wear produced from the model for AMMC machining, is shown in Figure 6.22. It is clearly seen that for the three cooling methods predicted, the values of the model are very close to the actual machining values. From the model developed for all three materials, the AMMC model provides the closest values of predictive data to the actual data.

6.4 Conclusion

To quantify the performance of each cooling method, the tool wear equations are formed from the multiregresssion analysis result and presented in Figure 6.23 - Figure 6.25. For liquid nitrogen applications (Figure 6.23), it is clear that the tool wear rate for Inconel increased sharply to over 500 µm at 25 seconds. For Titanium alloy and AMMC, the wear rate occurred gradually. AMMC tool wear rate is slightly higher than that of Titanium alloy. Liquid nitrogen provides the lower wear rate for cutting Titanium alloys compared to the other two materials.

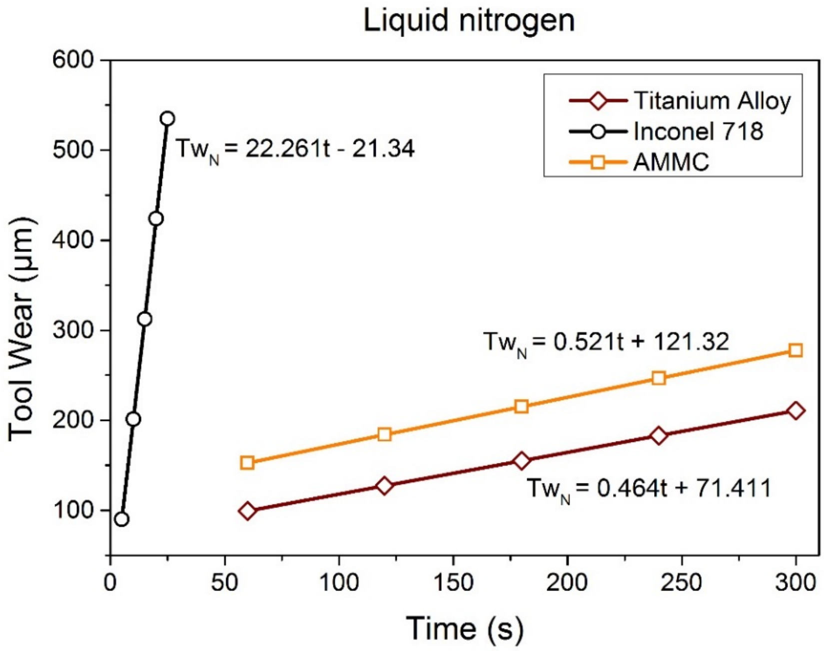


Figure 6.23 Tool wear prediction equation for liquid nitrogen

MQL gave a higher wear rate when compared to LN_2 for Inconel cutting (Figure 6.24). The constant value for MQL tool wear (115.236) is much greater than that of LN_2 (-21.34). Similar to LN_2, MQL produces a gradual tool wear rate for Titanium alloy and AMMC. The MQL application also produced the least tool wear for the Titanium alloy cutting.

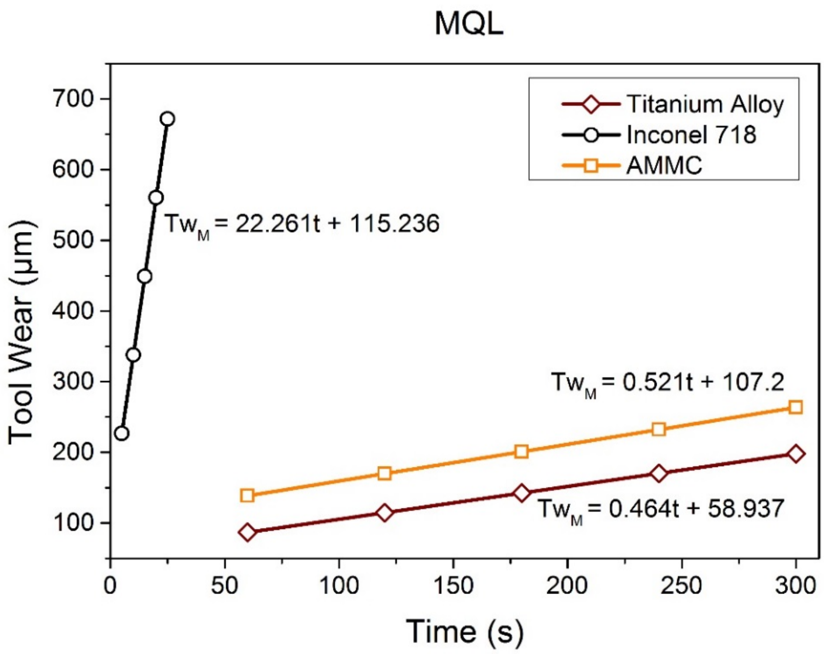


Figure 6.24 Tool wear prediction equation for MQL

Figure 6.25 shows that flood resulted in a similar performance for Titanium alloy and AMMC in reducing tool wear. However, this performance is still lower when compared to LN_2 and MQL. For example, the predicted tool wear for flood reached 249 µm within 5 minutes when machining Titanium alloy, while for the same time, tool wear for LN_2 and MQL were only 211 µm and 198 µm, respectively.

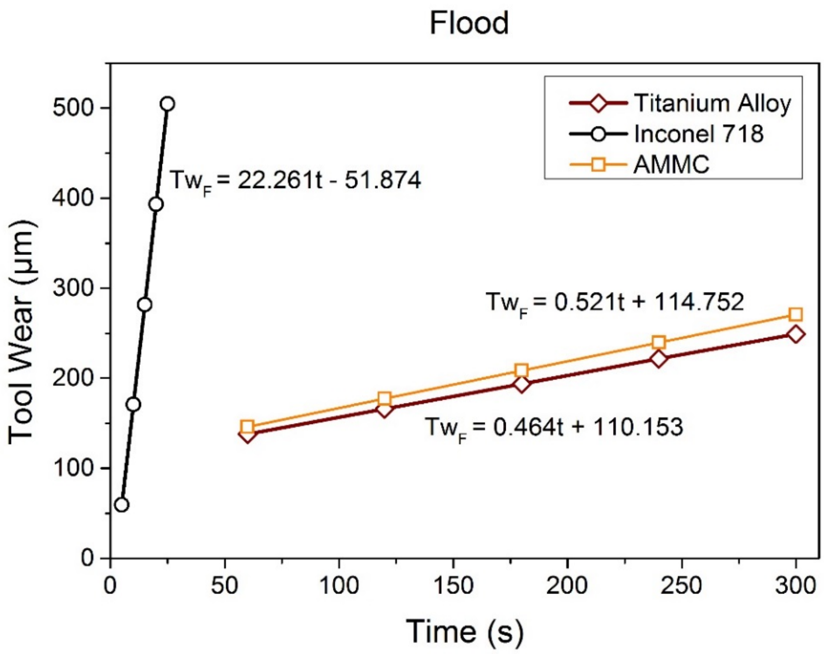


Figure 6.25 Tool wear prediction equation for flood

The tool wear rate for Inconel cutting under flood applications was still the highest, compared to the other two test materials (Figure 6.25). However, flood was capable of producing a lower tool wear for each level compared to that of LN_2 and MQL. In the fifth minute, predicted tool wear for flood was 505 µm, while LN_2 and MQL reached 535 µm and 672 µm, respectively.

From the above results, LN_2 and MQL can be recommended as an alternative cooling method for Titanium alloy and AMMC, as far as tool wear rate is considered. LN_2 and MQL are able to provide even better tool wear results than that of flood as an existing cooling method. As for Inconel, since flood gave better results than both proposed cooling methods, for high-speed cutting conditions, flood is recommended for Inconel cutting.

Chapter 7

CONCLUSION AND RECOMMENDATION

7.1 Introduction

Flood coolant is a cooling method that is widely used in the industry. Since the use of coolant in the machining process not only burdens the environment but also increases the production cost significantly, it is necessary to reduce or even eliminate the coolant from the machining processes. Machining without cooling, especially difficult-to-cut materials machining, presents great challenges related to machining performance, tool life and product quality. Since heat generation is a major problem in the machining process, this research aims to reduce heat by optimizing machining parameters and use an alternative environmentally friendly cooling method. This alternative coolant should be able to deliver better results or at least be similar to machining with coolant applications. In this research, the performance of machining process was compared with machining quality parameters such as surface roughness, cutting force, power requirement and tool wear.

This chapter presents the key findings and achievements of this research as an effort to support sustainable machining processes. The best alternative cooling method is recommended based on the machining quality. Also shown is the performance of the best cooling method in slowing the tool wear for each test material.

7.2 Achievements

7.2.1 Sustainable Machining Test (Chapter 5)

For Titanium alloy machining, it is relatively easy to determine the best cooling method as a coolant replacement. Judging from the three performance outputs: surface roughness, cutting force and power requirement parameters, MQL shows the best performance. In contrast, cryogenic cooling performance is the worst among the three cooling methods for surface roughness and cutting force. Cryogenic is better compared to flood in terms of power requirement only. From this result, MQL can be recommended as the cooling method to replace flood coolant.

MQL is also the best cooling method for Inconel 718 in terms of surface roughness and cutting force. Cryogenic is only able to match MQL in terms of power requirements.

For AMMC, cryogenic cooling provides the best surface roughness, while MQL requires the lowest cutting force and also needs the lowest power. Therefore, the selection of alternative cooling method for AMMC needs to be done with consideration of the desired surface quality (cryogenic), or the reduction of machining force/power.

This thesis proves that with the optimisation of machining parameters and sustainable cooling methods, flood coolant can be removed from the machining process, even for difficult-to-cut materials. Therefore, the environmental burden caused by the machining processes can be reduced.

7.2.2 Cooling Methods Performance on Tool Wear Test (Chapter 6)

It was found that MQL was able to provide the lowest rate of tool wear when machining Titanium alloy. This proves that lubrication is the most important requirement of Titanium alloy machining since it has a poor heat distribution rate.

For Inconel, the tool wear rate was very high. One of the important findings of this study indicates that 25 seconds machining of Inconel generates higher tool wear compared to 5 minutes machining of Titanium alloy or AMMC. The extreme hardness and low machinability rating of Inconel are the main cause of this result. MQL was found to be the worst cooling method for this material, so it can be concluded that, for Inconel, lubrication is not a significant factor in terms of tool wear. Cryogenic cooling also did not help much in reducing the wear rate. Flood gave the smallest wear rate for Inconel, but still the wear was too high and the tool can only be used for a very short time (less than 30 seconds). The cutting speed of 150 m/min seems to be too high for all the three cooling methods. Judging from the rate of tool wear, further research is needed to determine the replacement cooling method for Inconel 718 machining.

For AMMC, tool wear generated by MQL was lower than that of the other two cooling methods. The wear rate for flood was slightly lower than that of LN_2, and therefore, MQL can be recommended as a new cooling method for this material, as far as tool wear is concerned.

The model developed to predict the tool wear provides good results and very close to actual data, especially for AMMC and Titanium Alloy with R squared of 0.99 and 0.97, respectively. Inconel model with R squared 0.799 can also be considered as a good model to be used. It indicates that the developed models are reliable to predict the tool wear and feasible for further development for a more complex machining parameters.

This research achievement is expected to be applied in the industrial world to reduce the use of coolant in the machining process by replacing it with the recommended cooling method, so that the machining process can be done in a more environmentally friendly way.

7.3 Future Recommendations

Specifically for Inconel, in order to obtain an applicable test result, it is necessary to perform a separate test with a lower cutting speed, for example 100 m/min or lower. It is necessary to reduce the wear rate of the tool, so that the cooling effectiveness of each cooling method can be examined more thoroughly.

For AMMC, since all of the cooling methods show the good performance in slowing the tool wear rate, it would be interesting to do further testing using new cooling methods such as cold water or even dry machining. This test will be useful to see whether cold water or even dry machining are also able to slow the rate of tool wear effectively.

Testing the tool life by adding variations of cutting speed for each test material can also be done to study the tool wear rate in more detail. To develop a more comprehensive tool wear model, the quantity of cooling methods needs to be made as one of the test parameters.

The methods and the results from this research can be adapted for other materials to achieve better machining performance and economic benefits for machining industry.

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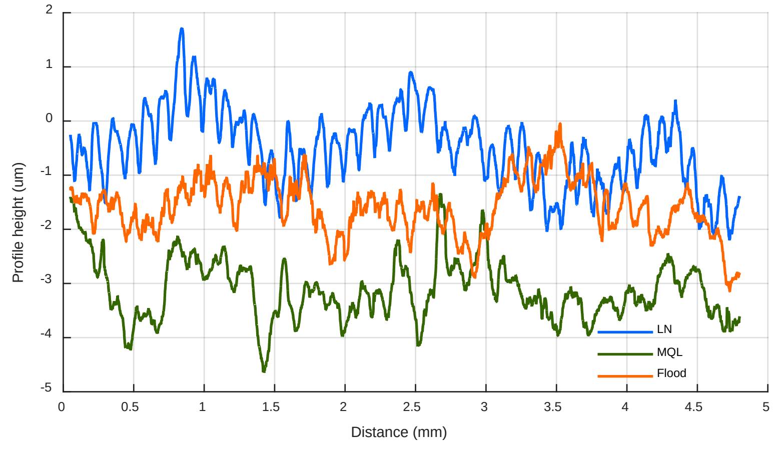
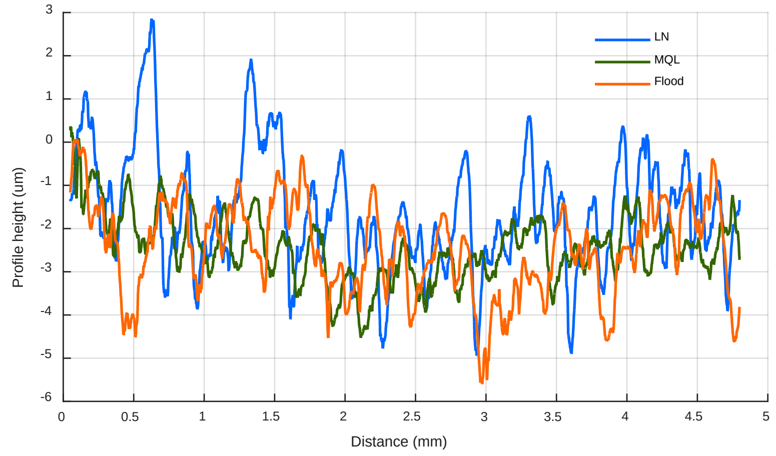
APPENDIX A-1
Sustainable End Milling of Titanium Alloy – Surface Roughness

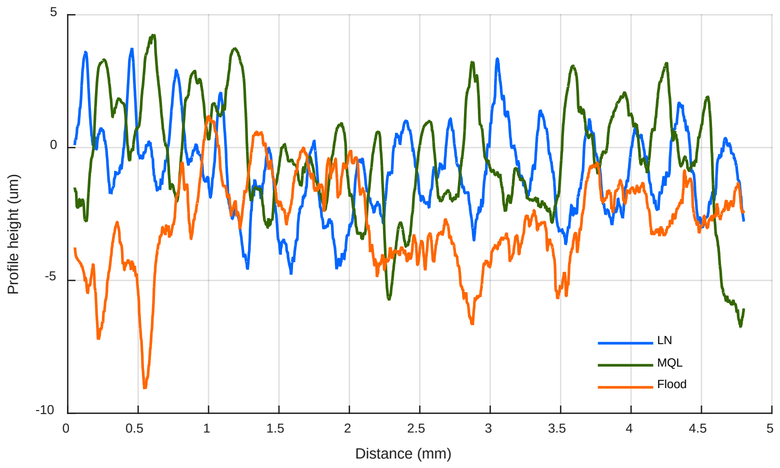
1. v = 60 m/min, f = 0.1 (mm/rev)



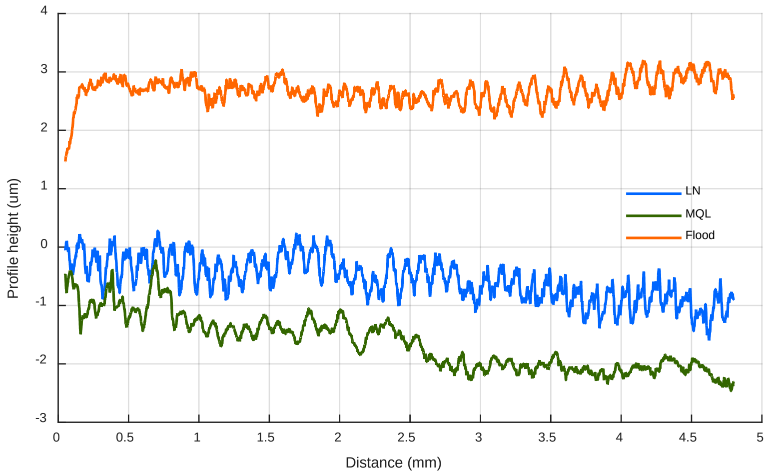
2. v = 60 m/min, f = 0.2 (mm/rev)



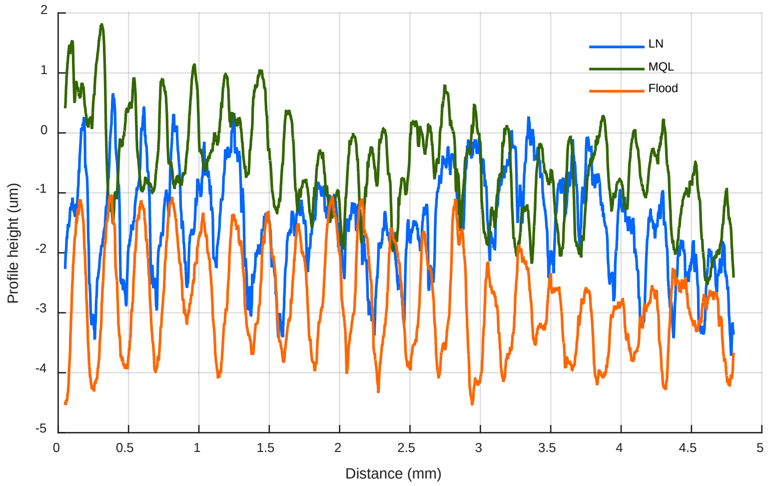
3. v = 60 m/min, f = 0.3 (mm/rev)



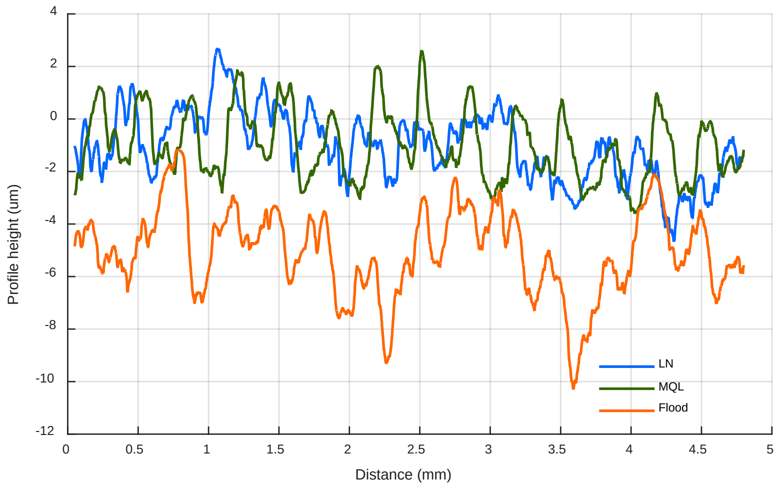
4. v = 80 m/min, f = 0.1 (mm/rev)



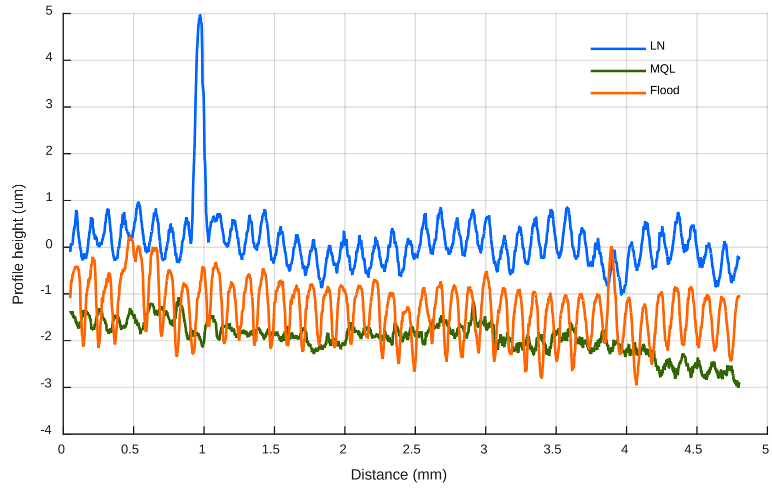
5. v = 80 m/min, f = 0.2 (mm/rev)



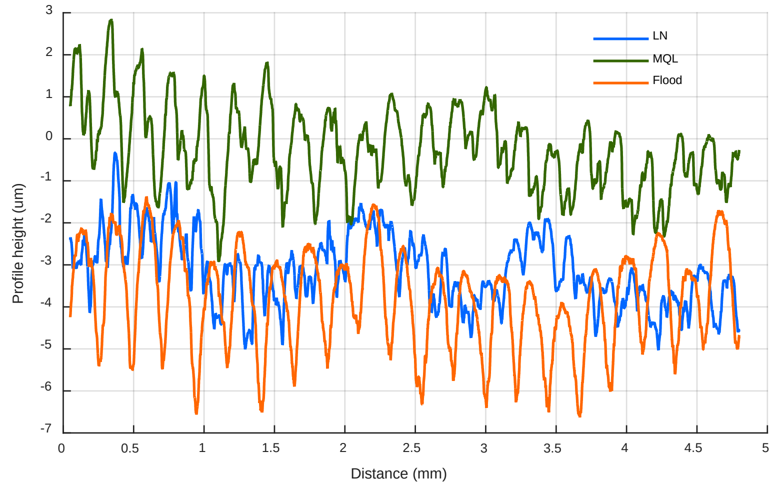
6. v = 80 m/min, f = 0.3 (mm/rev)



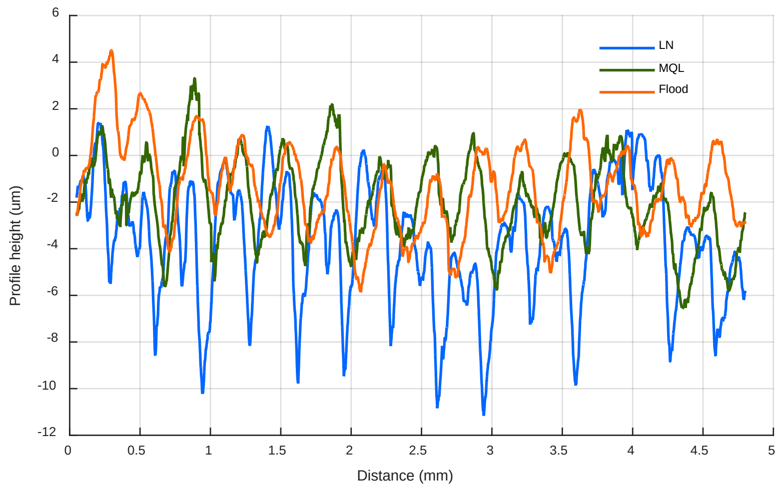
7. v = 100 m/min, f = 0.1 (mm/rev)



8. v = 100 m/min, f = 0.2 (mm/rev)

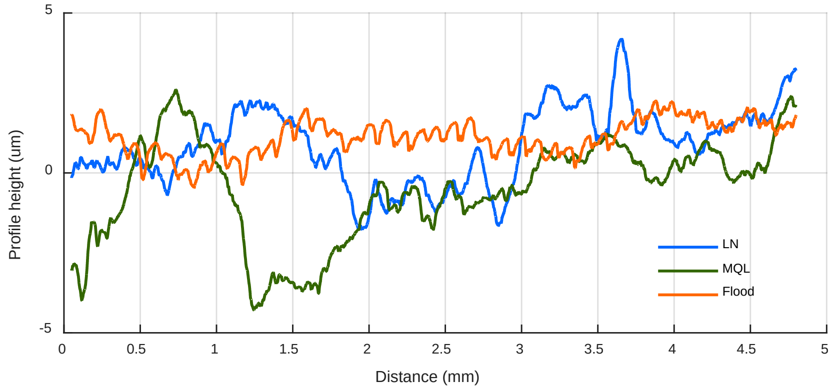


9. v = 100 m/min, f = 0.3 (mm/rev)

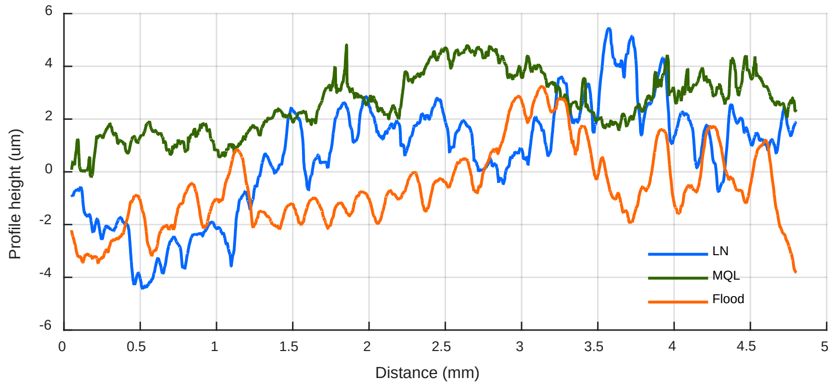


APPENDIX A-2
Sustainable End Milling of Inconel 718 – Surface Roughness

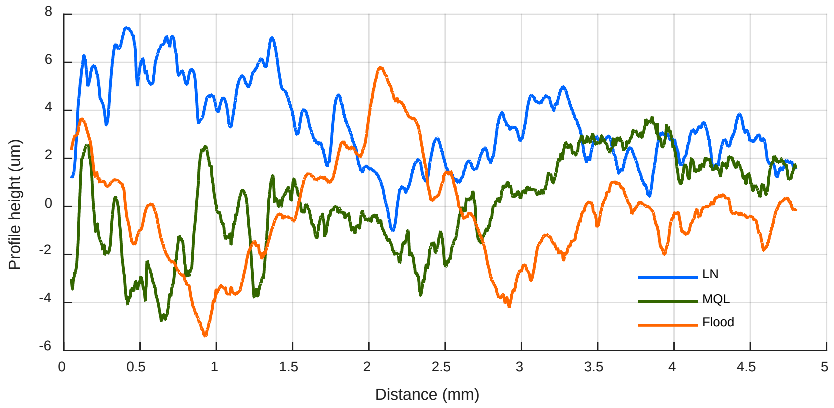
1. v = 40 m/min, f = 0.1 (mm/rev)



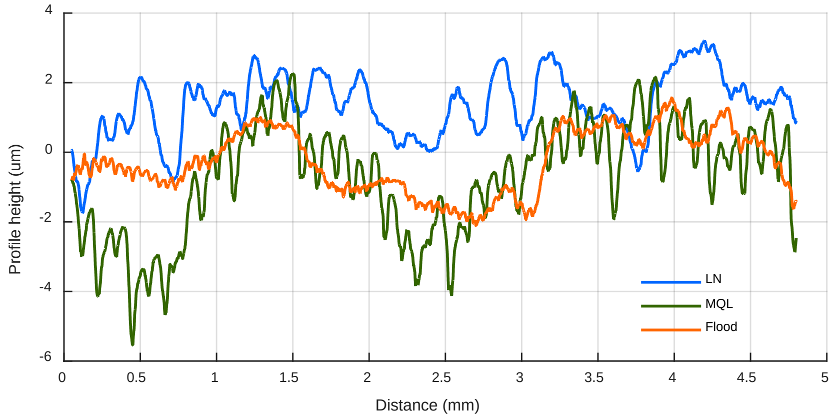
2. v = 40 m/min, f = 0.15 (mm/rev)



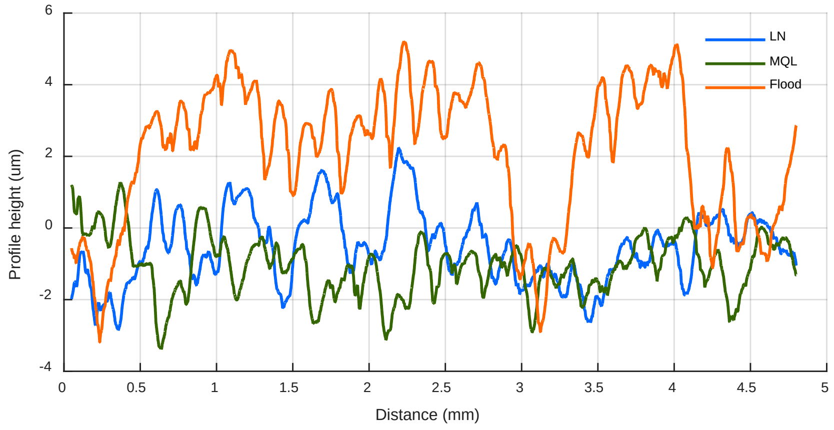
3. v = 40 m/min, f = 0.2 (mm/rev)



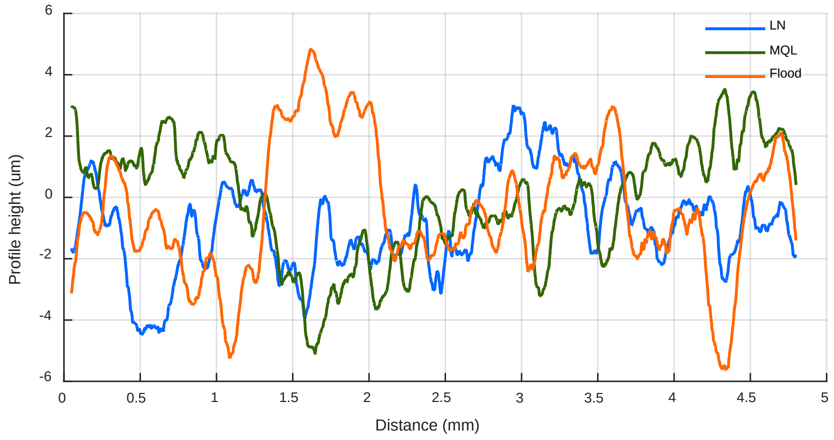
4. v = 60 m/min, f = 0.1 (mm/rev)



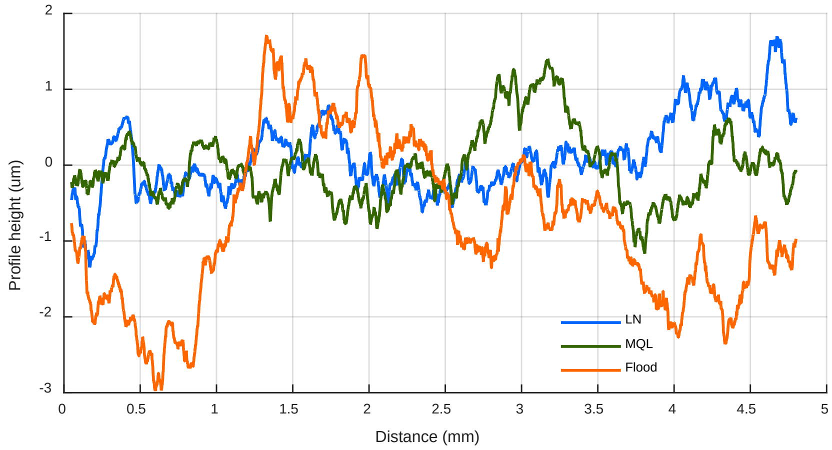
5. v = 60 m/min, f = 0.15 (mm/rev)



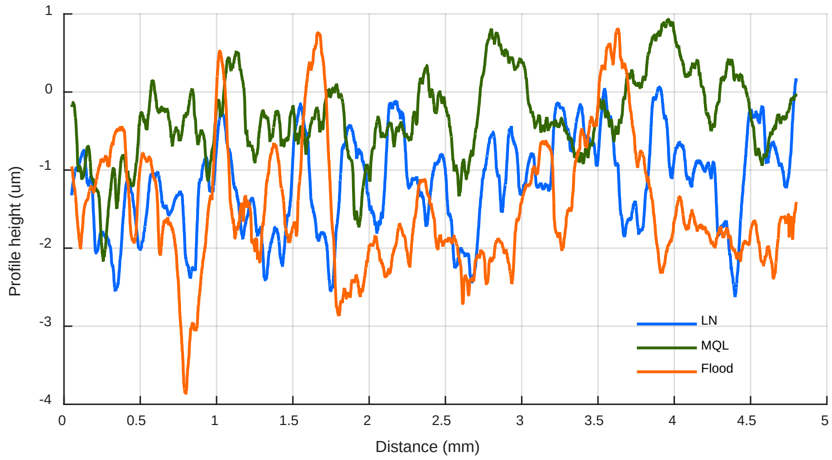
6. v = 60 m/min, f = 0.2 (mm/rev)



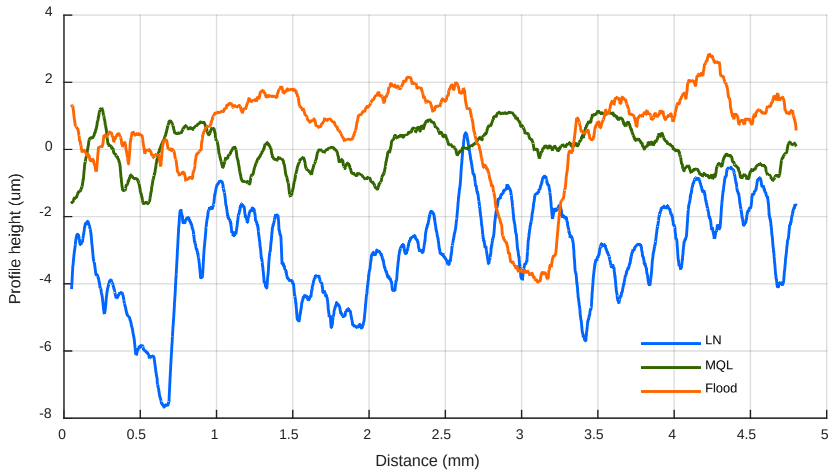
7. v = 80 m/min, f = 0.1 (mm/rev)



8. v = 80 m/min, f = 0.15 (mm/rev)

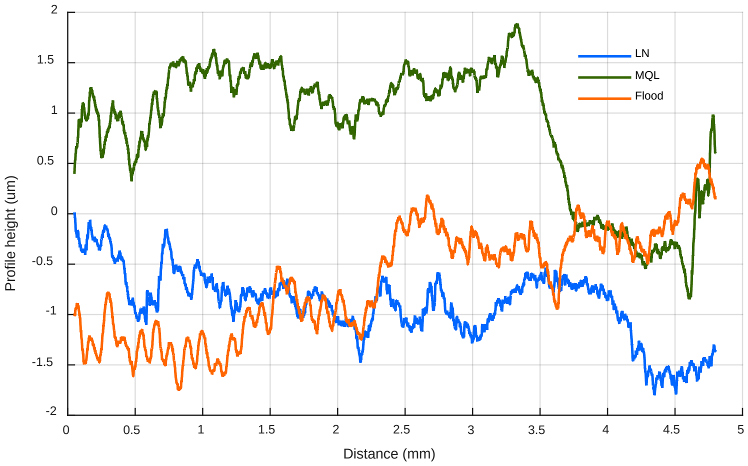


9. v = 80 m/min, f = 0.2 (mm/rev)

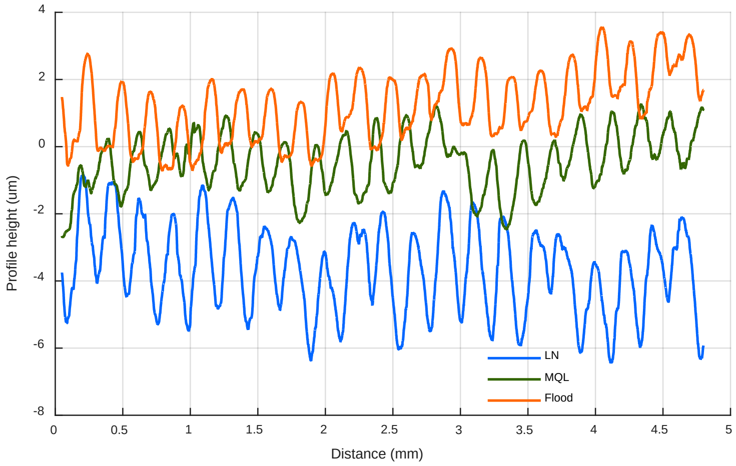


APPENDIX A-3
Sustainable End Milling of AMMC – Surface Roughness

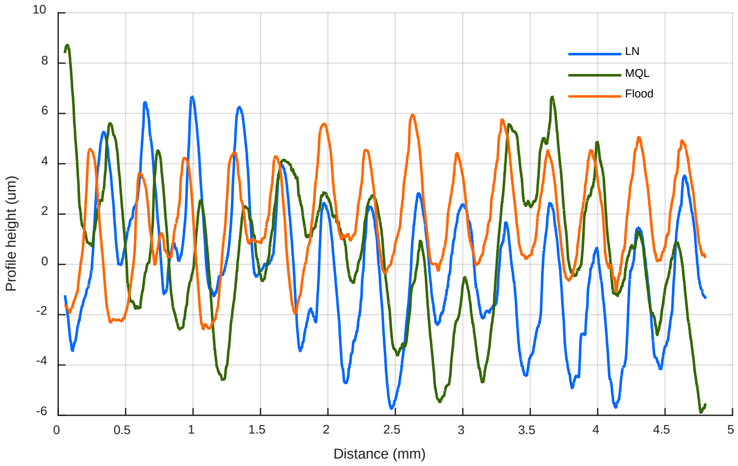
1. v = 50 m/min, f = 0.1 (mm/rev)



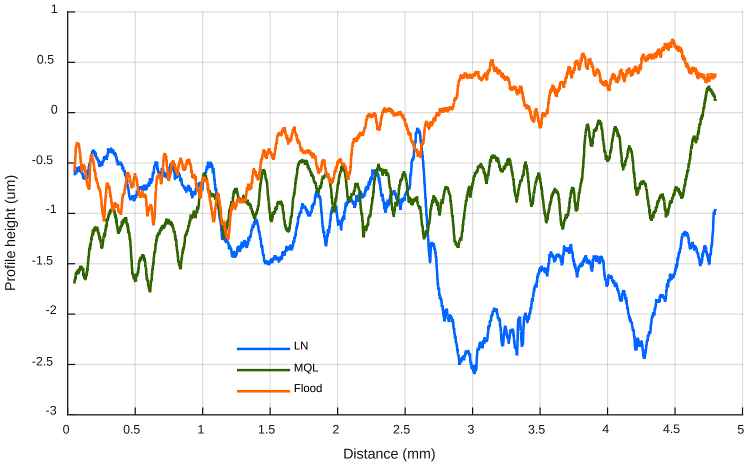
2. v = 50 m/min, f = 0.2 (mm/rev)



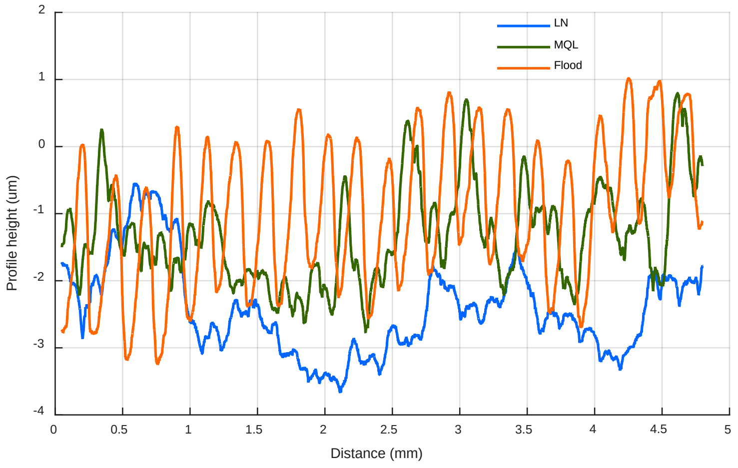
3. v = 50 m/min, f = 0.3 (mm/rev)



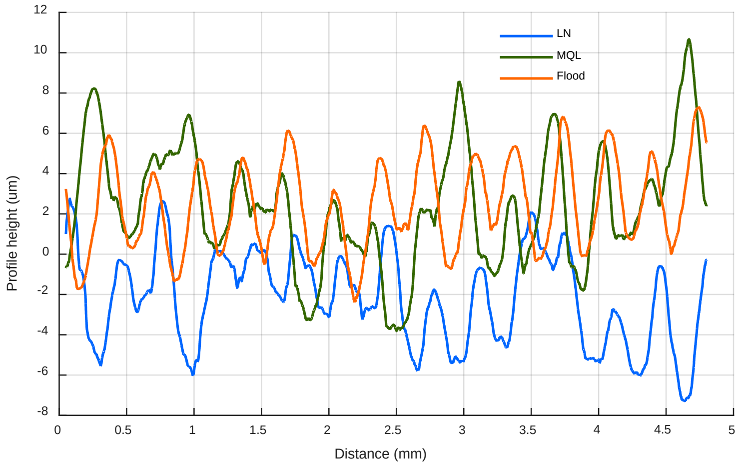
4. v = 100 m/min, f = 0.1 (mm/rev)



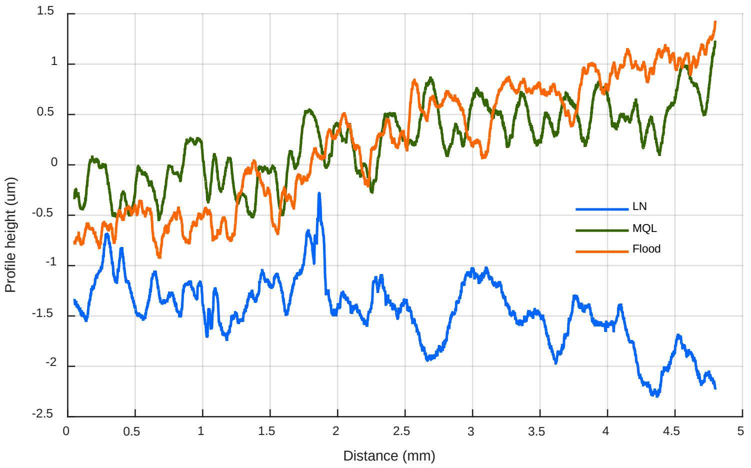
5. v = 100 m/min, f = 0.2 (mm/rev)



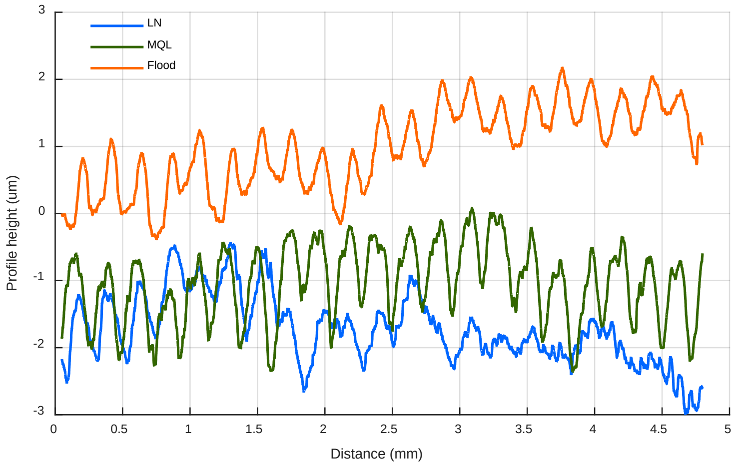
6. v = 100 m/min, f = 0.3 (mm/rev)



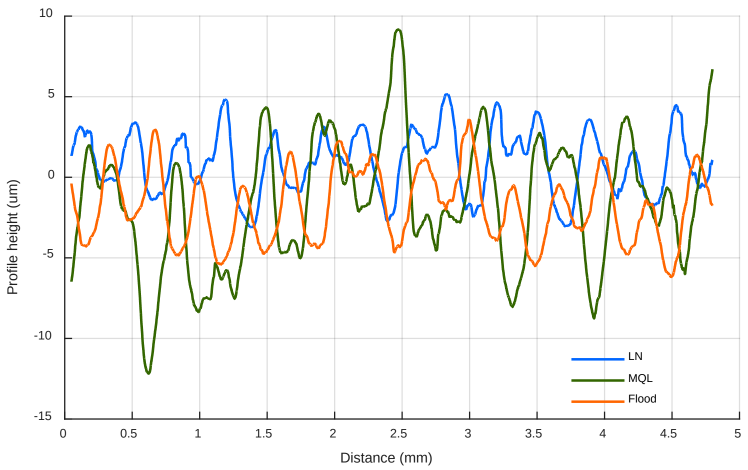
7. v = 150 m/min, f = 0.1 (mm/rev)



8. v = 150 m/min, f = 0.2 (mm/rev)

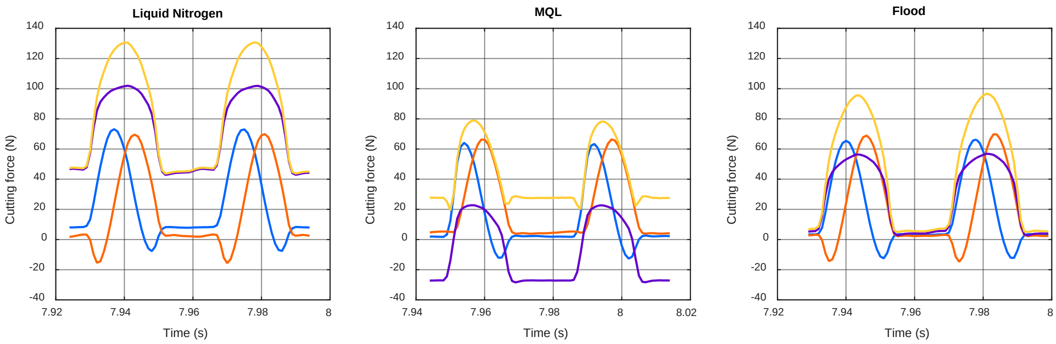


9. v = 150 m/min, f = 0.3 (mm/rev)

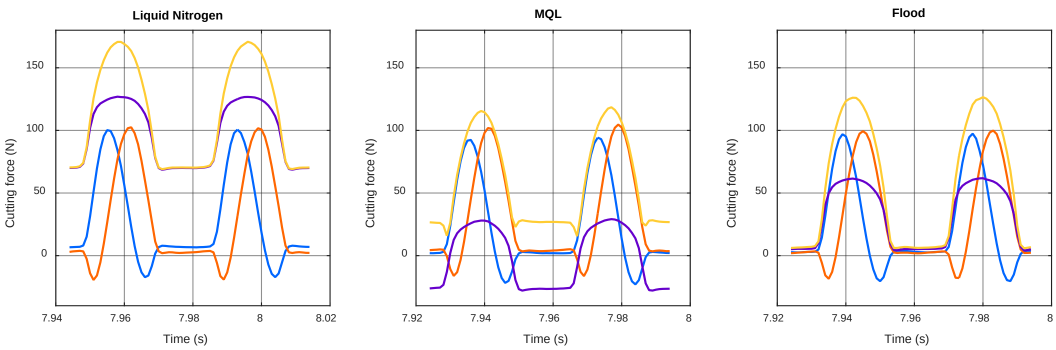


APPENDIX B-1
Sustainable End Milling of Titanium Alloy – Cutting Force

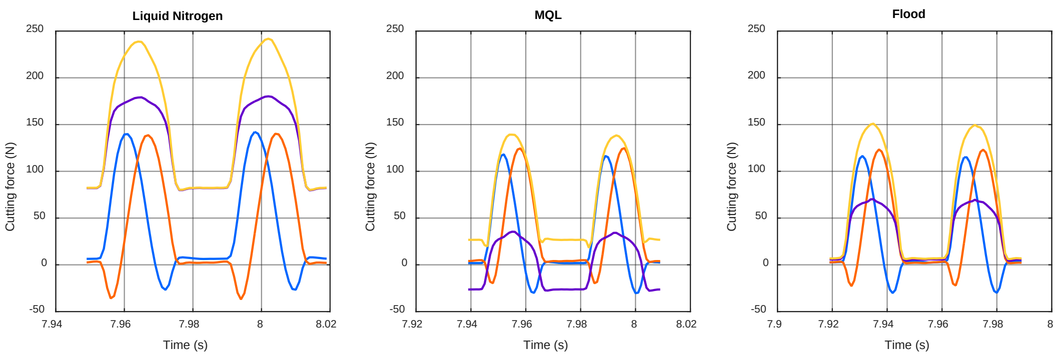
1. v = 60 m/min, f = 0.1 (mm/rev)



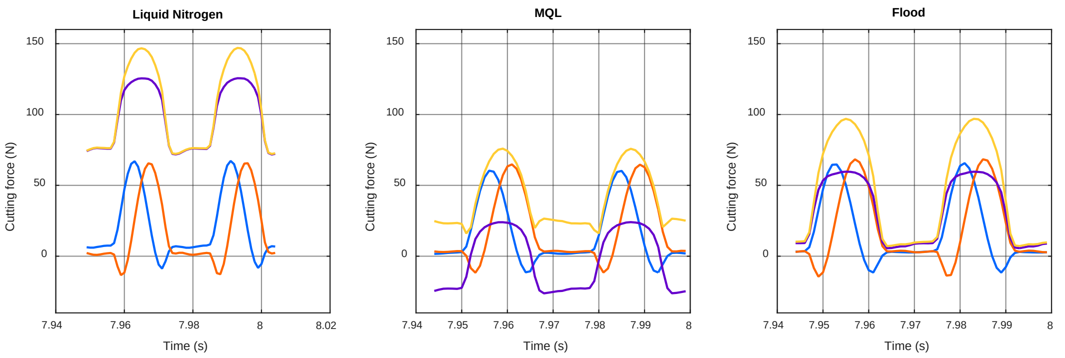
2. v = 60 m/min, f = 0.2 (mm/rev)



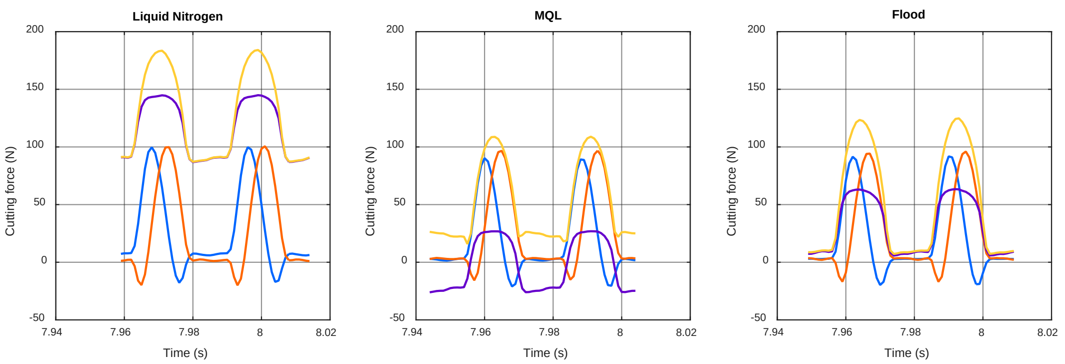
3. v = 60 m/min, f = 0.3 (mm/rev)



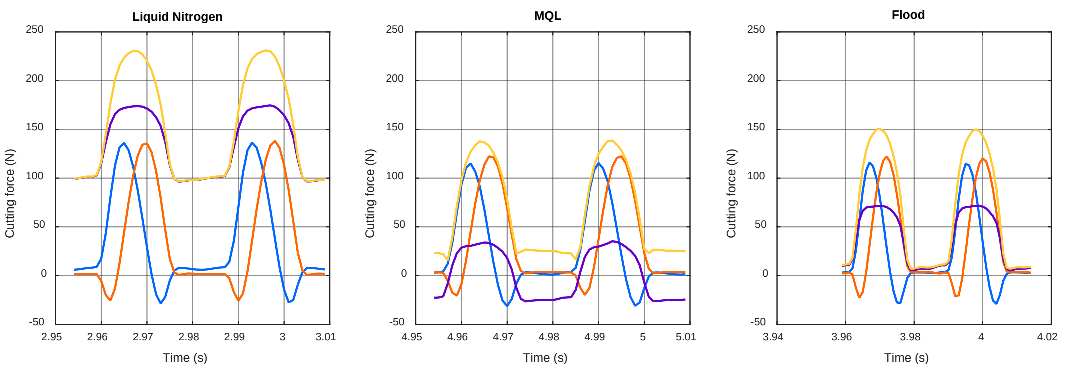
4. v = 80 m/min, f = 0.1 (mm/rev)



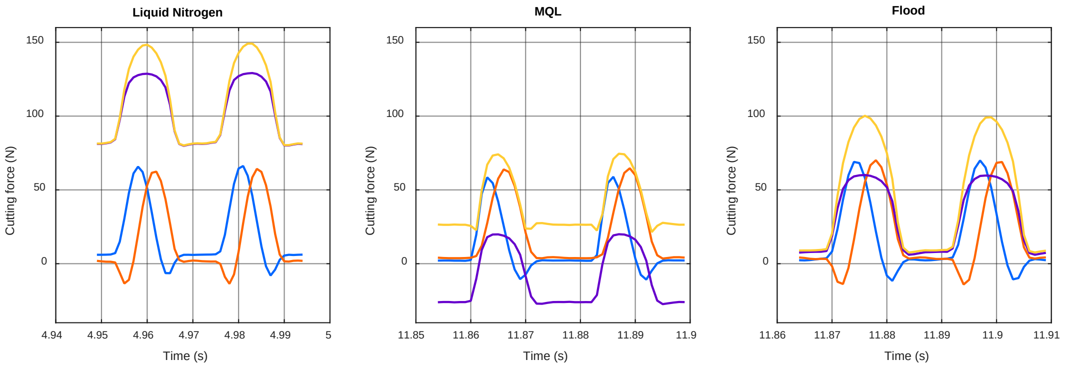
5. v = 80 m/min, f = 0.2 (mm/rev)



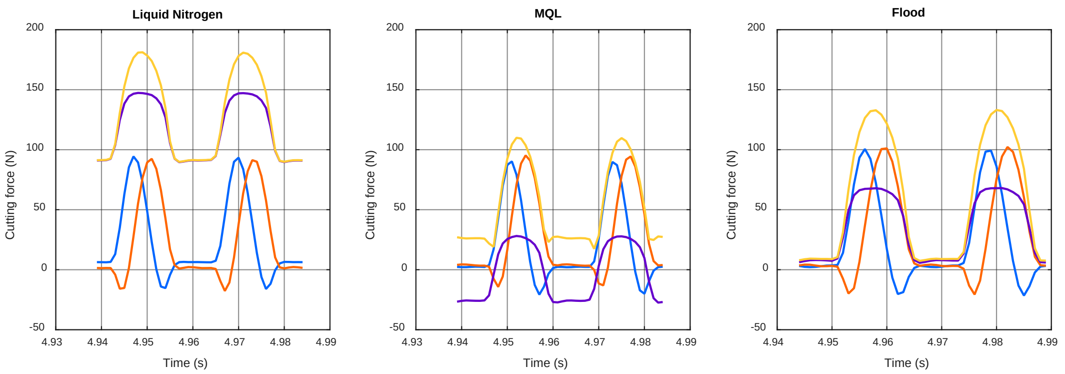
6. v = 80 m/min, f = 0.3 (mm/rev)



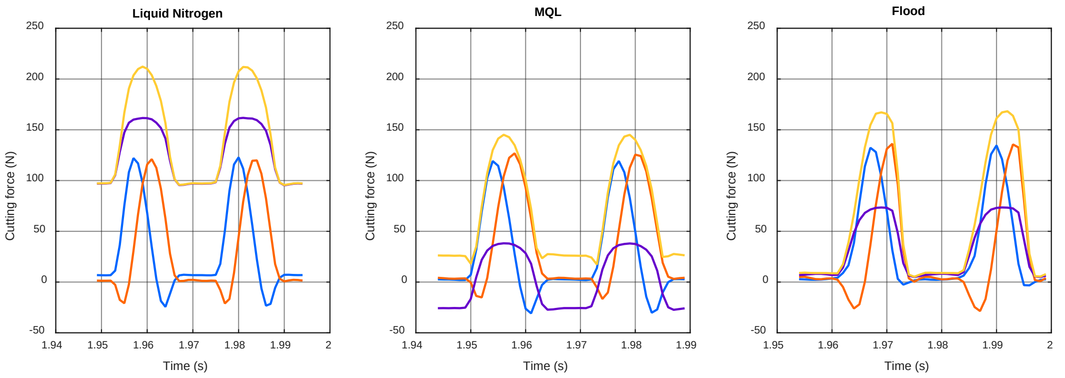
7. v = 100 m/min, f = 0.1 (mm/rev)



8. v = 100 m/min, f = 0.2 (mm/rev)

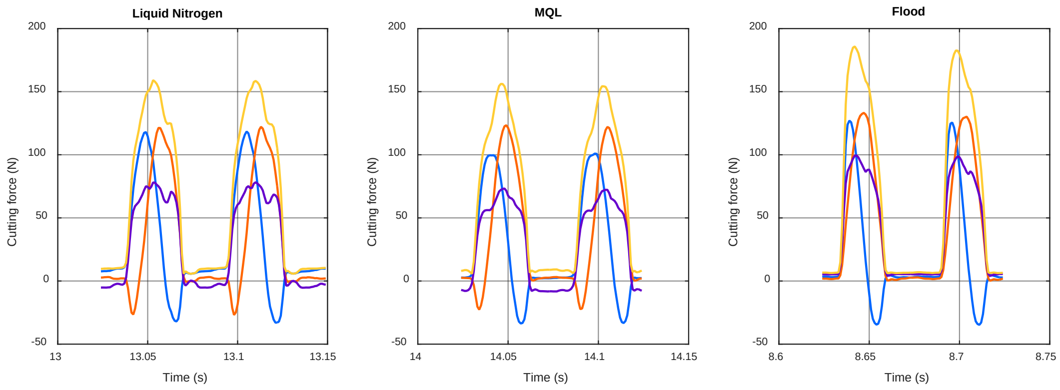


9. v = 100 m/min, f = 0.3 (mm/rev)

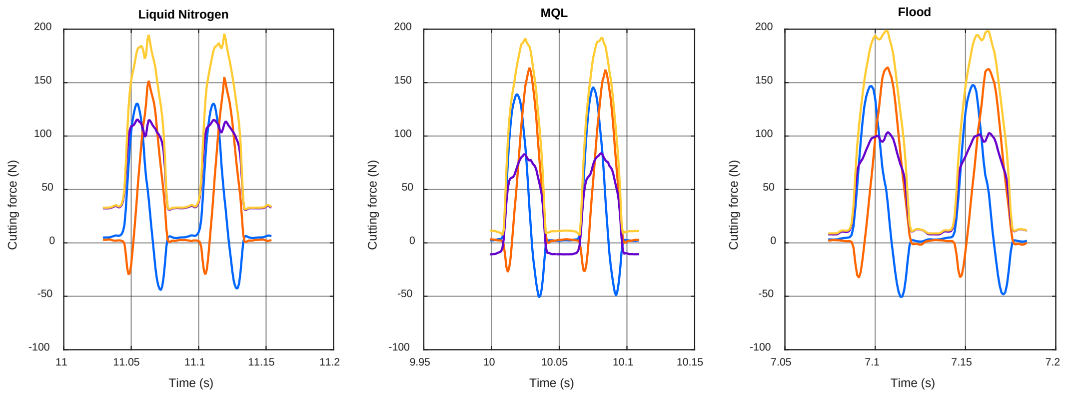


APPENDIX B-2
Sustainable End Milling of Inconel 718 – Cutting Force

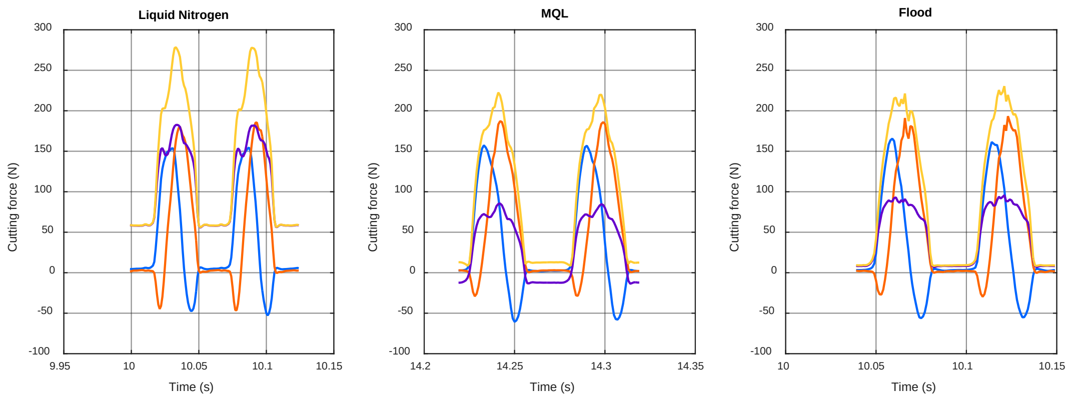
1. v = 40 m/min, f = 0.1 (mm/rev)



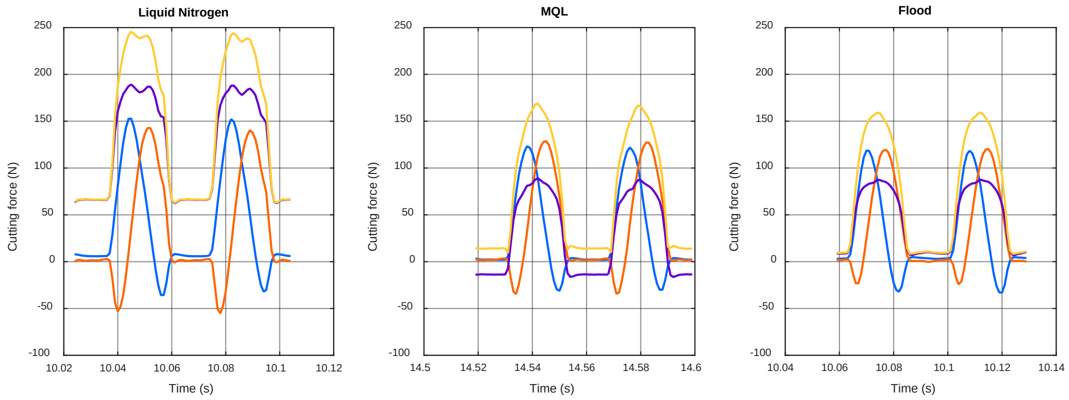
2. v = 40 m/min, f = 0.15 (mm/rev)



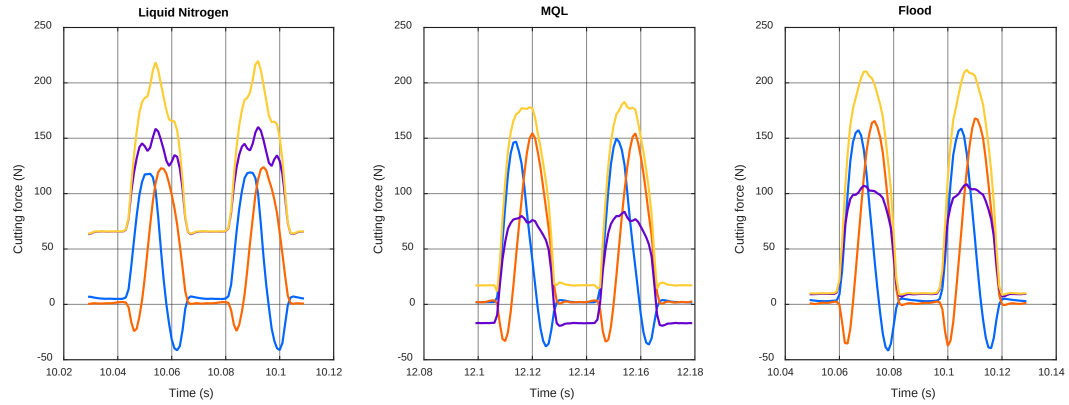
3. v = 40 m/min, f = 0.2 (mm/rev)



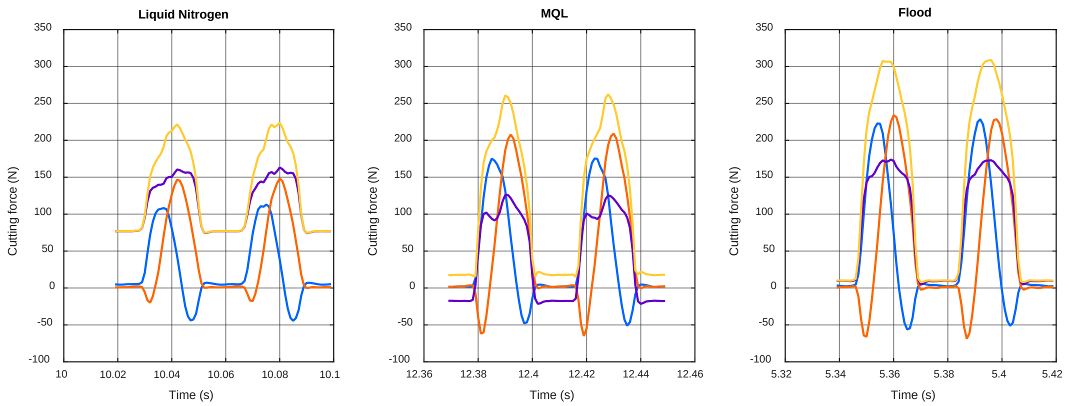
4. v = 60 m/min, f = 0.1 (mm/rev)



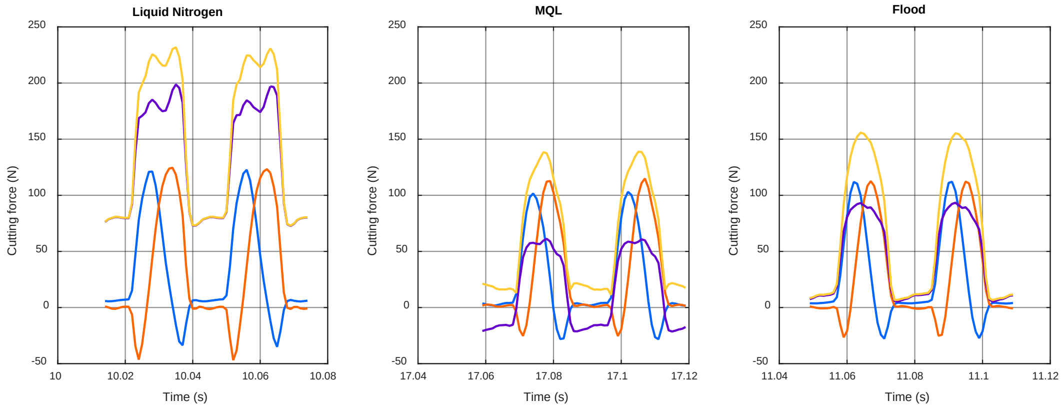
5. v = 60 m/min, f = 0.15 (mm/rev)



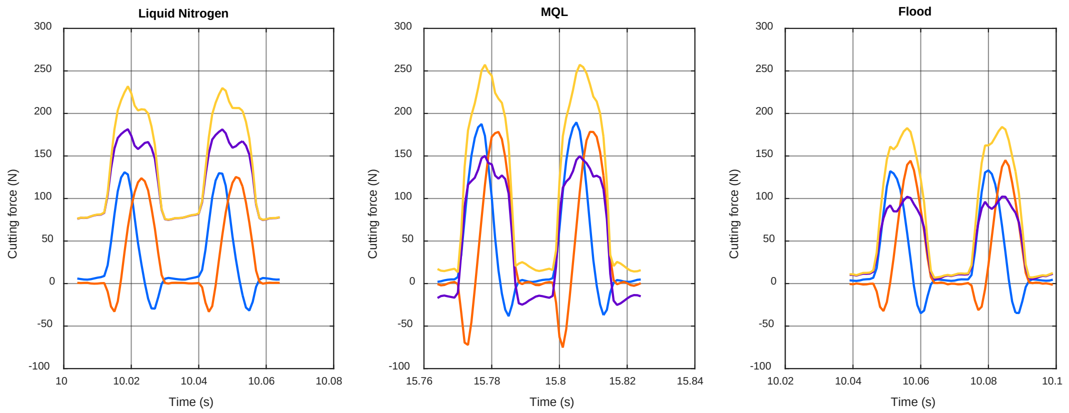
6. v = 60 m/min, f = 0.2 (mm/rev)



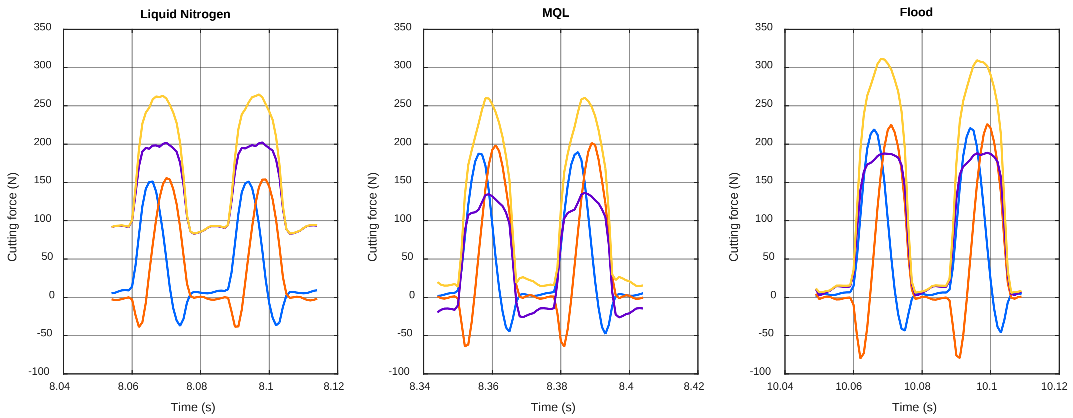
7. v = 80 m/min, f = 0.1 (mm/rev)



8. v = 80 m/min, f = 0.15 (mm/rev)

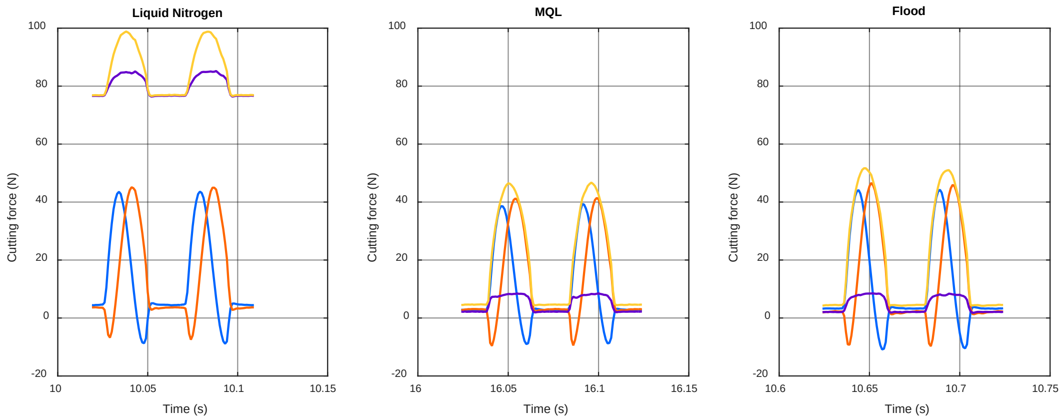


9. v = 80 m/min, f = 0.2 (mm/rev)

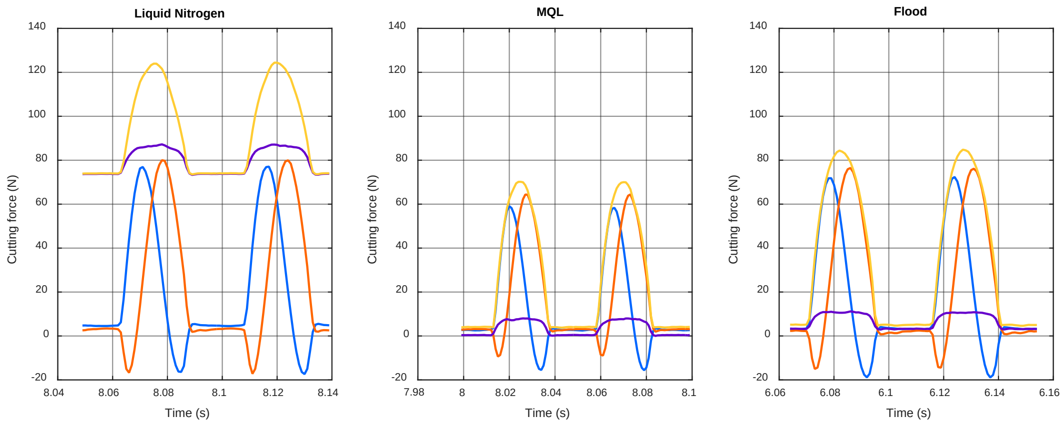


APPENDIX B-3
Sustainable End Milling of AMMC – Cutting Force

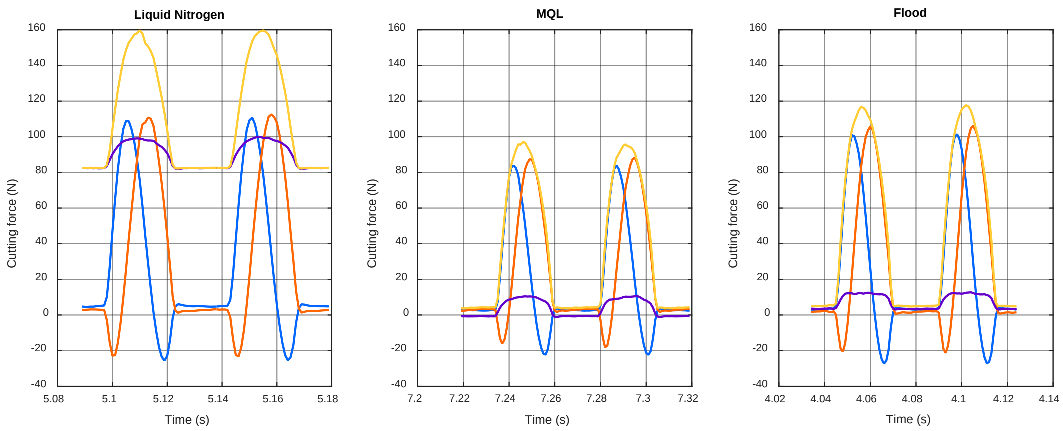
1. v = 50 m/min, f = 0.1 (mm/rev)



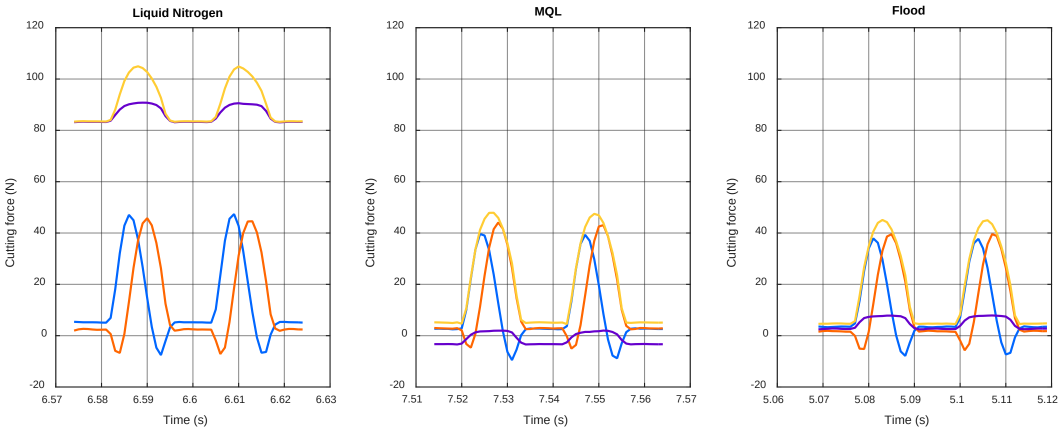
2. v = 50 m/min, f = 0.2 (mm/rev)



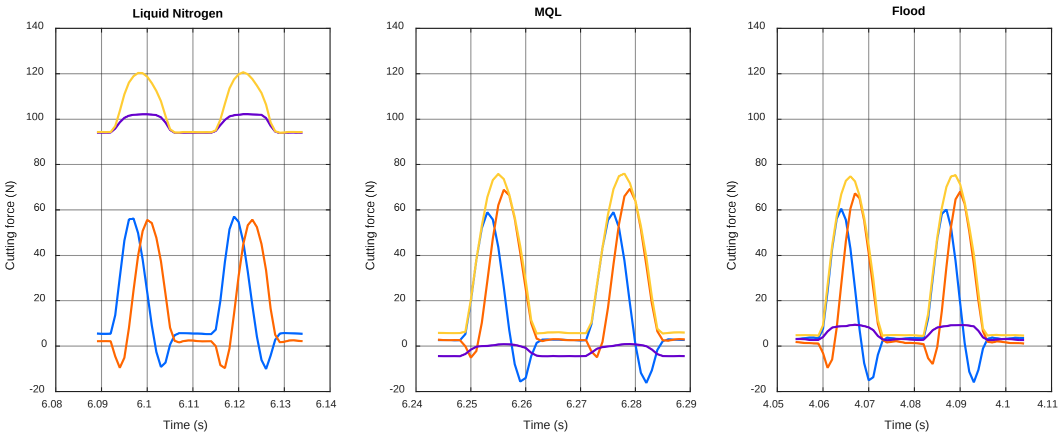
3. v = 50 m/min, f = 0.3 (mm/rev)



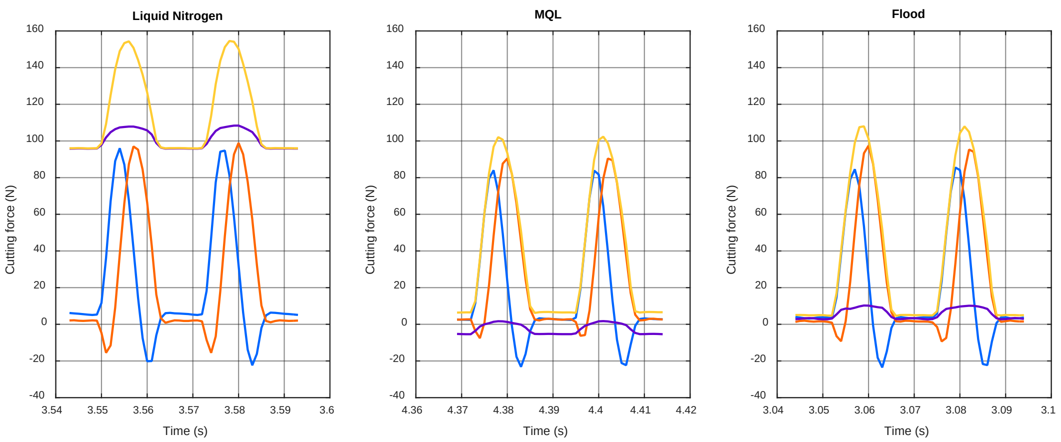
4. v = 100 m/min, f = 0.1 (mm/rev)



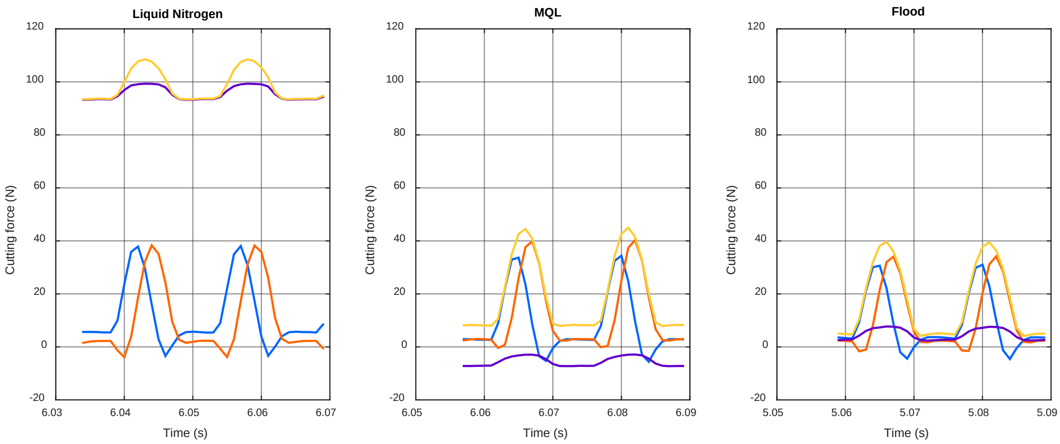
5. v = 100 m/min, f = 0.2 (mm/rev)



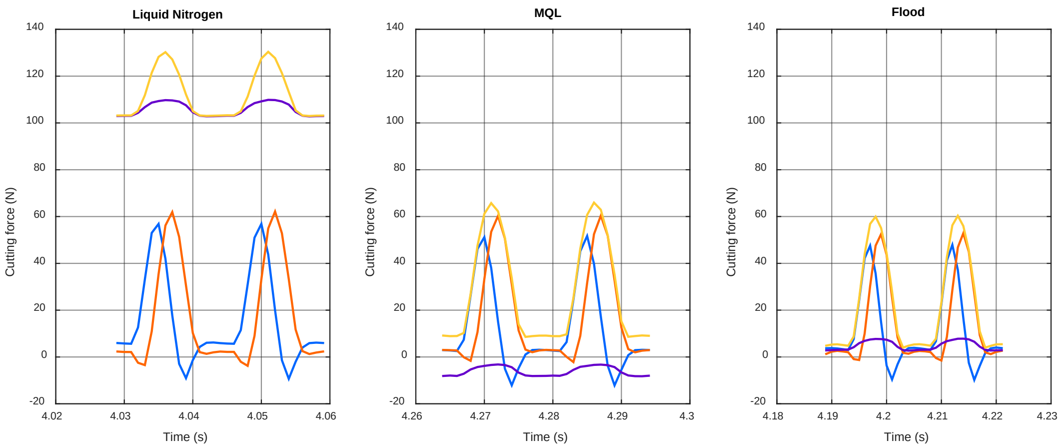
6. v = 100 m/min, f = 0.3 (mm/rev)



7. v = 150 m/min, f = 0.1 (mm/rev)



8. v = 150 m/min, f = 0.2 (mm/rev)



9. v = 150 m/min, f = 0.3 (mm/rev)