APPLICATION OF SUPERABSORBENT COOLANT AS A NOVEL APPROACH TO SEMI-DRY MACHINING

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Abstract

Cutting fluids play a significant role in manufacturing processes. Machining certain materials is impossible without them. Due to high temperature and friction during cutting operations, proper cooling and lubrication are necessary to improve the efficiency, quality of the final workpiece and to reduce tool failure costs.

This study presents a novel coolant suitable for different machining processes. The focus of this work is the application of a superabsorbent coolant (SAC) during hardened H13 steel machining, Inconel 718 turning, and aluminium silicon alloy tapping and drilling with an uncoated carbide tool. Hence, different machining operations have been attempted to better understand the range of function for SAC. Moreover, the possibility of superabsorbent material use as a coolant has been evaluated in comparison with dry and flood conditions. The use of SAC is a novel method of semi-dry machining that demonstrates the advantages of hydrogels as a coolant and opens a new window for industrial applications. SAC is a superabsorbent polymer enriched by a nanofluid and injected near the cutting zone. Its main purpose, besides improving machining performance, is to safely provide beneficial properties of nanoparticles (higher thermal conductivity and lubricity) and to prevent their distribution in air, which along with other chemical additives, can cause serious occupational and environmental hazards. The results of machining studies indicate that SAC can considerably reduce the friction conditions in the cutting zone, greatly reducing cutting force, while improving surface integrity and enhancing tool life. In addition, the friction conditions at the cutting zone have been improved. Ultimately, chip undersurface roughness was measured to ensure the penetration of the nanoparticles into the cutting region and to reduce friction between the tool and chip. The results show a lower surface roughness of the chip surface.

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Finally, none of this would have been possible without patient and lovely parents who have supported me in all parts of my life.

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Nomenclature

SAC – Superabsorbent Coolant

SAP – Superabsorbent Polymer

MQL – Minimum Quantity Lubrication

MQC – Minimum Quantity Cooling

EP – Extreme Pressure Additive

APS – Average Particle Size

DSC – Differential Scanning Calorimetry

SEM – Scanning Electron Microscopy

CNC – Computer Numerical Control

CoF – Coefficient of Friction

MWF – Metalworking Fluid

BUE – Built- up Edge

HPC – High Pressure Coolant

NF – Nanofluid

PSDZ – Primary Shear Deformation Zone

SSDZ – Secondary Shear Deformation Zone

TSDZ – Tertiary Shear Deformation Zone

Declaration of Academic Achievement

I, Yousef Shokoohi, declare this thesis to be my own work and I am the sole author of this work.

One part of this thesis, as is mentioned in thesis outline, is a collaborative work with another researcher in MMRI lab. Hence, to prevent any plagiarism issues, results of that study are contained in Appendix A.

To the best of my knowledge, the content of this document does not infringe on anyone's copyright.

My supervisor, Dr. Stephen Veldhuis and other technical staff in the MMRI lab have provided guidance and support at all stages of this project and I have completed all of the research work.

Chapter 1. Introduction

Over the past few decades, due to a greater demand for improving the efficiency of manufacturing processes, application of metalworking fluid has grown more extensive. During the last century, the nature of cutting fluids changed from a simple oil to a complicated water-oil based emulsion with numerous additives included to address corrosion and biological contamination issues, for example [1].

While this modification of cutting fluids did increase tool life and quality of the final workpiece, it also created many side effects in terms of post-processing, health hazards and environmental issues [2]. Water-based coolants can be dispersed in the air during machining which can exacerbate occupational health disorders and contaminate the work area. End of life disposal of these materials can impact water and soil, resulting in the potential for further health problems and harm to the environment [3].

1.1 Motivation

To address the aforementioned issues, a novel gel-based coolant has been introduced in this research that can be widely used in various machining processes: a superabsorbent polymer (SAP) developed to be a carrier for graphite, Copper and Magnesium Oxide nanoparticles. A superabsorbent polymer (SAP) is a type of material which can absorb liquids up to several hundred times its weight and is used in a wide range of applications such as drug delivery, diapers, filters, and separation processes [4].

Application of superabsorbents to carry lubricious nanoparticles as a potential eco-friendly coolant could lessen the dependence on petro-chemical based coolants and serve as a step towards greener manufacturing.

1.2 Research Objective

The main goals of the present work are:

1. Develop a new generation of coolants for semi-dry machining purposes with higher performance, controllable characteristics and safer conditions for the use of different nanoparticles or chemical additives during machining, with reduced dispersement in the air in the form of dust, mist or aerosol.

2. Increase the stability of nano- cutting fluids using hydrogels to alleviate sedimentation of nanoparticles, which is a big problem with nanofluid use in industry, particularly for cooling and lubrication purposes where materials need to have a relatively long shelf life.

3. Evaluate the performance of superabsorbent coolant (SAC) during different machining operations in terms of friction, chip undersurface roughness, cutting forces, tool wear, and workpiece quality.

1.3 Thesis Outline

This thesis is organized into six chapters and one appendix. Some parts of this writing have been taken from my recent publication "Evaluation of the Superabsorbent Coolant as a New Approach to Semi-Dry Machining" accepted by International Journal of Advanced Manufacturing Technology in November 2018 , and the idea of this thesis is protected by a provisional patent filed with the application number 65/557,966.

Additionally, further analysis of the performance of the SAC was conducted in a co-operative work with another researcher. Hence, to prevent any plagiarism issues, results of that study have been presented in Appendix A.

A brief summary of each chapter follows:

CHAPTER 1. INTRODUCTION- This chapter illustrates the motivation and research objective of the present work.

CHAPTER 2. LITERATURE REVIEW- This chapter discusses the history of metalworking fluids and detailed overview of different cooling techniques which have been developed by researchers along with their achievements in machining different alloys.

CHAPTER 3. EXPERIMENTAL DETAILS- This chapter explains material characteristics and machining conditions for each studied process and then describes a coolant preparation method with different nanoparticles. A new inexpensive and portable delivery system is also described, and different parameter measurements are provided.

CHAPTER 4. RESULTS AND DISCUSSION- This chapter contains the results of machining tests and detailed analysis to understand the reasons behind the observations.

CHAPTER 5. CONCLUSION- In this chapter a summary of all the observations and findings of the research is provided.

CHAPTER 6. FUTURE WORK AND RECOMMENDATIONS- This chapter proposes possible avenues for further investigations into SAC and provides recommendations for meeting specific industrial goals.

APPENDIX A. DRILLING AND TAPPING- This chapter is a collaborative work with another researcher. In order to prevent plagiarism issues it was included as an appendix. Experimental procedure and results of drilling and tapping tests on automotive die cast Aluminum Silicon with three different cooling strategies are reported in this section.

Chapter 2. Literature Review

2.1 Machining processes

Machining is a fundamental and essential manufacturing process which plays a significant role in the automotive, aerospace, power generation, medical component and mold/die industries. Widespread research on the mechanics of cutting demonstrated that during a cutting operation, there are two deformation zones: primary shear deformation zone (PSDZ) and secondary shear deformation zone (SSDZ) as shown in Figure 1. In the first, removal of excess material by plastic deformation and in the latter, friction between tool and chip are two sources of heat which can affect the performance of machining. There also exists another zone, which is the interaction between tool and the finished surface of the workpiece known as tertiary shear deformation zone (TSDZ). This area is important in cutting because it can directly influence the surface roughness and residual stress of the final part [5].

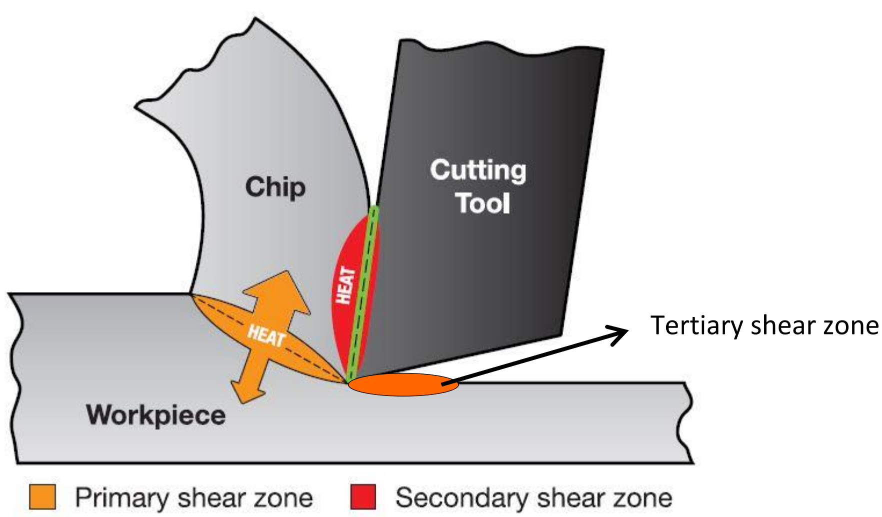


Figure 1 Schematic cross-section view of cutting zone [reprinted from [6] with permission]

Metal cutting can be accomplished by different methods. Normally, machining operations are classified into two main categories: conventional and non- conventional.

Conventional approaches are those in which material is removed through the interaction of a tool and workpiece. In this case, the tool needs to have high hardness to be able to deform the material and cut it into the desired shape and toughness to be able to withstand concentrated fatigue loading. Turning, milling, drilling and broaching are examples of conventional machining.

Non-conventional machining is when excess material is removed without interaction between a defined tool edge and the workpiece. These methods are categorized based on the source of energy that they use. The source of energy could be mechanical, electrical, thermal and chemical. Water jet machining (WJM), Ultrasonic machining (USM), Laser cutting, Ion beam machining (IBM), Electro discharge machining (EDM) and Electro chemical machining (ECM) are examples of common non-traditional techniques. There could also be a combination of conventional and non-conventional machining, which known as hybrid machining [7].

The focus of this study is the application of coolants under conventional/traditional machining methods, so it is worth briefly explaining some of the conventional methods used in this industry.

2.1.1 Turning

Turning is one of the most widespread processes of cutting materials [8]. Turning is commonly utilized to produce cylindrical parts in industry. In this process, a stationary tool that moves in only two directions (X and Z), interacts with a rotating workpiece at a certain depth of cut under which extra material is removed. For every material there exist optimized parameters such as depth of cut, feed rate, cutting speed and suitable cooling strategy. All of these parameters can affect the surface integrity of the workpiece, cost and energy efficiency of the process [9].

2.1.2 Milling

During the milling process, a multi-edge tool with rotary motion cuts the fixed workpiece on a machine-tool table. The tool or table may also undergo a linear motion. The main difference between milling and turning is that the tool typically rotates when milling while the workpiece rotates in turning. Because of this turning is a continuous operation where the tool is in constant contact with the workpiece, but milling is an interrupted cutting where each edge of the tool cuts the material for a short period of time and then exits the cut until it reaches the workpiece again [1]. This engagement and disengagement can cause thermal shock to the tool and needs to be precisely established by choosing suitable coolant and machining parameters.

2.1.3 Drilling

Drilling is a method to make holes in a workpiece with a rotary wedge-shaped tool that typically has a complex design. Complexities in drilling include managing the chips produced during drilling, which need to be evacuated from the hole. If they build up in the hole they may break the tool, reduce the quality of the hole and prevent cutting fluids from reaching the tool tip causing heat to build up, thus damaging the tool. [10].

2.1.4 Broaching

Broaching is a one pass machining process which removes excess material using a long stroke motion of the workpiece with respect to a tool. In this case, the operation is conducted by a long tool with multiple tips, such that each tip is positioned relative to the workpiece to remove material. The challenge is that cutting speeds are very low, making tool forces very high. Thus this operation requires considerable lubrication because of high friction between the tool and workpiece. Although broaching is a slow operation compared to other methods, it can create internal or external slots with various profiles simultaneously on a series of workpieces [10].

2.2 History of Metalworking Fluids

Application of metalworking fluids (MWF) is as old as metalworking itself. In ancient times people learned how to use oils in different applications such as wheels, axles, water proofing of ships and for manufacturing in forging and wire drawing to facilitate the process [1].

In the 15th century, Leonardo da Vinci designed a test setup to quantitatively investigate friction under different conditions [11]. Figure 2 shows this device.

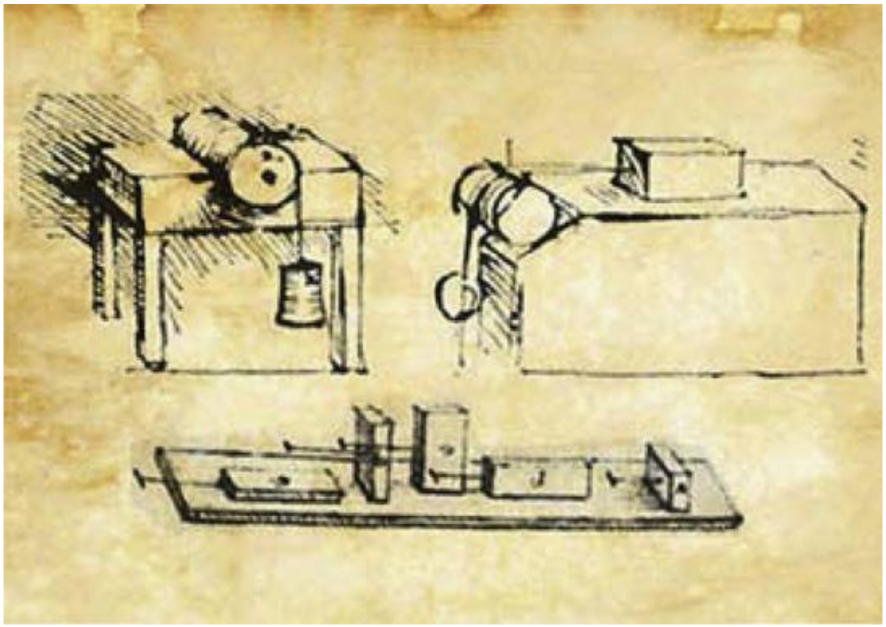


Figure 2 Leonardo da Vinci's design for friction measurement. [reprinted from [12] with permission]

Prior to the 19th century, primary MWF consisted of a combination of natural oils, water and some additives. Beginning with the 19th century, researchers discovered the importance of MWFs and lubrication at the same time as the first scientific investigations of the mechanics of friction and wear were performed. In the late 19th century, publications first mentioned that the lubricating properties of MWFs were capable of reducing tool-workpiece friction.

Over the course of the 20th century, due to mass production and application of new materials and alloys, different hazardous chemical additives such as chlorine and boric acid were added to the MWFs to improve the performance under high pressure and to reduce the percentage of costly mineral oil in MWFs. Meanwhile, Taylor observed that the material removal rate in a machining process could be increased up to 40 percent by applying water to the cutting zone during machining. This achievement led him to develop a novel system of circulating coolant.

In the 21th century, regulations are pushing MWF manufacturers to mitigate the amount of dangerous additives in MWFs and evaluate the human and environmental impacts [12].

2.2.1 Classification and Chemical Composition

To develop and increase the efficiency of manufacturing processes, various techniques have been incorporated into machining. For instance, the inherent heat generated during the high-speed material removal, the need to reduce the friction between the tool and workpiece, and the demand for more top quality surfaces of final products has led to the use of cutting fluids as coolants and lubricants during machining [13], and many operations cannot be carried out without the use of coolants [14]. Currently, MWFs serve as a coolant and lubricant that is applied during the machining processes to improve the tribological conditions between the tool, chip, and workpiece, stabilize the temperature in the cutting zone (avoid fluctuation and reduce heat generation) and facilitate chip removal [5]. Coolants usually are divided into three main categories based on DIN 51385: water- based (water soluble), oil-based and gases. Figure 3 displays this classification. Each type of cutting fluids is best suited for specific machining conditions.

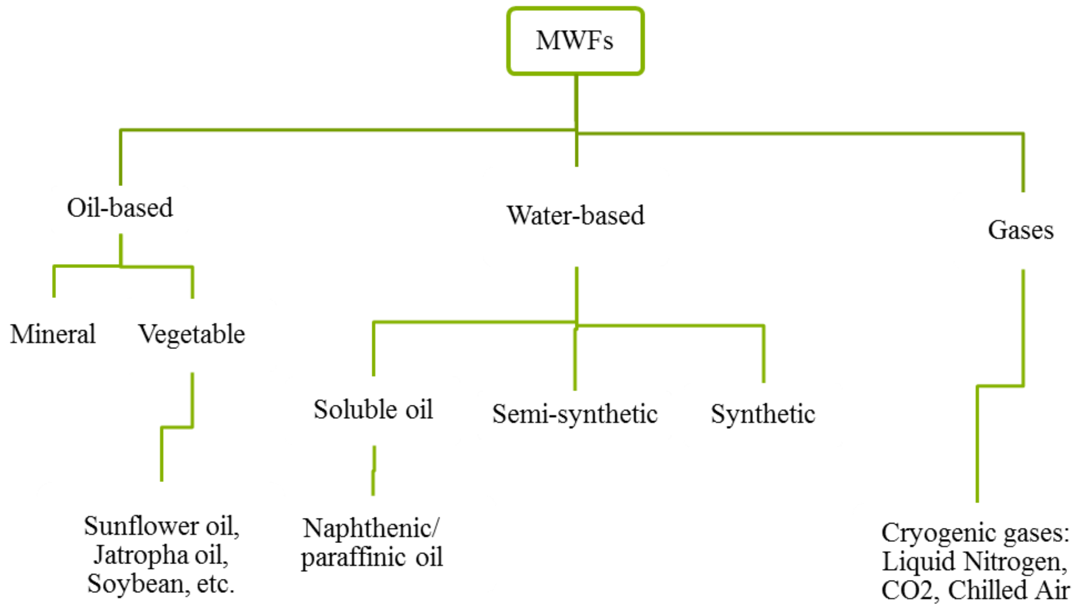


Figure 3 Classification of metalworking fluids (based on [1], [12] and [14])

When it comes to high speed machining where there is a relatively low pressure on the tool tip, water soluble coolants are preferred. Oil-based coolants are appropriate for lower cutting speeds and higher pressure. Cryogenic gases are desirable for conditions where high temperature poses a big challenge and fluids cannot penetrate into the cutting zone, such as high speed machining [14].

Generally, cooling action is more important when machining materials where the cutting zone temperature is high due to large scale material deformation and friction is significant at heavy machining and low cutting speeds [8].

MWF commonly consists of different ingredients to improve the performance in terms of friction, cooling and other factors like corrosion, stability over time and bio growth suppression. Table 1 shows some of the important components of synthetic and semi-synthetic coolants.

Table 1 Fundamental ingredients of coolants (Based on [15])

Component	Ingredients of semi-synthetic	% wt	Ingredients of synthetic	% wt
Emulsifier	✓	10-25		-
Oil	✓	5-50		-
EP additives	✓	2-15	✓	0-5
Corrosion inhibitor	✓	10-25		15-30
Rust inhibitor		-	✓	10
Coupler	✓	1-5	✓	1-5
pH buffer		-	✓	5
Biocide	✓	2-8	✓	1-5
Boundary lubricant	✓	2-15	✓	0-35
Water	✓	20-70	✓	40-70

To improve the efficiency of cutting fluids, compounders add various chemical substances. The importance of additives is not confined to machining but also plays a role after machining and post-processing. Extending tool life, providing acceptable finished surface, enhancing fluid stability and preventing rust on machine-tools are just some of the functions of additives [15]. However, every company utilizes a different "prescription" to meet customer's requirements. Some of the most common ones are listed in Table 2.

Table 2 Some of the important chemical additives in coolants and their functions (based on [1] and [12])

Component	Function
Fatty acid soap, alkylphenol ethoxylates, PEG esters, etc.	Emulsifier; to create a uniform oil in water emulsion with high stability
Silicone polymers	Antifoam; to prevent foam formation during coolant circulation and machining
Sulfur, phosphorus, Chlorineparaffin	EP (extreme pressure) additives; forms a layer

	on tool surface to prevent wear
Sulfonate, amine carboxylate, tall oil fatty acids	Corrosion and rust inhibitor; Protects surface from corrosion
Formaldehyde, Phenol derivatives	Biocide; to control bacterial growth
Propylene glycol	Coupler; to regulate viscosity of the MWF

2.3 Cooling Techniques

Cooling is one of the most critical challenges in the machining process and is faced by numerous industries such as automotive and aerospace. In recent years, methods such as cryogenic cooling [16], high pressure coolants [17], flood cooling [18], minimum quantity lubrication (MQL/MQCL) [19], and solid lubricants [20] have been developed in order to enhance the overall effectiveness of the machining process [3]. However, each of these methods has associated advantages and disadvantages.

2.3.1 Flood

Flood cooling is the most common method used in the manufacturing line [21]. It is easy to apply and re-use the coolant for an extended period, and it also flushes chips away from the cutting zone [22].

In order to understand the effect of cutting parameters and cutting fluids during milling AISI 304, Kuram et al. [18] applied two different vegetable based coolants, sunflower and canola oils, with 8% extreme pressure additive, in comparison with semi-synthetic cutting fluid. Vegetable based coolants were selected to reduce the environmental and operational side-effects. Results indicate that canola cutting fluid (CCF-II) performed better in terms of surface finish and specific energy. Considering overall cost, CCF-II is almost comparable with commercial semi-synthetic cutting fluid (CSSF).

Winter et al. [23] studied the application of glycerol-based coolant in the inner cylindrical grinding of hardened carbon alloy steel. Two different wheels, c-BN and Al_2O_3, were used with glycerol coolant and results were compared to grinding oil and mineral based emulsion. The glycerol-based fluid provided a better surface finish and less grinding wheel wear as compared with other cutting fluids. Furthermore, the application of MWFs has a larger impact on performance at higher material removal rates rather than lower ones due to the higher levels of energy involved.

Grosse et al. [24] conducted honing on grey cast iron with a different type of lubricant which is known as a polymer dilution. Testing was performed under various concentrations, rotational speeds, and contact pressures to find out which concentration results in the best performance. Results revealed that increasing the polymer dilution concentration lead to better surface finish at higher rotational speeds. However, at low rotational speeds and contact pressures, up to 5% polymer concentration showed a lower rate of honing stone wear.

Currently, there is less focus on utilizing flood coolant techniques for machining purposes because conventional cooling techniques conflict with new environmental restrictions and health/safety practices [25].

Brinksmeier et al. [12] has speculated that 23% of occupational disease in Germany is related to exposure to MWFs. According to Weinert et al. between 7 and 17% of the manufacturing cost goes toward metalworking fluids [26]. Alternatives to flood cooling are sought to lower the costs associated with purchasing and disposing of cutting fluids, as well as reducing their environmental and health impacts [18]. Due to this trend new cooling and lubricating technologies such as MQL, high-pressure cooling, and the use of nanofluids are becoming more popular. However, despite the promising features that many investigators have reported when using these methods, there are some drawbacks to their practical application in industry [9].

2.3.2 MQL

Minimum quantity lubrication (MQL) was designed to simultaneously use the benefits of both dry and wet conditions [2]. The heat dissipation method in MQL is mostly due to evaporation rather than conduction and convection realized in flood based coolant approaches [8].

Application of various vegetable-based fluids during form tapping of A306 cast aluminum alloy with MQL strategy was investigated. The use of MQL was found to reduce the torque value by 17% as compared to the use of conventional coolants. Specifically, it was mentioned that Ecocut fluid is more effective in reducing friction and torque, consequently preventing tool breakage [27]. Furthermore, from an environmental point of view, MQL has a lower environmental impact. Whereas conventional cooling needs to be recycled and disposed of after usage, MQL provides better cooling while consuming minimum fluid volumes. Parts still need to be washed, but the consumption of liquids is lower so recirculation is not needed resulting in reduced waste treatment after the liquid is used.

Liao et al. [28] applied minimum quantity lubrication (MQL), in high-speed end milling of NAK80 hardened steel with coated carbide tools. Their results show that, despite the positive effect of MQL on the finished surface and tool life, it was unsuccessful in decreasing the cutting forces compared to flood cooling across all milling speeds.

Joshi et al. [29] studied the performance of MQL, flood and dry techniques in machining Incoloy 800. Two flow rates for MQL were chosen (150 and 230 ml/h) and compared to a flood condition set at 600ml/h. MQL with 230 ml/h flow rate showed superior performance both in tool life and surface quality as compared to the use of a flood based coolant approach.

Grinding GH4169 nickel –based alloy was performed under MQL and flood strategies with seven different vegetable oils and liquid paraffin oil. The aim of this research was to compare the efficiency of vegetable oils in an MQL based grinding operation to one using flood cooling. Results indicate that vegetable oils could achieve a higher G-ratio which is the volume of removed material divided by volume of grinding wheel wear) , a better surface finish and a lower CoF due to existence of oleic acid, ricinoleic acid and more fatty acids which could improve lubrication feature of the vegetable oils. For instance, specific grinding energy and CoF for Caster oil were 73.47 J/mm^3 and 0.3, respectively, which represents a 49.4% and 50.1% reduction in these values in comparison to a flood coolant method [30].

Rahim et al. [31] investigated the superiority of MQL over dry turning of AISI 1045 with an uncoated carbide insert. Orthogonal cutting was chosen and cutting temperature, cutting force, tool-chip contact length and chip thickness were measured. They concluded that MQL was able to reduce the cutting zone temperature about 10-30% and cutting force up to 28%. Furthermore, observations from conducting a standard four ball friction test revealed that synthetic ester oil which generates a CoF of 0.08 could facilitate a favourable frictional condition between the tool and chip.

In another study, Kaynak [32] machined a difficult-to-cut Inconel 718 alloy to compare cryogenic machining with MQL and dry conditions. His experiments showed that applying MQL at the low cutting speed of 60 m/min resulted in a more moderate cutting force than cryogenic or dry machining. However, at a high cutting speed (120 m/min), the force components in cryogenic machining were lower than in the other two methods. Neither of the chosen methods reduced the progressive notch wear or addressed the chip breakability issue. It was also mentioned that the main drawbacks of using the cryogenic method are the high cost of liquid nitrogen and the need to precool the workpiece, which can lead to hardening of the workpiece material and dimensional variation during machining [16].

In most of the scientific notes, MQL machining is described as an environmentally friendly technique. However, this technique does not protect operators from respiratory diseases, because some of the cutting fluid still becomes airborne and disperses around the machine. This can be harmful to the operator’s health. Another drawback of MQL is its requirement to use often expensive and noisy equipment [3].

2.3.3 Cryogenic

In the cryogenic approach, liquid nitrogen at -196°C is applied as a cooling agent and has been found to be beneficial when machining many types of materials. Liquid nitrogen absorbs heat and evaporates into the air, so it has been found to be beneficial for reducing diffusion related tool wear issues when machining [8]. Liquid nitrogen also evaporates into the air leaving no residue or unfavourable by-products. In this way this method directly addresses the environmental concerns associated with coolant disposal because it does not generate any waste or extra residue [33].

Cryogenic machining was done on two different steels, AISI 1040 and E4340C, with two carbide tools to better understand the effect of tool geometry on the process when utilizing liquid nitrogen as coolant. Compared with dry turning, cryogenic cooling can decrease the secondary shear deformation zone temperature by up to 34%. A reduction in the contact zone temperature through this technique can postpone diffusion wear, which leads to less tool wear and built-up edge (BUE) formation. Additionally, improving tool wear increased the surface quality and dimensional accuracy of the workpiece. It was also demonstrated that tool geometry affects the effectiveness of cryogenic machining by enabling greater liquid nitrogen flow into the cutting zone [34].

Bermingham et al. [35] evaluated tool life and chip morphology when using cryogenic and high-pressure coolant strategies in turning Ti-6Al-4V and found that both methods improve tool life as compared to the use of dry conditions, but that neither was able to reduce the cutting temperature sufficiently to prevent diffusion wear. They also noted that cryogenic cooling is more sensitive to nozzle position than the use of a high-pressure coolant.

Considering surface quality, cryogenic cooling demonstrated lower surface roughness values as compared to dry turning of AISI 52100. However, while this method improves the surface integrity of the workpiece, by reducing the white layer thickness, and achieves a smaller grain size on the surface of the part, dry machining results in a higher compressive residual stress on the surface that has been found to enhance the fatigue life of a part [36].

The turning of AISI 1040 medium carbon steel with an uncoated tungsten carbide was evaluated under dry and cryogenic conditions by Gupta et al. Liquid Nitrogen delivered at a pressure of almost 5 atm externally on the rake face of the insert was studied. In this study the use of cryogenic machining conditions achieved a 55.45% to 65.53% improvement in tool life and up to 125.9% and 96.6% reduction in surface roughness and cutting forces, respectively, as compared to dry machining [16].

Studies performed using cryogenic and dry machining of magnesium alloy ZK60 with multiple feed rate and cutting speeds was done by Dinesh et al. [37]. They applied liquid nitrogen on the machined surface, and an uncoated tungsten carbide tool was used in their cutting test. Their results revealed that cutting temperature and surface roughness decreased up to 60% and 40%, respectively, when cryogenic cooling was utilized. A further improvement of hardness value (40%) was observed during micro hardness testing of the machined surface. At a relatively high cutting speed of 120m/min the cutting and thrust forces for the dry cutting condition were less than that of the cryogenic one due to the thermal softening of the workpiece. In this study the cutting forces were observed to be lower.

2.3.4 High Pressure Coolant (HPC)

High pressure cooling is another approach which has been developed in recent decades, and the idea is to use coolant jets operating under 100 to 1000 atm aimed to the tool-chip and tool-workpiece contact area so that greater penetration into the cutting zone can be achieved [2][8]. HPC was observed to work well during a turning operation because of its ability to manage the constant contact pressure between the tool and work material. Use of HPC was found to enhance chip breakability and effectively reduces cutting temperature. Furthermore, the use of through-tool HPC in drilling was found to improve chip evacuation and facilitated the drilling operation, thus prolonging tool life [15].

Mia and Dhar [38], applied Taguchi method to optimize the machining parameters of three types of hardened steel while using HPC. They indicated that material hardness and the localized cooling condition appear to be the most effective factors in determining cutting temperature and workpiece roughness. After studying different combinations of cutting conditions and cooling environments the use of HPC was found to decrease surface roughness and temperature by approximately 13 and 11%, respectively.

Ceramic tools are known for their high hardness and abrasion resistance but they have known issues related to thermal shock. In order to understand the influence of coolant on ceramic tools, Vagnorius and Sorby [39] carried out a machining study on Inconel 718 with SiAlON under HPC and conventional coolant. They reported smaller chips as well as lower flank wear and chip contact length while using HPC, because the coolant in this method can achieve a greater penetration into the tool-chip contact area and dissipate heat faster than the flood coolant.

Fang and Obikawa [40], introduced a novel concept to conduct HPC with 13 MPa through the insert during Inconel 718 machining. Channels were made by electric discharge machining (EDM) on the flank side of the inserts and the idea was to improve heat extraction from the tool tip by creating a turbulent flow. They reported that the tool life with this method, regardless of the depth of cut, was double that of a regular high pressure technique. The findings were supported by CFD simulation which confirms the turbulent flow at the entrance of the channel.

Another study on Inconel 718 during rough turning with a PVD TiAlN coated carbide assisted by a high pressure jet, was performed by Courbon et al. [41]. This method could reduce cutting temperature by 30% compared to the flood cooling method. Other benefits of HPC include remarkable chip breakability and less BUE allow the increase of cutting parameters such as speed and feed rate.

Klocke et al. [17] addressed the application of HPC from a different point of view. Although adding HPC to a machine increases the productivity and machinability of the problematic materials, it places an extra equipment demand on the machine tool and consumes more energy. For example, Inconel 718 was machined under both a low pressure flood coolant and HPC to compare their individual energy consumption and footprint. It was found that the HPC technique is suitable for processes and materials where chip breakage is a major challenge. High pressure cooling also poses health issues, as coolant vapour is harmful to the operator.

2.3.5 Solid Lubricant

Researchers also developed solid lubricants to reduce the environmental effects of machining processes. Solid lubricant, in the form of a powder or thin film, protects surfaces by reducing friction between the tool and the workpiece and, consequently, minimizing the wear of the tool [42]. Utilizing boric acid powder with uncoated cemented carbide in the turning of Aluminum alloy showed a 5 to 25% surface finish improvement [43].

Reddy and Rao [13], conducted end milling tests on AISI 1045 with various tool geometries. Graphite and molybdenum disulphide fine powder with 2µm average particle size was fed near the tool tip. They concluded that this strategy achieved lower cutting forces, specific energy and surface roughness. These improvements were greater for molybdenum disulphide than graphite and conventional cooling, which is probably related to its “layer- lattice structure”. Moreover, it was stated that strong adhesion of MoS_2 particles to the surface may be the reason for the superior performance compared to graphite particles.

Rao and Krishna [44], evaluated the importance of solid lubricant particle size in the turning of EN 8 steel. Graphite and boric acid with four different particle sizes ranging from 50 to 200 µm were applied by a powder feeding system with an adjacent air connection to propel the powder to the machining point. They concluded that boric acid with the smallest particle size was the most effective solid lubricant due to lower cutting force and tool wear generation and relative harmlessness for the operator and the environment.

Utilizing an electrostatic solid lubrication system as a new method of graphite powder delivery was suggested by Reddy et al. [20] for the drilling of AISI 4340 steel. The purpose was to provide a uniform and constant solid lubricant to the tool tip. It was demonstrated that, under this method, graphite mixture better penetrates to the cutting zone, thus improving tool life. Moreover, the lubricating property of the graphite mixture film reduced friction, and in turn, resulted in a smaller thrust force and better surface finish.

Graphite and molybdenum disulphide were employed during the hard turning of AISI 52100 steel with a mixed ceramic tool under variable tool geometry and cutting conditions. Results revealed that the benefits of MoS_2 as a solid lubricant in reducing cutting forces and surface roughness were superior to graphite. Additionally, tool parameters play a significant role in determining machining performance. Thus, the appropriate combination of rake angle, nose radius and lubricant is necessary to obtain the most efficient conditions [45].

In a recent investigation by Sartori et al. [46] an attempt was made to enhance the efficiency of the solid lubricant by combining MQL and MQC techniques. In this case, an aqueous solution, enriched with different graphite percentages as a “solid lubricant-assisted MQC” along with a vegetable oil which contained PTFE as a “solid lubricant-assisted MQL” was used for the turning of a Ti-6Al-4V titanium alloy. The solid lubricant-assisted MQC exhibited a 36% improved minimum tool wear and surface integrity over pure MQL due to water cooling and high lubricity of the graphite additive.

While solid lubricants demonstrate a noticeable improvement in the machining processes, they are difficult to apply as a powder and suspended in a thick emulsion or paste. Not only is it challenging to suspend them into an emulsion, but also particles stick to the surface of the chip and the workpiece after machining, making it hard to clean the machine parts [15].

2.3.6 Nanofluids

A nanofluid (NF) is created by the uniform distribution of solid nanoparticles within a fluid. NFs normally have higher thermal conductivity and lubricity compared with regular fluids [9]. They are used in a wide range of applications such as engine cooling, water heating with solar energy, chillers and manufacturing processes. The purpose of applying NF in machining is to use the lubricity of nanoparticles to decrease the friction between surfaces in cutting zone [9] and [47].

Li et al. [48] compared six different nanofluids in vegetable-based oil with the MQL technique on a nickel-based alloy. They found that carbon nanotubes (CNT) produced the lowest grinding temperature because their high thermal conductivity transferred heat faster from the grinding zone and because of the low surface tension and large contact angle of the CNT particle-rich fluid compared to other nanofluids.

Micro-drilling of aluminum 6061 with NFs applied by MQL indicated that nano-diamond particles in paraffin oil-based liquids decreased the drilling forces and torques as well as improved the quality of the drilled holes. It was determined that the nanoparticles prevented chip adhesion to the drill [49].

Mao et al. [50] demonstrated the advantages of MQL with NF over pure MQL in a grinding operation. A pin-on-disk tribometer was used to determine the coefficient of friction while applying a nanofluid containing Al_2O_3 and MoS_2. NFs showed a reduction in tangential grinding force and grinding force ratio as well as a reduction in the coefficient of friction by approximately 34%. This is probably associated with the rolling effect of spherical nanoparticles acting to decrease surface to surface contact.

Chetan et al. [51] prepared NFs with alumina and silver nanoparticles and employed them for turning Nimonic 90 with MQL. Wettability of the NF droplets was examined by contact angle and surface tension measurements before machining tests, and it was found that the Alumina (Al_2O_3) NF had the lowest contact angle and surface tension as well as smaller droplets. The vegetable-based emulsion formed larger droplets. It was reported that tribo- film formation on the rake face of the tool upon which the Al_2O_3 NF was applied protects the tool by lowering cutting forces and tool wear. The silver NF contributes to BUE reduction at higher concentrations and flow rates.

To address environmental concerns, Talib et al. [52] used crude jatropha oil, a sustainable and biodegradeable vegetable oil, mixed with hexagonal boron nitride (hBN) nanoparticles as a cutting fluid. They used the four ball test and torque measurement in tapping to evaluate the tribological behaviour of different concentrations of hBN in jatropha oil. The lowest concentration of hBN showed a significant decrease of approximately 75% and 25% in friction and wear, respectively, and an 18% improvement in tapping torque. However, greater concentrations of nanoparticles resulted in concentration of stress and, consequently, abrasive wear.

The effect of nanoparticle concentration on coolant performance was also verified by Zhang et al. [53]. A certain percentage of nano-additive is required to show the best lubricity, otherwise agglomeration impact affects the surface roughness and grinding force ratio.

Ultimately, after weighing the evidence and reviewing different methods, Table 3 briefly illustrates some of the problems associated with each cooling technique.

Table 3 Challenges of different cooling techniques

Cooling technique	Challenges and Problems	References
Flood	Environmental and operator problems (especially for petrochemical based oils), messy	[20]
Cryogenic	Costly, not suitable for hard materials, the high temperature gradient in tool tip can lead to tool crack and failure	[14], [54]
MQL	Needs compressor, noisy, supplying constant air pressure for long periods in a manufacturing line is difficult and costly, particular delivery system and nozzle are needed	[3]
High-pressure coolant	specialized equipment is needed, messy, fast nozzle wear, high energy consumption	[55]
Nanofluids	Sedimentation is a big challenge; some nanoparticles are harmful to humans, very costly	[47], [22]
Solid lubricant	Injection into the cutting zone is problematic, should be suspended in emulsions or media, generates dust during machining	[1]

In the next chapter, a coolant preparation method, the experimental procedure of each test, and tools utilized to measure machining parameters will be described in detail.

Chapter 3. Experimental Details

3.1 Coolant Preparation and Delivery System

Based on the manufacturer's suggestion, a semi-synthetic soluble oil in the ratio of 1:10 was added to water and used as a flood coolant. The concentrations of the cutting fluid measured before and after the tests were 9.5% and 10%, respectively. This small change is due to the evaporation of water during the machining tests caused by heat and high surface area. This concentration was applied for both the milling of H13 and turning of Inconel 718. A change in concentration of this level is not expected to affect the final results.

The main focus of this study is another coolant, prepared with various additives, which is known as SAC or Superabsorbent Coolant. Prior to any description of this coolant, the superabsorbent polymer and its effects will be discussed. The composition of SAC will be provided in detail in section 3.1.2.

3.1.1 What is Superabsorbent?

A superabsorbent polymer (SAP) is a type of material which can absorb up to several hundred times its weight in liquid and is used in a wide range of applications such as drug delivery, diapers, filters and separation processes [4]. Superabsorbents are primarily produced from cellulose and polymers such as polyvinyl alcohol (PVA). Over time, more cost-effective polymers such as poly acrylic acid and poly acrylamide have been introduced to the market. Figure 4 shows how SAP particles absorb and trap water in their structure. The coiled structure of the SAP particles acts like a network prior to adsorption and prevents disintegration of the powder into an aqueous solution. Upon contact with water, the bonds stretch as much as possible and absorb liquid into the matrix. It was mentioned that this is caused by of the elastic retraction of the network [56].

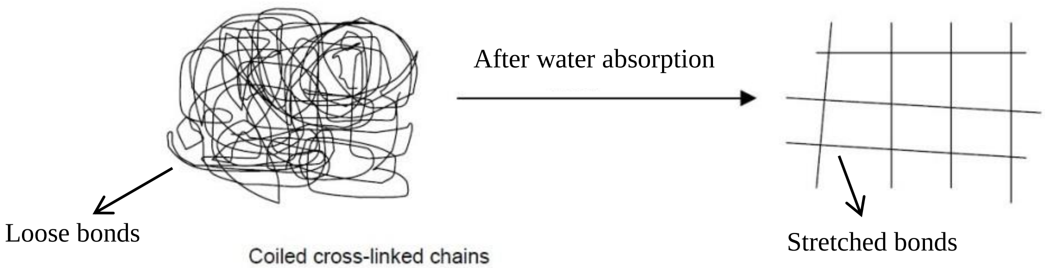


Figure 4 SAP structure before and after exposure to water (Based on [56])

Superabsorbent powders are commercially available in different formulas and they are normally used to absorb hydrophilic liquids. Equation 1 [57] shows the absorbency ratio of the superabsorbent polymers. Solutions with a greater concentration of soluble substances show a lower absorbency ratio.

$$Absorbency\ Ratio = \frac{Weight\ of\ liquid}{Weight\ of\ polymer\ added} \tag{1}$$

In this research, a SAP known as Wastelock 770, which is a cross-linked Sodium Polyacrylate produced by M2polymer Technologies, Inc., was used. The company reports in their MSDS file that after usage, the residual powder can be easily flushed with water for regular wastewater treatment. If in a solid form, it is suitable for solid waste landfill disposal [58].

3.1.2 Coolant Composition

To prepare the SAC for a milling operation, graphite nanoparticles were added to soluble oil and mixed with a magnetic stirrer for 20 min. Next, water was added to the suspension, which was immersed in an ultrasonic bath for two hours to disperse the nanoparticles uniformly in the fluid. Finally, the superabsorbent polymer was added to the nanofluid and allowed to gel for about 10 minutes. One of the most critical issues with nanofluid use in industry, especially as cutting fluids, is the sedimentation of nanoparticles over time and their dispersal into the environment. This changes the thermal conductivity and lubricity of the fluid and can lead to environmental hazards depending on the composition of the nanoparticles. However, when a superabsorbent polymer is applied, the nanoparticles penetrate the porous network of the polymer, remain stable indefinitely and are not free to leave the cutting surfaces. Figure 5 outlines the ingredients for the preparation of one kilogram of SAC, Figure 6 provides characteristics for the nanoparticles that were used in this study, and Figure 7 summarizes the sequence for SAC preparation.

The same procedure was used when copper (Cu) and Magnesium Oxide (MgO) was added instead of graphite for cutting Inconel 718. The only difference is that the percentage of graphite was 1% and Cu and MgO 1.5 % wt. The reason was that adding more graphite lead to the sedimentation of extra particles, so it seems that 1% wt. was suitable in this case. The absorbency ratio (equation 1) in this case was about 50 for SAP when graphite and copper were additives, and a slightly less for the coolant containing Magnesium Oxide (approximately 40).

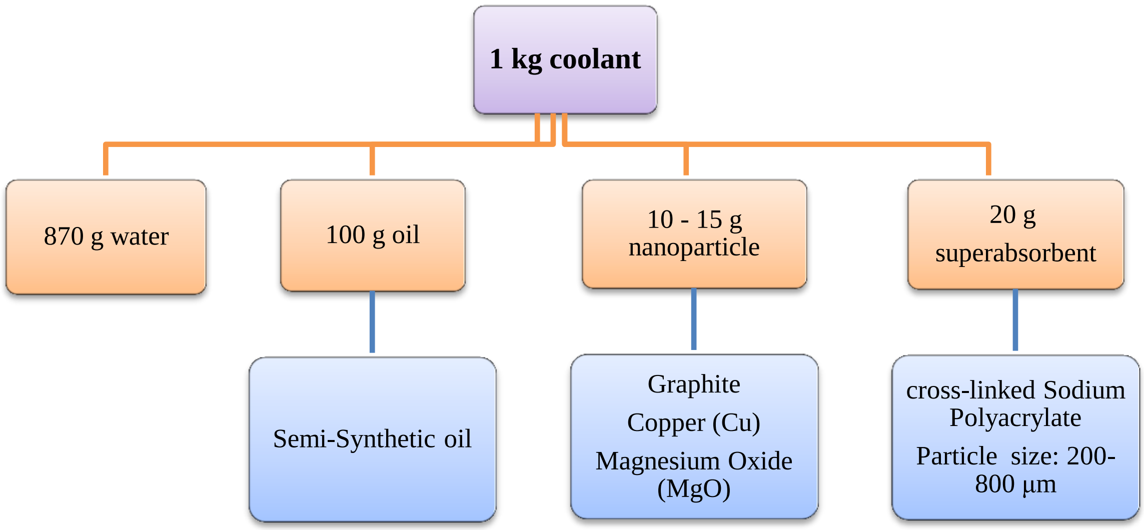


Figure 5 SAC ingredients (percentage of different additives in SAC)

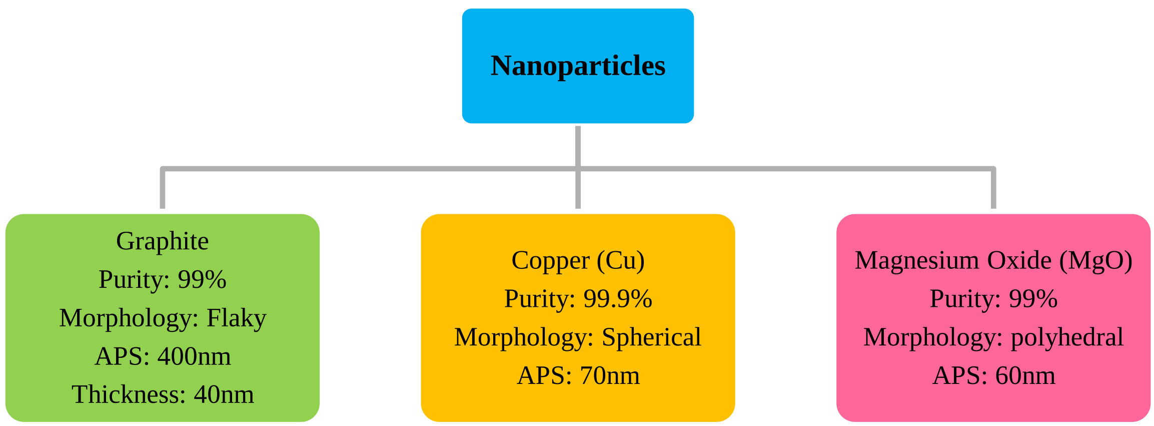


Figure 6 Information about nanoparticles used for machining tests

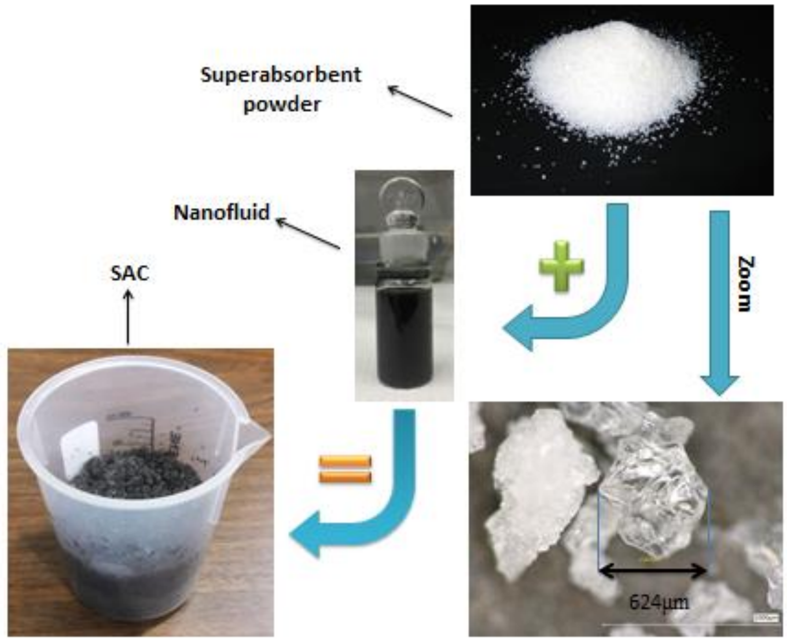


Figure 7 Sequence of the SAC preparation (polymer powder is mixed with a nanofluid, and after 10 min stabilization, SAC is ready for use.)

After the preparation of SAC, one of the polymer particles was dissected and imaged using SEM to determine whether the nanoparticles are embedded in the polymer network or only adhered to the surface. For the best stability, it is necessary to have nanoparticles embedded deep inside the porous structure of the superabsorbent particle. Figures 8-10 show a cross-sectional view of a superabsorbent particle under SEM and confirm the presence of nanoparticles throughout the polymer structure.

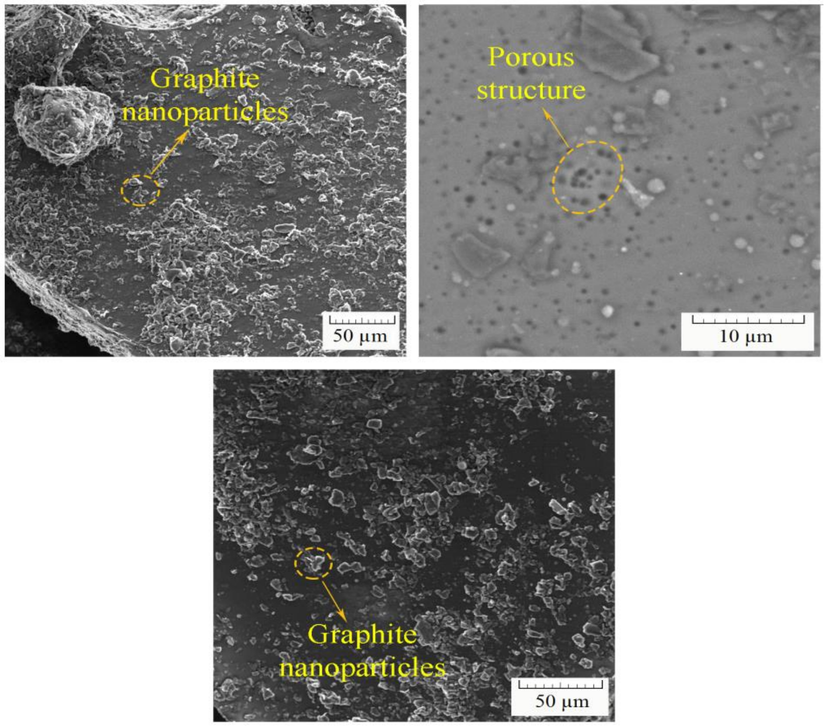


Figure 8 SEM cross-sectional view of SAC particles with graphite nanoparticles at different magnifications demonstrating that the nanoparticles are preserved

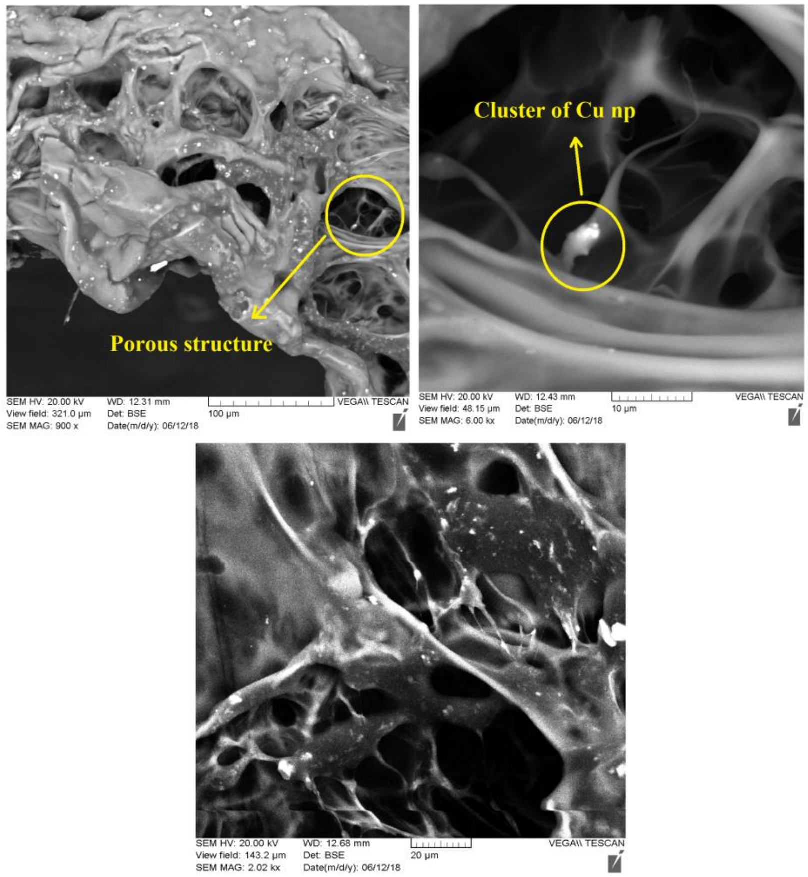


Figure 9 SEM cross-sectional view of SAC particles with copper nanoparticles at different magnifications demonstrating that the nanoparticles are preserved

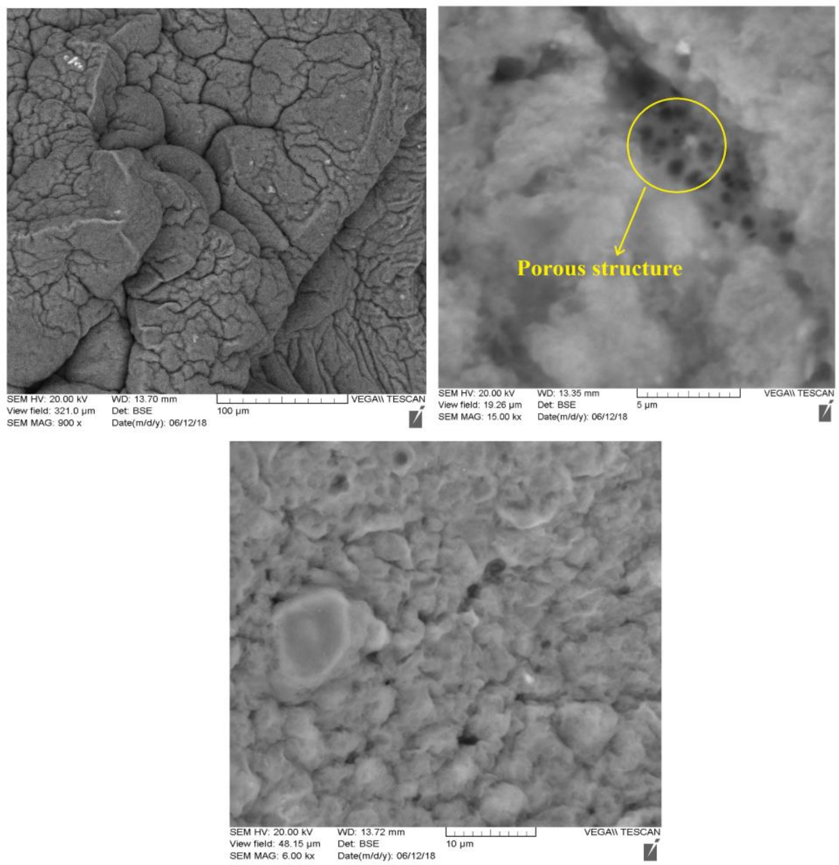


Figure 10 SEM cross-sectional view of SAC particles with MgO nanoparticles (even at high magnification porous structure is not really visible)

3.1.3 Delivery System

For dry milling, compressed air with a pressure of about 4.5 atm was used for chip evacuation to prevent re-cutting of the chips. The nozzle position for the flood coolant was chosen according to previous work on milling of steel ST60: nozzle feed position, elevation angle, and distance of the nozzle tip from the tool were set at 120°, 60° and 30mm respectively [22]. The coolant pressure was set to 1.8 MPa and flow rate to 9.7 L/min on the milling machine. Due to the viscosity of the SAC, it was not possible to pump it efficiently using a typical flood cooling system. Thus, to deliver the SAC gel to the cutting region, a 200mL syringe was used. Approximately 45 mL/min of SAC was used for each pass. Because SAC was applied to the surface before machining, there was no flow rate or coolant pressure. The adhesive nature of the gel caused some of the chips to stick to the gel, leading to re-cutting of the chips. To solve this problem, a compressed air nozzle with 3 atm pressure was positioned to remove the chips from the cutting zone.

Table 4 includes coolant characteristics, and Figure 11 illustrates the viscosity of SAC at different shear rates measured by DHR-2 (Dynamic Hybrid Rheometer). A ThermTest TPS 2500 S Thermal Constants Analyzer with 20 second test time was used to measure the thermal conductivity of the coolants.

Table 4 Coolant characteristics

Coolant	Viscosity @ 25°C (Pa.S)	Thermal conductivity ($W.m^{-1}.k^{-1}$)
Graphite nanoparticles	-	-
Copper nanoparticles	-	-
Magnesium Oxide nanoparticles	-	-
Semi-synthetic coolant	1.71	0.58
SAC (with graphite additive)	Figure11	0.60
SAC (with copper additive)	Figure11	0.58
SAC (with Magnesium Oxide additive)	Figure11	0.62
SAC without nanoparticles	Figure11	0.56
Vegetable oil (sun flower) [3]	-	0.14

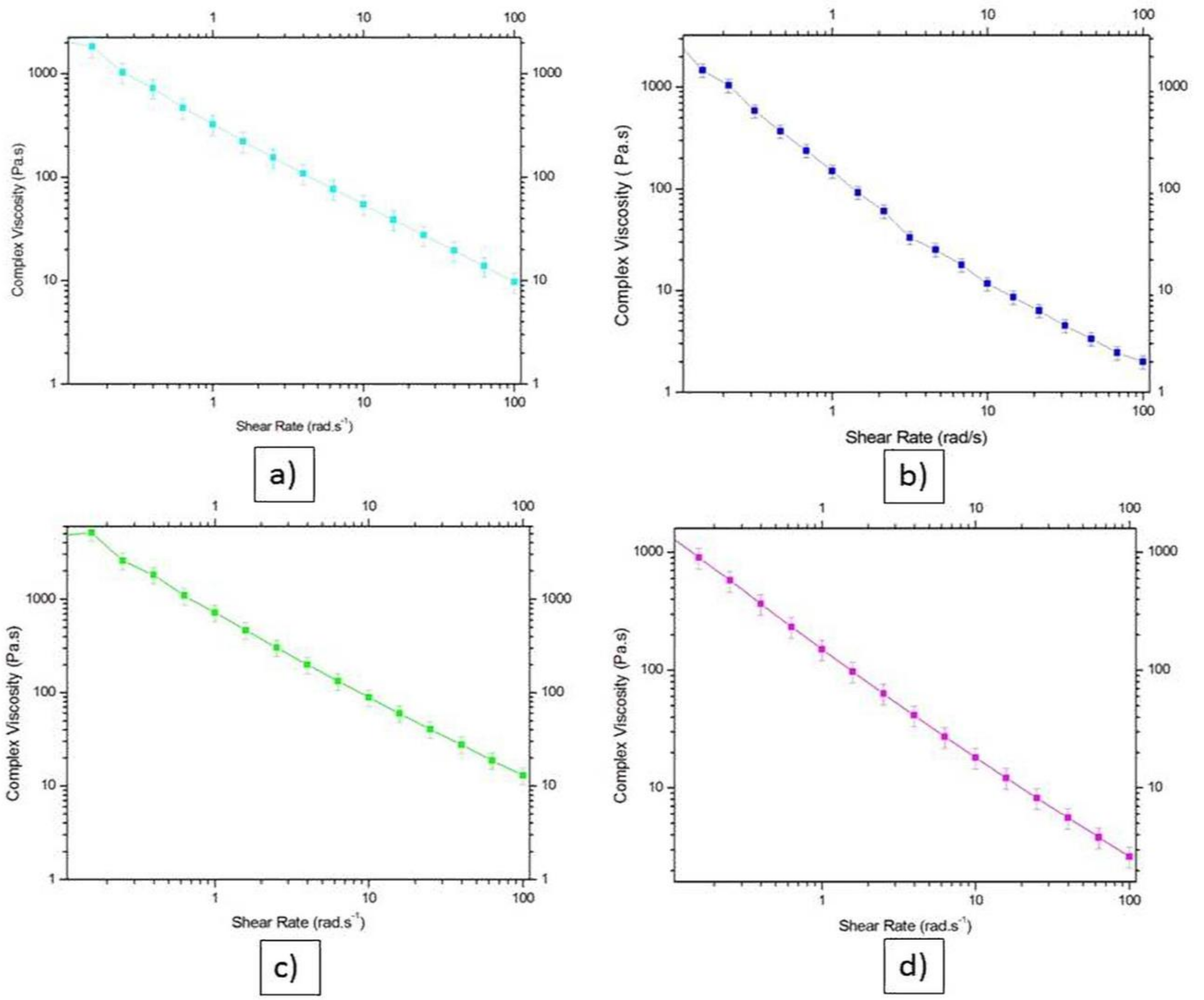


Figure 11 Viscosity measurement of SAC containing various nano- additives; a) SAC without nanoparticles, b) SAC with Graphite nanoparticles, c) SAC with Copper nanoparticles and d) SAC with Magnesium Oxide nanoparticles showing different values depending on the shear rate (due to its non-Newtonian behaviour)

During turning of Inconel 718, compressed air was removed because dry cutting has stopped. Then, flood coolant with a flow rate of 86 L/min and 13.6 atm pressure was used. The condition for applying SAC was developed, and a new inexpensive delivery system for continuous and uniform pressure and flow rate was designed and built (Figure 12). The operating mechanism of the new system is easy to use and applicable for most machine tools. An ABS pipe with internal diameter of 76 mm and length of 50 cm was chosen, and one end was connected to the air pressure regulator and the other to a valve which controls flow rate. Then, a valve with a plastic hose and a couple of fittings was connected to a flow distributor. This allows SAC to be applied near the cutting point with a regular nozzle. SAC added to the pipe is pushed downward by air pressure applied from the top, forcing it through the hose. The normal pressure required for this process is about 1.36 atm. This device can be attached to any machine by two magnets.

Figure 12 New gel delivery system

3.2 Materials and Methods

Machining conditions, which include cutting parameters, material characteristics and tools, will be discussed in this section under two subheadings.

3.2.1 Machining Conditions for H13

For this investigation, machining was performed under dry, flood and SAC conditions so that the results could be compared. Machining conditions and parameters are listed in Table 5.

Table 5 Machining conditions for milling H13

Machine tool	***Makino MC56 CNC milling***
Operation	*Side Milling*
Tool	*Uncoated Carbide tool*
Tool Diameter	*10 mm*
Cutting Speed	*35 m/min*
Feed rate	*480mm/min*
Axial depth of cut	*10 mm*
Radial depth of cut	*0.2 mm*
Length of each pass	*265mm*
Material removal rate	*960 mm^3/min*
Measuring parameters	*Cutting force, tool wear, chip undersurface roughness and surface roughness*

Milling tests were done on hardened H13 steel (Table 6).

Table 6 Workpiece characteristics and composition

Material					**Hardened H13**			
Size	265*40*200(mm)			**Hardness**		47 HRC		
Carbon	**Chromium**	**Molybdenum**	**Vanadium**	**Iron**	**Silicon**	**Sulfur**	**Phosphorus**	**Manganese**
0.38 (Weight in %)	5.0	1.4	1.0	Balance	1.0	0.03	0.03	0.35

The cutting tool applied was an uncoated carbide end mill manufactured by OSG (code - 414-3937). Figure 13 shows the experimental setup on a Makino MC56 CNC milling machine.

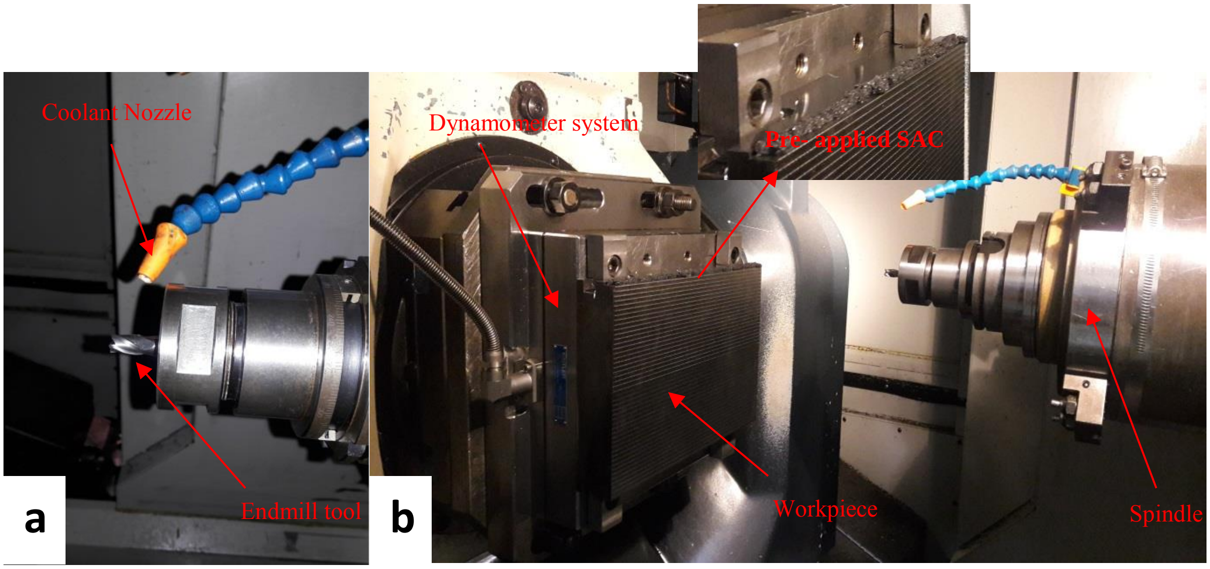


Figure 13 Machining setup a) Nozzle location for flood coolant b) pre-applied SAC on surface

3.2.2 Machining Conditions for Inconel 718

Machining was carried out on Nakamura CNC lathe:

Flood: semi-synthetic soluble oil in the ratio of 1:10 mixed with water

SAC without nano-additive: semi-synthetic soluble oil in the ratio of 1:10 mixed with water and superabsorbent powder added at the end to form SAC

SAC with Cu nano-additive and SAC with MgO nano-additive: Composition is recorded in Figure 5.

Widia CNGG uncoated carbide inserts (code: 120408FS) were used to cut Inconel 718. Cutting parameters are indicated in Table 7, and Table 8 illustrates material characteristics.

Table 7 Machining conditions for turning Inconel 718

Machine tool	***Nakamura CNC Lathe***
Operation	*Turning*
Tool	*Uncoated Carbide tool*
Nose radius	*0.8 mm*
Cutting Speed	*40 m/min*
Feed rate	*0.1225 mm/rev*
depth of cut	*0.25 mm*
Cutting length	*20mm*
Material removal rate	*1225* mm^3/min
Measuring parameters	*Tool wear, chip undersurface and surface roughness*

Table 8 Workpiece characteristics and composition

Material							**Inconel 718**						
Size			**Diameter: 70mm, Length: 400mm**				**Hardness**		**44**				
Nickel	Cobalt	Chromium	Molybdenum	Silicon	Iron	Copper	Titanium	Aluminum	Manganese	Carbon	Phosphorus	Sulphur	Boron
52.50 (Weight in %)	1.00	19	3.05	0.35	17.0	0.30	0.9	0.6	0.35	0.8	0.015	0.015	0.006

The nozzle position for the flood condition was set based on the author's previous research [3]. To provide a continuous flow of SAC in this test, the nozzle was set on the edge of the rake and flank faces around 10 mm from the tool tip and directed towards both the rake face to facilitate chip flow and the flank face to reduce flank wear. Figure 14 shows the machining setup and nozzle position for this set of tests.

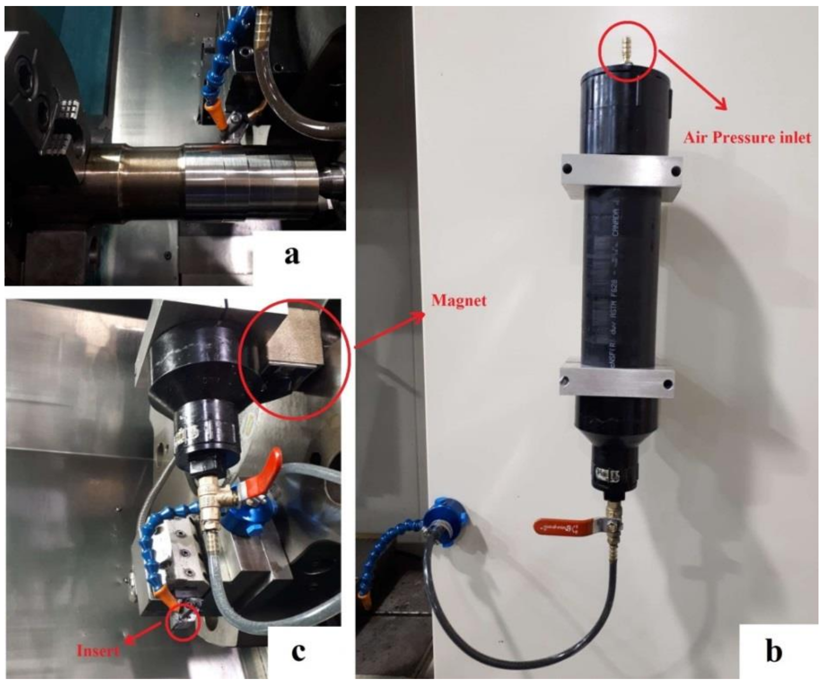


Figure 14 a) machining setup on lathe machine, b) SAC delivery device (installed on outside of machine for better view), c) delivery system in place for machining

3.3 Measurement

As outlined in Table 7, the cutting force, tool wear, surface roughness and chip undersurface roughness were measured and evaluated during machining. The cutting force was measured with a Kistler 9255b piezoelectric dynamometer on the milling machine. Tool flank wear at each stage was assessed with a Mitutoyo TM optical microscope and a Keyence microscope model VHX-5000. A machining cycle was defined on the CNC machine to stop cutting after 2.5 minutes. Each time the machine stopped, tool wear and surface roughness were measured. Surface roughness was measured at each stage of the tool wear, and the average of four measurements was taken using a Mitutoyo SJ-201 at three different points. For each point, the scattering length is 1.7 mm. Differential scanning calorimetry (DSC) was used to determine the energy per gram of SAC required to change phase in each stage.

The same microscopes and surface roughness tester were used for the turning operation. Tool wear and roughness were measured at the end of a 20 mm cut. The chips were collected from both processes at the beginning of the cutting before any tool wear effect or tribo-layer formation. Alicona 3D microscope was also used to measure chip undersurface roughness.

Finally, results of chip under surface roughness and surface roughness of the Inconel 718 workpiece were analyzed with analysis of variance (ANOVA single factor). This technique was useful to determine the means of the roughness measurements that were performed in each cooling conditions. The presented results were obtained with 95% reliability. The average of each group of measurements, as well as the standard deviation, was presented for chip undersurface roughness.

Chapter 4. Results and Discussion

4.1 Results of Milling Hardened H13

In this section, the machining performance of SAC will be outlined with regard to cutting forces, surface roughness, tool wear and chip morphology. Cutting force represents the amount of energy that a machine tool needs to remove the material and it is one of the factors that affects the economics of machining and quality of the final part. Results indicate that different cooling conditions lead to different machining outcomes. The effects of dry, flood and SAC conditions on cutting forces, surface roughness, tool wear and chip undersurface roughness in milling hardened H13 will be discussed separately. Under tool wear, the Marangoni effect, influencing the drawing of the fluid to the hot surface of the tool, will be addressed, and it will be demonstrated that SAC overcomes this adverse effect. DSC test results will also be analyzed to evaluate the heat absorbency of the SAC during its phase change. Some of the explanations in this section are also valid for turning parts and drilling/tapping which are discussed in Appendix A.

4.1.1 Tool Wear

Tool wear is one of the determining factors impacting the economics and efficiency of manufacturing processes [34]. Rapid tool wear due to poor cutting parameter selection or unsuitable tool material choice will increase processing cost. During this investigation, tool wear was observed and recorded using an optical microscope after each 2.5 min of cutting. Figure 15 exhibits flank wear and total material removal under different cooling environments.

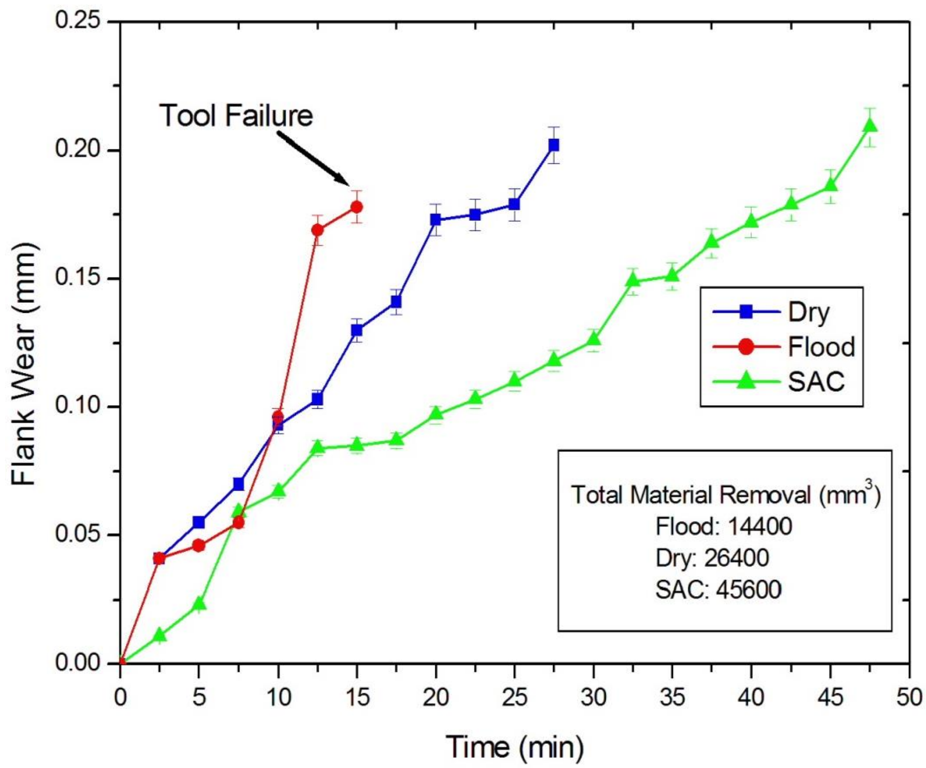


Figure 15 Growth of flank wear during machining of hardened H13 under dry, flood and SAC with graphite nanoparticle conditions

During the cutting process, friction in the cutting zone generates a significant amount of heat. This can result in substantial heating at the workpiece – cutting tool – chip interface, especially in a hardened steel such as H13, which is difficult to machine due to its high hardness and low thermal conductivity. Additionally, the low thermal conductivity of H13 tends to increase the cutting temperature, which further promotes tool wear and tool failure, such as chipping and fracture [59]. Furthermore, in a milling operation, the intermittent process can produce oscillating temperatures, in combination with loading and unloading forces; cracking and fracturing of cutting edges follow, mainly when flood coolant is applied. Therefore, early tool failure in flood machining is a combined effect of thermal fatigue and wear [60].

High temperatures generated in the cutting zone also decrease the shear strength of the material during dry cutting. Thus, the material becomes easier to cut, and the cutting tool experiences less resistance. In wet cooling, fluid quenches the work material, and the process requires greater force. Furthermore, milling is an interrupted cutting operation in which each cutting flute cuts the workpiece for a short period and then briefly rests. This short rest allows the fluid to penetrate to the tool tip and cool down the cutting edges. When this occurs, the tool experiences a high-temperature gradient that can cause premature failure due to thermal shock, in the case of brittle tools such as uncoated carbide. In the case of SAC, due to the gradual release of the emulsion from the hydrogel and generation of less heat in the secondary shear deformation zone owing to the lubricating action of the nanoparticles (which decrease the friction and heat), the tool experiences a smaller temperature gradient. Moreover, graphite nanoparticles have a relatively high thermal conductivity, thus, conduct some heat away, further reducing the severity of the temperature gradient during their dwell time on the surface of the tool.

There is another phenomenon behind the success of the SAC technique. A fundamental principle known as the Marangoni effect restricts the penetration of cutting fluid into the contact zone. The Marangoni effect occurs where the surface tension of a fluid changes according to temperature. Since there is less surface tension at higher temperatures, the liquid tends to move toward a point with a lower temperature [12]. In machining, the Marangoni effect causes the coolant to move away from the high temperature cutting zone. This effect is minimized with SAC because its viscosity is greater than that of flood coolant and the nanofluid is trapped inside the porous structure of the superabsorbent. Equations 2 and 3 [12] demonstrate why SAC is more efficient than conventional coolant.

$$\mathrm{Ma} = {}^{\mathrm{rv0}}/_{\mathrm{k}} \tag{2}$$

$$\mathrm{v0} = {}^{|\sigma\mathrm{T}||\nabla\mathrm{T}\infty|\mathrm{r}}/_{\mu} \tag{3}$$

Where Ma = Marangoni number, r= drop radius, v0= reference velocity, k= thermal diffusivity, σ= surface tension between the drop and workpiece, ∇T∞= temperature gradient and μ=dynamic viscosity. The dynamic viscosity of SAC is much higher than that of commercial coolants due to its gel form. Accordingly, v_0 tends to zero and the Marangoni number tends to zero as well. Therefore, the Marangoni effect is minimal or negligible for SAC, which leads to better penetration into the hottest area to directly reduce its temperature and, consequently, tool wear. Figure 16 shows the optical images of the worn tool at 200μm flank wear.

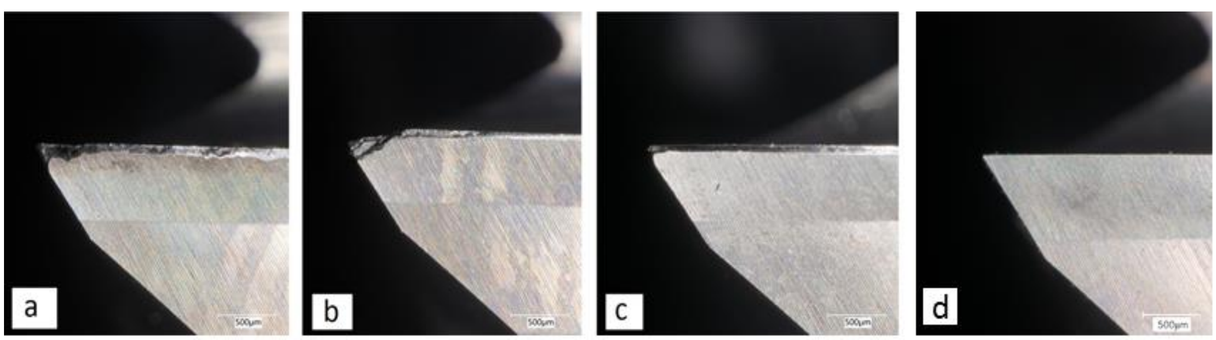


Figure 16 Optical microscope images of tool wear under different cooling conditions; a: Dry, b: Flood, c: SAC and d: fresh flute before cutting

One of the questions that may be raised is how the high viscosity SAC manages to move and penetrate into the cutting zone. An attractive feature of hydrogels is that they exhibit non-Newtonian behaviour in viscosity experiments: viscosity is not a constant value, it changes according to the shear rate; (Figure 11). As the shear rate increases, the complex viscosity decreases. During the cutting operation, when SAC comes into initial contact with the tool, its viscosity is high, and it does not splash away. Due to elevated temperature and high shear rate related to the high relative speed between the chip and tool, viscosity decreases rapidly, and two phenomena may occur: if the temperature is high enough, the superabsorbent particles evaporate (and to some extent burn), leaving graphite nanoparticles on the tool to perform lubrication and transfer away heat. At lower temperatures, behaviour of SAC changes from a gel to a liquid and propels the nanoparticles into the secondary shear deformation zone. Thus, nanoparticles and emulsion are present at the tool-chip interface and act as a coolant and lubricant. The second phenomenon was mainly observed in this study, as the volume of SAC was sufficient to prevent a great deal of evaporation or burning. Only a small amount of smoke was noted during machining. It is worth mentioning that when SAC changes phase to liquid, capillary flow replaces the Marangoni effect to fill in micro cracks and fissures in the chips and the tool-chip interface. Thus, the Marangoni effect seems to be the functional determinant during the initial contact between the coolant and the hot tool, but the capillary flow is effective in the contact area due to the presence of cracks and fissures.

There is another advantage to the SAC technique. With the wet cooling method, the fluid that comes into early contact with the hot tool surface evaporates and creates a pocket of vapor around the hot point of the tool, which prevents subsequent efficient heat transfer [8]. This challenge is addressed by atomizing the coolant in MQL, which eliminates the vapor pocket. Small droplets use latent heat, which is higher than heat transfer in the same phase, to conduct heat away. This phenomenon also occurs in SAC because the superabsorbent gradually releases coolant and the amount of coolant used in SAC is much lower than in the flood method. This means that the emulsion within the polymer network of the superabsorbent draws on latent heat to evaporate. Moreover, the behaviour change of the polymer from a gel to a liquid and then phase change from a liquid to gas are endothermic. Figure 17 shows the result of the Differential Scanning Calorimetry (DSC) test on the dry superabsorbent polymer. DSC is a solid laboratory method to determine the thermodynamic behaviour of a material [61]. The graph indicates that each gram of superabsorbent absorbs approximately 1.5 W of heat to change its phase from solid particles to gas (at 94.55 °C it turns the phase to liquid, and at 214.88 °C it evaporates).

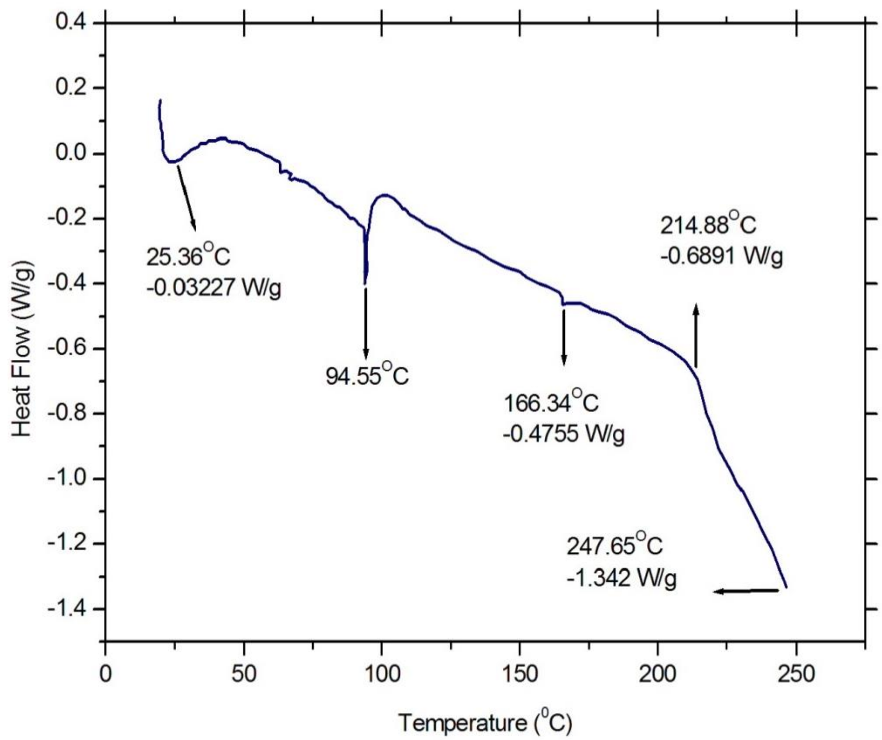


Figure 17 DSC test of superabsorbent polymer to measure the amount of energy required for phase changes

4.1.2 Cutting Forces and Energy

The cutting force in Figure 18 indicates that the use of SAC results in lower cutting forces over time compared to dry and flood machining. The coefficient of friction (CoF) was calculated according to [5] at the beginning, which represents the state of two new contact surfaces (chip and cutting tool).

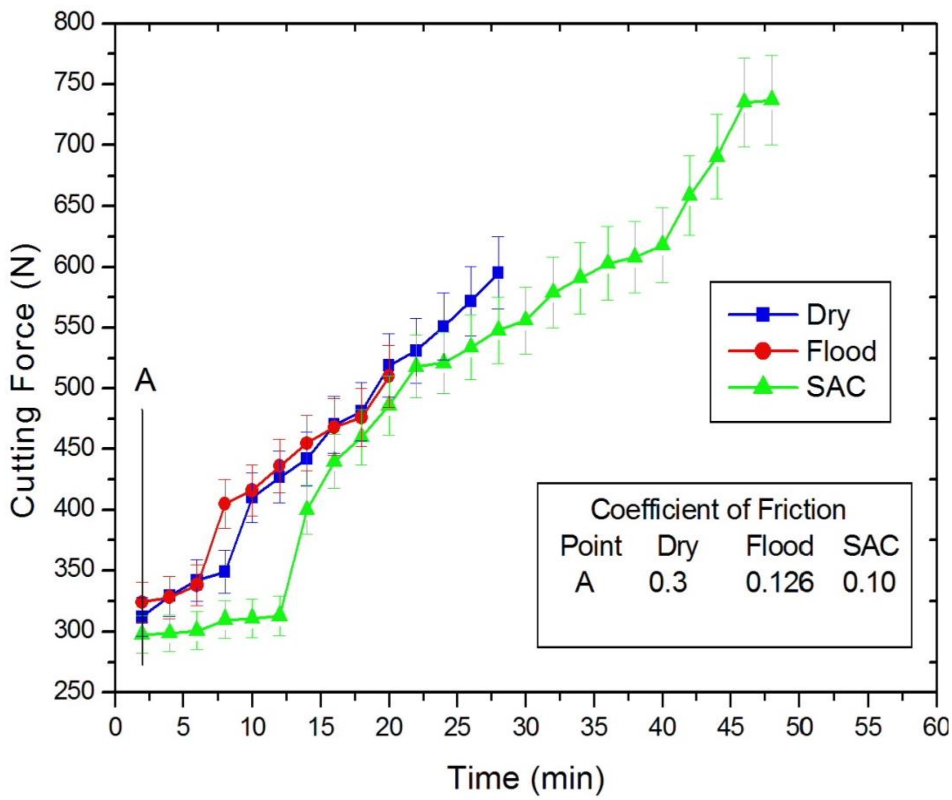


Figure 18 Results of cutting force at different times

In machining, tool-workpiece and tool- chip friction are very high and lead to high cutting forces. The tool-chip contact area is divided into two sections: the sticking zone and the sliding zone [5]. Penetration of the coolant into the sticking zone is almost impossible due to the high normal stresses. The small size (APS: 400nm and thickness: 40nm) and superior lubricity of the nanoparticles enables them to penetrate the sliding zone and change the sliding friction into the combination of rolling and sliding friction, [62] decreasing the resistant force and, consequently, generated heat. Another way to interpret the frictional condition is with the equation (4) [5];

$$\mu = \tau / \sigma \qquad (4)$$

Where τ is shear strength and σ is normal stress of the material.

Under dry conditions, heat generated during cutting softens the material locally at the cutting zone and reduces shear strength. Hence, in the equation, the numerator decreases while the denominator remains constant, which means reduction in CoF.

Under flood conditions, the coolant can achieve penetration due to interrupted cutting, and the oil content of the coolant lubricates the sliding zone. However, the Marangoni effect and the vapour pocket, as discussed earlier, pose two restrictions on flood effectiveness. According to equation 4, a reduction in the numerator leads to a decrease in CoF. Thus, the coolant serves as an agent in the tool- chip- workpiece interface with lower shear strength.

In the case of SAC, the tool is always immersed in the gel. Because of their size and interrupted cutting, nanoparticles can better penetrate the cutting area (as explained earlier, this is due to high viscosity which results in lower Marangoni effect and removal of the vapour pocket). Graphite particles with a laminar structure and very low shear strength compared to the workpiece material are present in the tool-workpiece- chip interface. Therefore, the lowest coefficient of friction is observed.

The cutting forces for dry conditions are initially lower than for flood conditions because the heat produced locally softens the material, thus the tool can remove the material with less force. In the case of flood cooling, the water-based coolant cools the surface and dissipates heat, so the material retains its hardness and the tool experiences greater resistance from the workpiece material as it deforms. However, in the case of SAC, the work material is cooled, but the friction is lowered by the presence of the lubricious nanoparticles. As the tool wear increases with time for flood conditions, the contact area between the tool and workpiece increases, excluding the liquid cutting fluid from a larger area. Thus, cutting forces become the same as those experienced under dry conditions. Cutting forces experienced while applying SAC increase gradually to nearly double the initial value by the end of the experiment, which is expected due to growth of the contact area arising from the larger flank wear region and increased tool engagement with the workpiece material.

To demonstrate that friction conditions were improved during machining with SAC, the energy required to remove the material was also calculated (Figure 19).

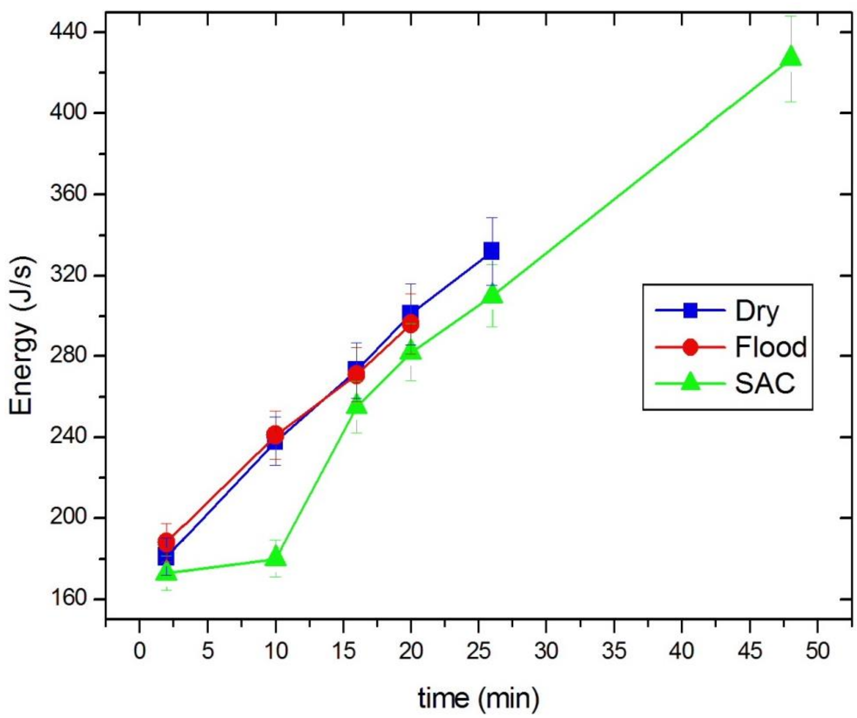


Figure 19 Results of cutting energy at different times

These values were defined according to Shaw and Cookson [5].

$$P = F_c . \mathrm{V} \tag{5}$$

Where F_c is cutting force and V is cutting velocity.

The data represent a tribosystem of extreme frictional conditions as an evident phenomenon of the cutting process. During cutting, this phenomenon damages the cutting tool, increasing the cutting force and energy for material removal. However, during cutting process with SAC, the energy for material removal is lower than in the other conditions (dry and flood), due to decreased friction.

4.1.3 Surface Roughness

Average Surface roughness (Ra) of the workpiece was measured after each machining cycle (2.5 min) at three different points. The results reveal that for all three conditions surface roughness fluctuates over time (Figure 20).

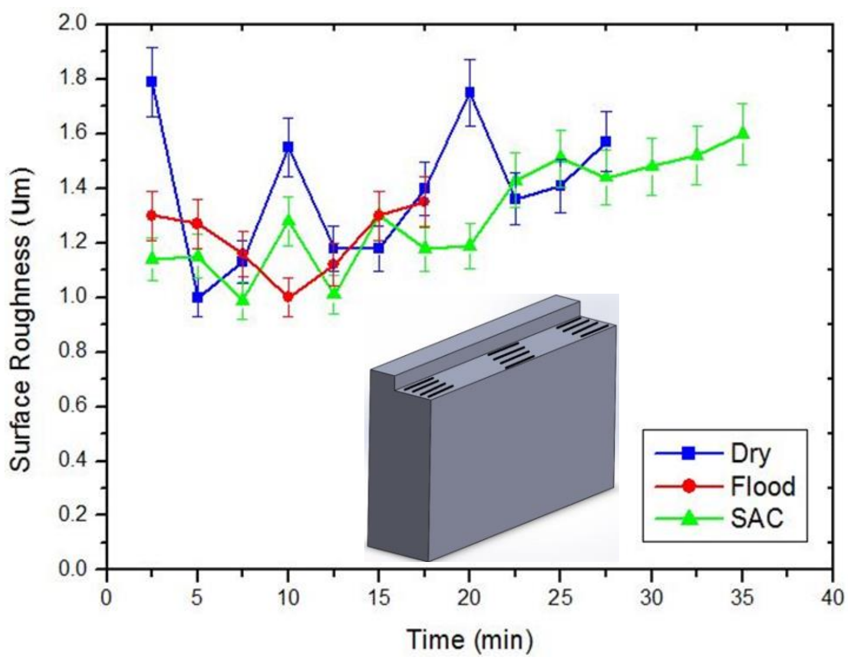


Figure 20 Fluctuation of surface roughness values vs. machining time

At the start of cutting, the roughness is high in all conditions, because of the sharpness of the tool. As cutting progresses, tool flank wear reduces sharpness, and roughness values reduce, but then chipping and BUE take place.

Dry cutting has the greatest degree of fluctuation, followed by flood and SAC. One reason for the better performance of SAC is the presence of nanoparticles. The inclusion of graphite nanoparticles in the contact zone efficiently reduces the friction and prevents metal to metal contact, resulting in decreased scarring of the machined surface. Furthermore, less tool wear and better cooling action, which were discussed in the tool wear section, lead to better surface finish and less oxidation [63]. A logical explanation for the fluctuations in the graph is vibration. Vibration in interrupted machining such as side milling is exacerbated when working with hardened H13 steel, which is unable to absorb vibrations to the same extent of softer materials. This increases the impact of the tool on the workpiece, so higher surface roughness is observed under dry conditions. This explanation is supported by Ginta et al. [64] who found that preheating the workpiece to 650°C reduced the amount of vibration during end milling of Ti-6Al-4V.

By lubricating the tool-workpiece contact area, SAC and flood coolant allow the tool to slide on the surface, reducing the effects of vibration [64]. It should be noted that during machining, every time that the operator unclamps the tool to measure tool wear and then replaces it, the tool position may be changed. This would alter the eccentricity and, consequently vibration, leading to variations in surface roughness values.

4.1.4 Chip Undersurface

Studying chip shape and formation can give useful information about machining performance and the effectiveness of each cooling method. Chips collected during machining were inspected under an SEM. Direction and depth of the parallel lines on the chip undersurface is good indications of friction between the tool and chip. Shallower lines indicate that the force between the tool - chip was lower for SAC than other conditions; SAC prevents metal to metal contact and decreases friction. As is seen in Figure 21, dry machining creates deeper lines, meaning that there was no lubricant to reduce the friction. Lines become shallower in flood cooling due to the lubrication agent, and the chip surface becomes almost smooth under the SAC cooling technique because of the superior lubricity of acting graphite nanoparticles in addition to the oil in water emulsion.

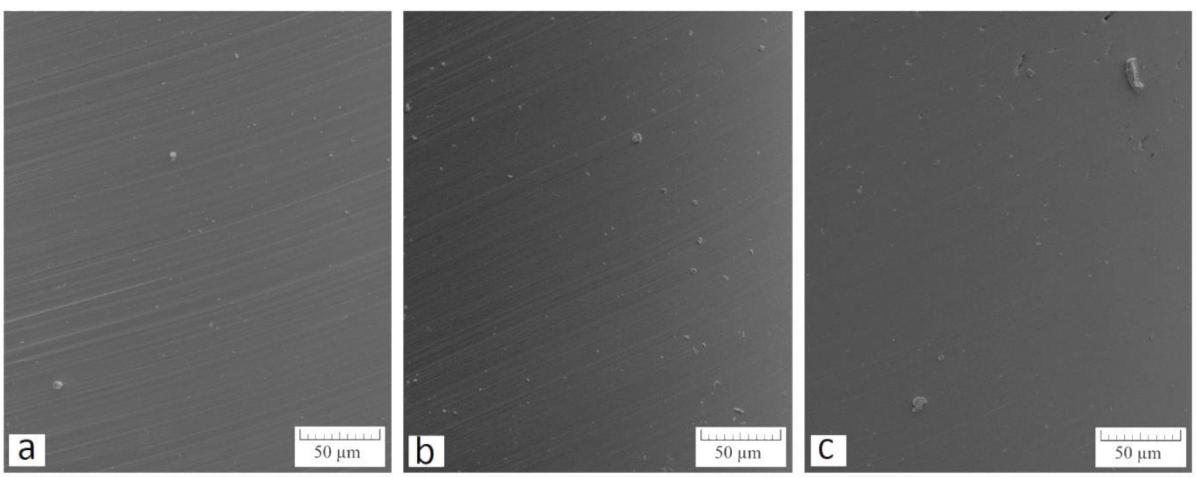
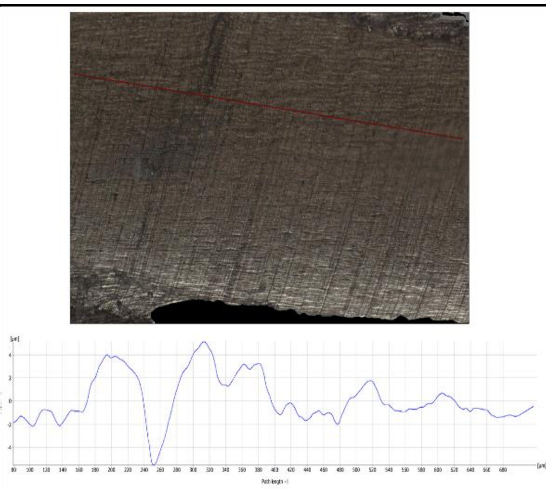
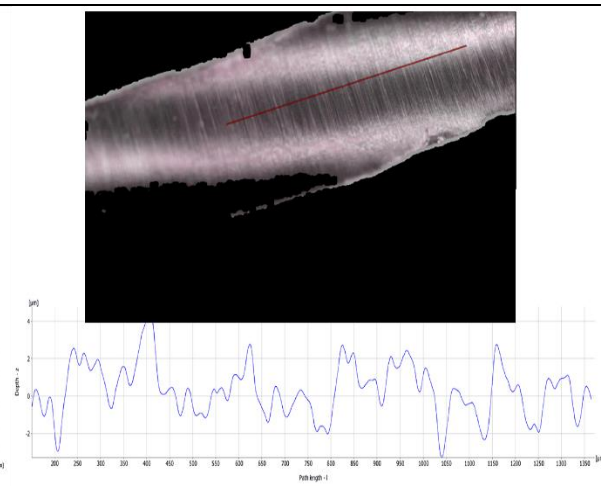


Figure 21 Chip SEM images; a: Dry, b: Flood and c: SAC. Scratch depth changes under different cooling conditions

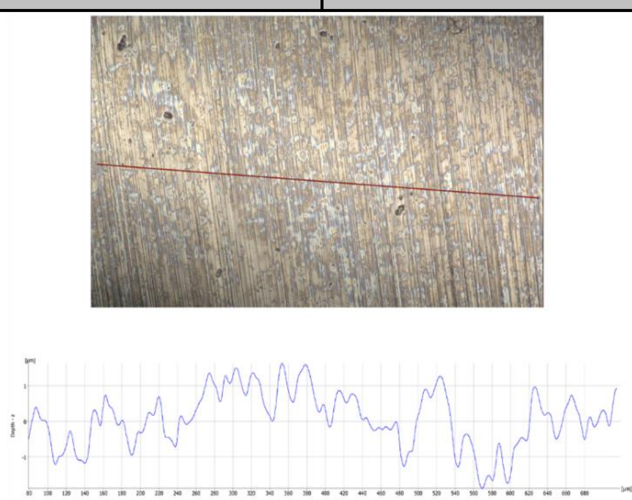
To verify these results and measure the depth of the scratches, an Alicona microscope (high resolution optical 3D microscope) was used to scan the chips and measure the surface roughness. The result of undersurface roughness can be seen in Figure 22. The level of significance (P-value) for this set of measurements was 0.00012 and variance of each value was added beside the average value.



(1) Ra: 1.628±0.02 μm



(2) Ra: 1.124±0.0003 μm



(3) Ra: 0.625±0.018 μm

Figure 22 Chip 3D scanning under Alicona microscope; (1) Dry, (2) Flood and (3) SAC

4.2 Results for Turning Inconel 718

This section records the performance of four different coolant conditions in the turning of Inconel 718. Copper and magnesium oxide nanoparticles were added to the SAC, and results were compared with two benchmarks, flood and SAC without any nanoparticles. The machine tool was equipped with a new delivery system for these tests so that SAC was supplied continuously to the tool-chip interface. Tool wear, chip undersurface roughness and surface roughness of the final workpiece were evaluated for performance comparison.

4.2.1 Tool Wear

Inconel 718 alloy is known as one of the most challenging materials to cut. This nickel-based alloy is used extensively in the aerospace, nuclear and defence industries [65]. Low thermal conductivity (compared to steel alloys), strength maintenance at high temperature, hard abrasive particles inside the material matrix, tool tip adhesion during machining and tendency to create a BUE make Inconel a difficult-to-cut material. A great deal of energy and force is required to remove the excess material, and a large temperature increase occurs in the cutting area [66]. This can result in poor surface quality and rapid tool wear during Inconel machining.

As is shown in Figure 23, the application of Cu and MgO nanoparticles in SAC significantly improve tool life. An uncoated carbide tool under flood conditions reaches maximum flank wear just after 440m of machining, whereas SAC without nanoparticles extends tool life to 570m. However, tool failure is observed before reaching maximum flank wear (300μm). The addition of nanoparticles to the SAC improved the performance of the coolant and extended tool life almost twice compared to SAC without nanoparticles.

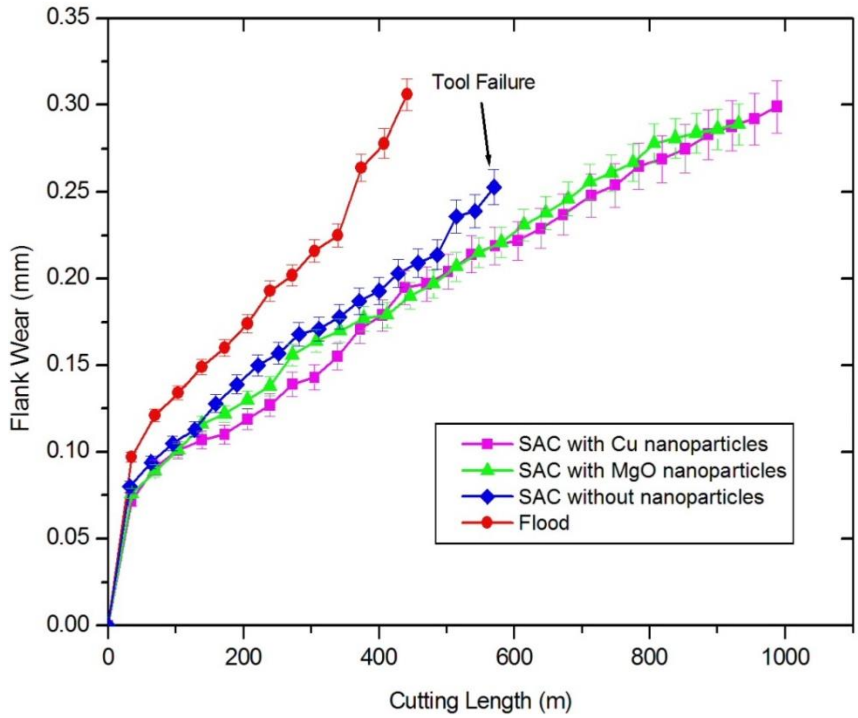


Figure 23 Growth of flank wear during machining of Inconel 718 under flood and SAC with Cu and MgO nanoparticle and SAC without nanoparticles conditions

There are different theories regarding the function of nanoparticles during the cutting operation. According to Lee et al. [67], different mechanisms are possible when nanoparticles act between two surfaces; the rolling effect, protective film, mending and polishing effects.

In this case, the tool is in constant contact with the workpiece material and gel is supplied near the cutting region. High temperature and shear rate of the cutting area reduce the viscosity and locally release the nanofluid from the gel. Actually, the superabsorbent gel works as a carrier to deliver nanoparticles to the tool tip at a low flow rate to prevent nanoparticles spreading into the air. As shown in Figure11, SAC with Copper is more viscous at higher shear rates than SAC with Magnesium Oxide. Based on the Marangoni equation (eq. 2), higher viscosity leads to a lower Marangoni number. It means more and better penetration to the tool-chip interface. Following this, the nanoparticles can fulfill their purpose as lubricants (it could be a combination of mentioned mechanisms) and decrease the tool-chip contact. Figure 24 depicts the schematic of the cutting operation in the presence of SAC with nanoparticles.

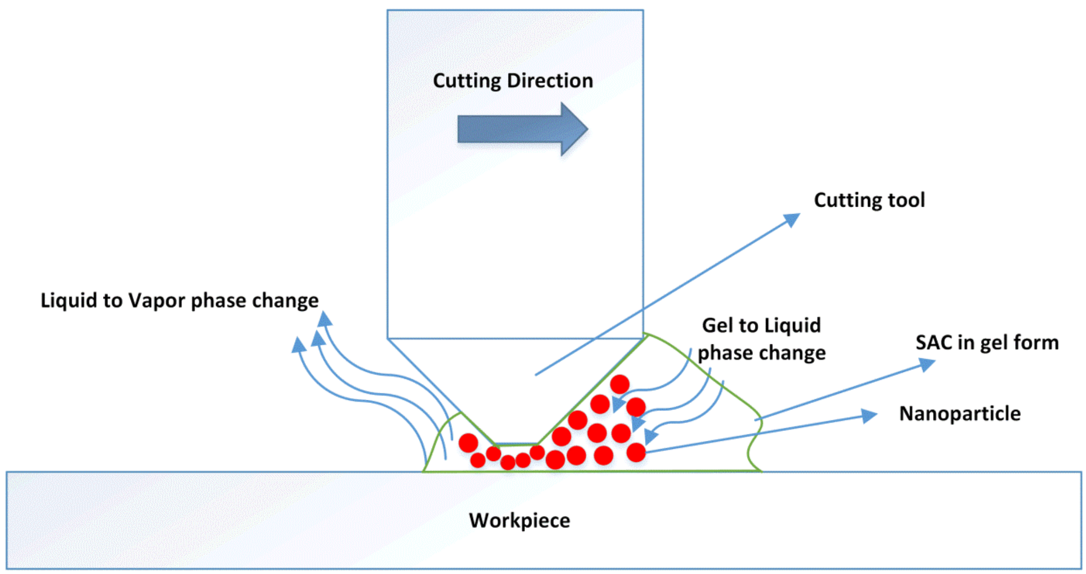


Figure 24 Schematic of cutting in presence of nanoparticles as additive to SAC

Besides the penetration of nanoparticles to the cutting zone, another reason for SAC's superior performance to flood coolant is the higher thermal conductivity of nanoparticles and latent heat due to phase change of SAC. Low thermal conductivity of Inconel 718 (11.2 W/m.K) keeps most of the generated heat in the cutting area, causing tool softening, BUE and finally tool failure. Flood coolant creates a pocket of vapour around the cutting point and is incapable of penetrating and removing heat [39]. Thus, in this case, latent heat as well as high thermal conductivity of nanoparticles help extract more heat from the tool tip and the tool faces a smaller temperature gradient. As a consequence, tool life increases.

According to Figure 23, SAC with Copper additives shows a slightly higher tool life than SAC with Magnesium Oxide. One possible explanation for this is the morphology of the particles. The manufacturer's technical data sheet indicates that the copper nanoparticles have a spherical shape but the magnesium oxide particles have a polyhedral shape. Therefore, it is logical to presume that for the nanoparticles' rolling action, copper works better than magnesium oxide. Figure 25 shows the optical microscope images of the worn tools at the end of the machining.

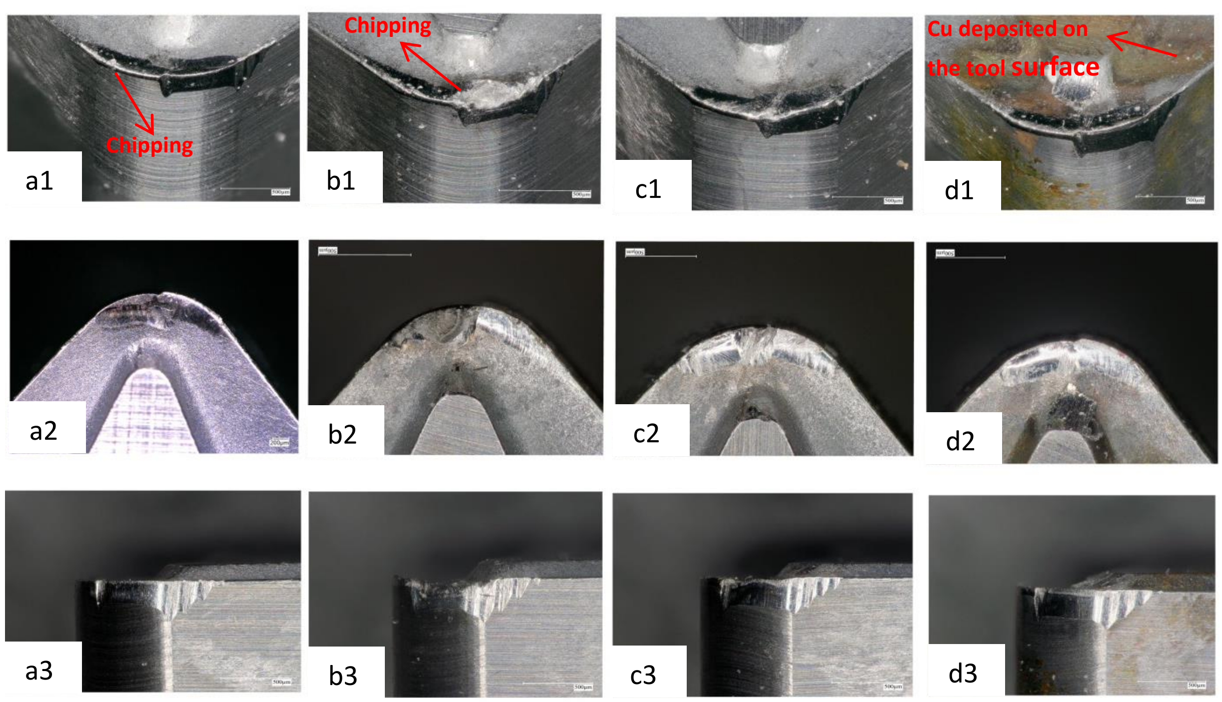


Figure 25 Optical microscope images of tool wear under different conditions; **a1**: Flood 45°, **a2**: Flood rake face, **a3**: Flood flank face, **b1**: SAC without nanoparticles 45°, **b2**: SAC rake face, **b3**: SAC flank face, **c1**:

SAC with MgO nanoparticles 45°, **c2**: SAC with MgO nanoparticles rake face, **c3**: SAC with MgO nanoparticles flank face, **d1**: SAC with Cu nanoparticles 45°, **d2**: SAC with Cu nanoparticles rake face and **d3**: SAC with Cu nanoparticles flank face

4.2.2 Surface Roughness

Surface roughness (Ra) is another criterion used to judge the effectiveness of a coolant during cutting. It impacts the fatigue strength, friction between surfaces and corrosion resistance [45].

Workpiece roughness was measured after the last pass of machining with a surface profile tester. According to Table 9, roughness values are almost the same for all of the cases. Nanoparticles in this case could not bring about any specific improvement. One possible reason could be that during the turning operation, the coolant was applied to the tool-chip interface (SSDZ), but not to the tertiary shear deformation zone (TSDZ), which is the contact point and second source of friction between the tool and workpiece. Therefore, nanoparticles were incapable of reducing friction at the TSDZ and generating a better surface finish. In the worst case scenario, SAC with nanoparticles works as well as the flood condition in terms of surface quality.

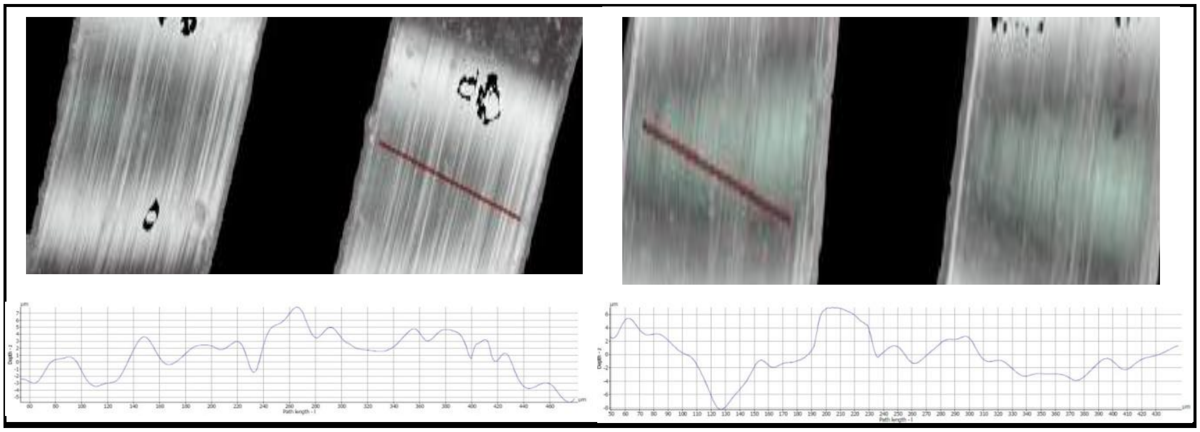
Table 9 Surface roughness values of the Inconel 718 workpiece under different conditions

Condition	Flood	SAC without nano-additive	SAC with MgO nano-additive	SAC with Cu nano-additive
Roughness Value (μm)	0.88± 0.001	0.88± 0.002	0.79± 0.05	0.80± 0.01

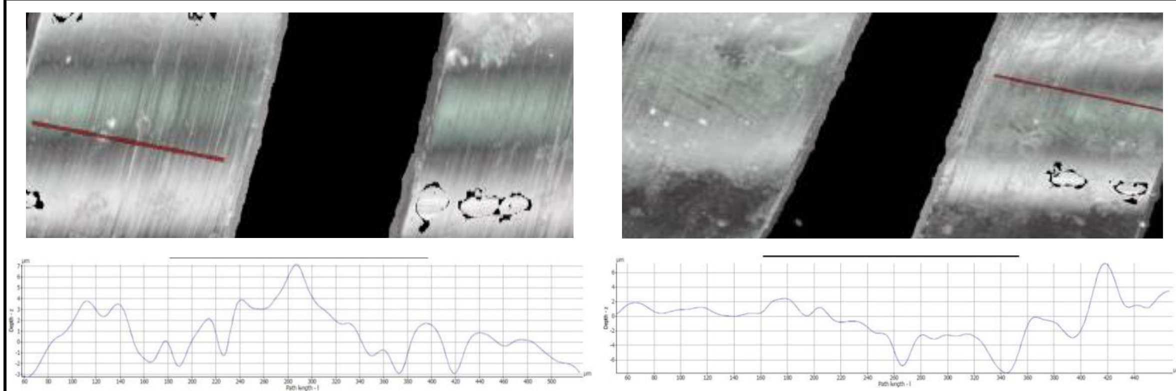
4.2.3 Chip Undersurface

If there remains any doubt as to the role that nanoparticles perform, chip undersurface roughness confirms the function of nanoparticles in SAC during Inconel 718 cutting. Chips were gathered after the first machining pass for each cooling condition. The reason for gathering chips in the very beginning is to observe the effect of the coolant before the formation of any tribo-layer or tool wear. An Alicona microscope was used to scan the collected chips and measure roughness. Results indicate that Ra values with use of Cu and MgO nanoparticles are lower than both SAC without nano-additives and flood coolant.

All of the nanoparticle lubrication mechanisms could play a role in reducing chip roughness. As it was mentioned in section 4.1.4, lower values of chip roughness indicate that the scratches are shallower and there exists an agent which reduces the contact area and severity of contact between the tool and chip, and that agent is nanoparticle additive. Moreover, Figure 26 demonstrates that SAC, despite its high viscosity (at low temperature and shear rates) was able to penetrate effectively and reduce friction (level of significance in this set of experiments was 0.00033).



(1) Ra: 2.896± 0.1 μm	(2) Ra: 2.544± 0.03 μm



(3) Ra: 1.931± 0.02μm	(4) Ra: 2.01± 0.1μm

Figure 26 Chip 3D scanning under Alicona microscope; (1) Flood, (2) SAC without nanoparticles (3) SAC with Cu nanoparticles and (4) SAC with MgO nanoparticles

4.3 Sustainability

Besides the practical benefits that SAC provides during the cutting operation, environmental and occupational effects need to be considered. Disposal of metalworking fluids after machining poses concerns for the government and extra expenses for industry. Some of the challenges of cutting fluids are mentioned below:

- Almost 17% of the industrial cost of machining is spent on metalworking fluids [68] and [26].
- Chemical disintegration and phase separation occurs in cutting fluids due to bacterial growth and high temperature in the cutting area [3]
- Exacerbation of operator diseases such as respiratory problems and skin irritation.
- Soil and water pollution and high cost of post processing due to strict environmental regulations [2] and [27].

While new techniques such as MQL improve both cutting performance and sustainability, they do not provide full operator protection since the coolant is atomized into the air and can get in the respiratory system to cause serious problems [3].

A superabsorbent coolant can simultaneously provide the benefits of MQL and a solid lubricant while reducing the environmental and human side-effects. In actuality, this method introduces a safer condition of nanoparticle use by its focus on "cutting zone proximate release" and dust or mist mitigation during machining. Therefore, nanoparticles are contained within the SAP until the temperature is high enough to loosen the internal bonding of the SAP to release the nanofluid. This prevents operator exposure to mist and nanoparticles. In addition, the SAC can absorb dust or small chips generated during operations. As an example, due to the brittle nature of the material, machining cast iron produces very small chips, and when mixed with coolant, they can agglomerate and stick to the machine tool, which would then require cleaning. This problem is addressed by SAC. In a set of tests on cast iron in the MMRI lab Figure 27, where SAC was applied, due to the sticky nature of the gel form, small chips were automatically absorbed by superabsorbent particles, which made cleaning easier for the operator after machining. Other alloys such as stainless steel, nickel based alloys and chrome are reported to have the same problem, and applying MWF during machining absorbs the microscopic dust and reduces the potential hazard of cutting these materials for the operator [15].

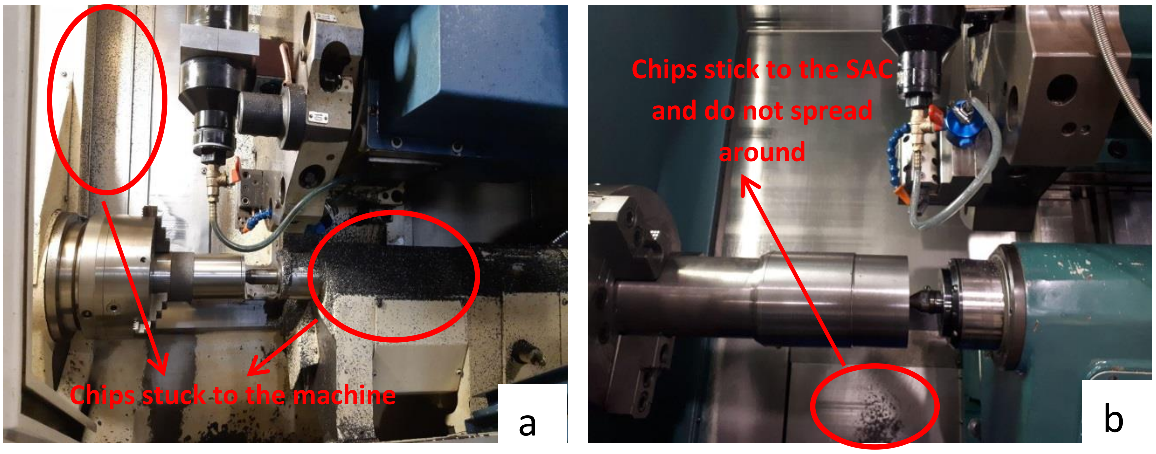


Figure 27 Machining grey cast iron; a) Flood cooling and b) SAC technique

From a post-processing point of view, disposing of MWFs is costly and some techniques such as thermal evaporation, ultrafiltration, reverse osmosis (RO) and nanofiltration consume a lot of energy [15]. SAC reduces the amount of coolant consumption remarkably. This means a lesser volume of MWF needs to be treated after use, which saves cost, energy and reduces soil and water pollution.

At the end, for economical comparison it is useful to have a cost estimation based on the current market. This estimation has been done in December 2018 in North America.

The calculation for coolant consumption in flood condition has been done by HAAS automation, a machine tool manufacturer in the U.S. They mentioned that 20 hours machining using flood technique costs $45 [69] but SAC with graphite nano-additives costs approximately $23.5 which is almost half a price of flood coolant. Another point is that waste handling of flood coolants after usage is a costly process and environmental concern but in case of SAC with suitable flow rate it could be removed or minimized.

Overall, this chapter assessed the performance of SAC by measuring tool wear, surface roughness, cutting forces and chip undersurface roughness. At the end of the chapter, sustainability analysis and cost estimation for economic analysis were included for better understanding of the potential effects of SAC on human health and the environment.

Chapter 5. Conclusions

In this study, a new generation of coolants and lubricants to improve machining performance was introduced. It was found that it is possible to apply a superabsorbent hydrogel, widely used for drug delivery and agricultural purposes, as a new coolant and lubricant in an industrial field. A superabsorbent polymer (SAP) was selected as a carrier and was enriched by a nanofluid with high thermal conductivity and lubricious nanoparticles to produce a gel-based coolant known as superabsorbent coolant (SAC). Furthermore, a new delivery system was designed to deliver SAC near the cutting area. In order to evaluate the performance of the gel-based coolant, cutting force, surface roughness, tool wear, and chip undersurface roughness measurements were conducted, and the results were compared with dry and flood conditions. This technique was performed with three different nanoparticles and three workpieces during various machining operations.

The results obtained lead to the following conclusions:

- SAP can effectively trap nanofluids in the polymer matrix and release it at a high enough temperature, so that the cutting zone can be specifically targeted. This phenomenon has many benefits. It reduces the coolant consumption, harmful side effects of nanoparticles and solves the problem of nanofluid sedimentation.
- SAC provides the benefits of both MQL and solid lubricant methods. Because the volume of cutting fluid is much lower than that of flood cooling, latent

heat is used for evaporation. Additionally, nanoparticles are solid lubricants which decrease friction. Furthermore, the phase changes of the polymer are endothermic and can be helpful in extracting more heat from the cutting area.

- Use of SAC leads to reduced thermal shock and temperature gradient on the tool: The tool is immersed in the hydrogel throughout the cutting process, so temperature changes are gradual. Also, the Marangoni effect is minimized, which enables the SAC to penetrate to the tool tip and reduce the temperature gradient. In contrast, with the flood method, the Marangoni effect prevents the coolant from reaching the hottest area, and in cryogenic cooling, the tool suddenly encounters a temperature of -196 °C, which can cause thermal shock and micro cracks.
- Due to the high viscosity and semi-solid nature of the SAC, it is stable in the machining zone and does not splash around. Therefore, it is not messy like flood coolant, and there is less operator contact with the cutting fluid, which decreases the likelihood of occupational disorders such as skin problems, eye irritation, and pulmonary diseases.
- When applied in milling hardened H13, SAC significantly extended the tool life from 27.5 min in dry condition to 47.5 min and decreased the workpiece and chip undersurface roughness. Moreover, since it provides better lubrication, a lower coefficient of friction and cutting force follows.

- When applied in turning Inconel 718, SAC improved tool life from 440m in flood cooling to about 990m and 930m with Cu and MgO nano-additives, respectively.
- When applied in drilling an Aluminum Silicon alloy, SAC demonstrated comparable thrust and cutting force to commercial flood coolant and during tapping, it showed comparable tapping torque but overall the thread profile was much improved.

In conclusion, based on the machining outcomes and comparisons with dry and flood machining, the author is hopeful that use of hydrogels as coolants can be implemented to increase the efficiency of machining by increasing tool life, yielding better surface finish and reducing cutting forces, while at the same time exhibiting superior environmental and occupational characteristics. Future studies will investigate the optimization of the different parameters related to hydrogels and their controlled release for various machining operations and work materials.

Chapter 6. Future Work and Recommendations

The promising results of the investigation of superabsorbent hydrogel application in the machining industry, open a new window for further analysis and study. SAC is like a newborn baby and needs to be evaluated from different aspects. Before meeting industrial requirements, like every idea, SAC requires deep analysis to assess its limitations.

Directions for future work are listed below:

- Studying the performance of other hydrogel polymers with a different chemical composition.
- Formulating a new biodegradable superabsorbent polymer with a higher absorbency ratio to meet environmental regulations and achieve easier post-processing.
- Conducting more machining tests on different alloys and composites.
- Investigating the potential side-effects of SAC on operator by biological tests.
- Further development of the automatic recycling system so that it would collect the gel after machining and send it back to the delivery system.

Hopefully one day SAC will achieve widespread industrial application, helping mitigate the health hazards of MWFs and to reduce dependence on petrochemical based coolants.

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Appendix A. Drilling and Tapping (collaborative project)

As was mentioned earlier, drilling and tapping was a cooperative project with another researcher, and in order to avoid plagiarism this work has been added to this thesis as Appendix A.

This work was part of an automotive industrial project whose focus was on improving the performance of form tapping and creating a better thread profile and less tool wear by testing three different coolants; SAC, Hocut 795H and vegetable-based coolant on Die-Cast Al-12Si alloy. The results of this study are briefly represented.

A.1 Materials and Methods

Drilling and tapping tests were conducted on Okuma Cadet 4020 vertical CNC machining centre. The chemical composition of the alloy used in this research has been illustrated in Table 10. 100 holes were drilled in a workpiece measuring 240 x 65 x 75 mm and tapped on one side. Before doing the machining tests, the hardness of the workpiece was measured by the Rockwell hardness tester in E scale. The average bulk hardness of the Al-Si alloy was 76 HR-E.

Table 10 Chemical composition of Die-Cast Al-12Si alloy

Element	Cu	Si	Mg	Zn	Fe	Mn	Ni	Pb	Sn	Al
Weight	1.5	10.5	0.3	2.5	1.3	0.5	0.5	0.2	0.35	Rest
%	4.5	12	Max	Max	Max	Max	Max	Max	Max	

Table 11 shows the geometry of the drilling and tapping tool and machining parameters have been listed in Table 12.

Table 11 Tool geometry for both drill and tap tools

Drill	Tap
Type: Metric, Twist, no coolant through	Type: Metric, Bottoming Form tap
Uncoated Carbide	Uncoated High Speed Steel
Diameter: 7.37 mm	Diameter: 8 mm
Point Angle: 118 ◦	Pitch: 1.25 mm
Helix Angle: 20◦	Grooves: 6, straight
Flutes: 2	Thread Engagement: 74.12%

Table 12 Machining parameters

Parameters	Drilling	Tapping
Diameter	7.37 mm	8 mm
Hole depth	25 mm	19mm
Spindle speed	2500 rpm	1000 rpm
Feed rate	625 $mm.min^{-1}$	1250 $mm.min^{-1}$

Three different MWFs were applied in both the drilling and tapping processes. Mineral based oil - Hocut 795H and Sunflower oil in the ratio of 1:10 were added to the water to form an emulsion. 2% by weight Polyethylene glycol (20) sorbitan monolaurate, known as Tween 20, was utilized as an emulsifier to create a uniform emulsion of vegetable oil in water. SAC with graphite nanoparticles was prepared according to Figure 5. Figure 28 presents the complex viscosity of these three coolants at 40°C, and Table 13 shows coefficient of friction (CoF) when each coolant is used. The CoF was measured with a high load tribometer at room temperature.

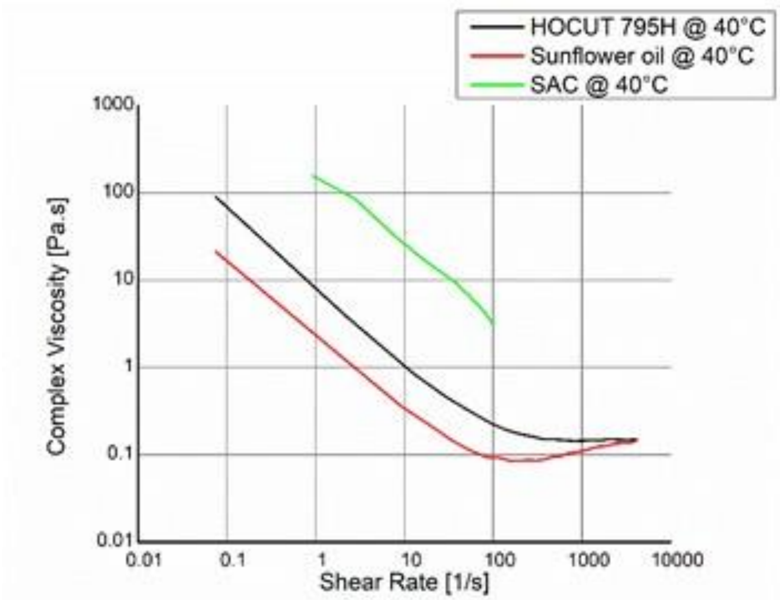

Figure 28 Viscosity measurement of three MWFs at 40°C under different shear rates

Table 13 Coefficient of friction (CoF) of three different MWFs measured by high load tribometer

MWF	Emulsion Concentration (%)	CoF
Hocut 795H	10	0.282
Sunflower Oil	10	0.372
SAC (with graphite nanoparticles)	10	0.292

Hocut 795H and the vegetable-based coolants were delivered by the flood method as shown in Figure 29 (A) and SAC was pre-applied in a layer on the workpiece after every pecking cycle of the drilling (Figure 29 (B)). Drilled holes were filled with SAC before tapping.

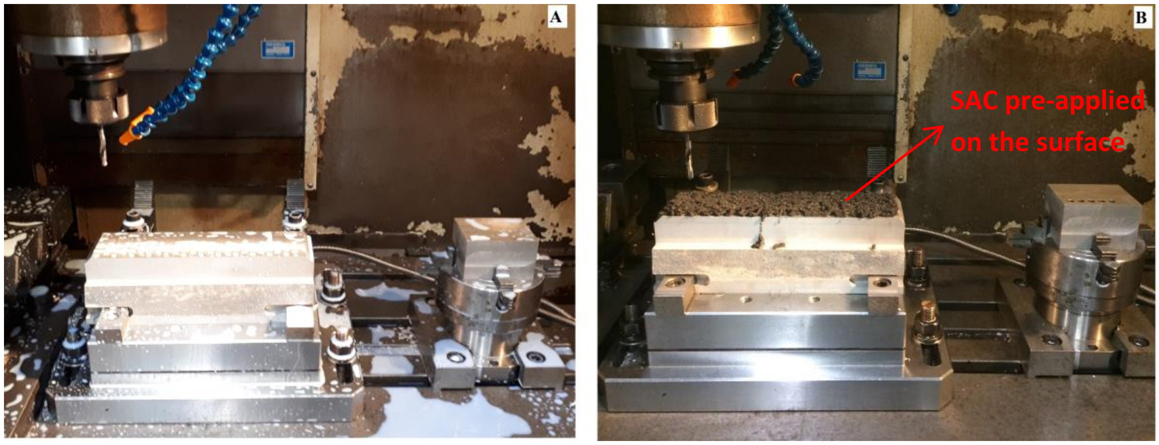

Figure 29 Machining setup for A: Flood and B: SAC applied on the surface

In order to measure thrust (feed) force and torque, a small block of the workpiece was mounted on a 9272 Kistler stationary 4-component dynamometer. Measurement was done after every 24 holes and a total of 100 holes were drilled and tapped on the workpiece. A pecking cycle with a following depth of 5mm, 15mm and 25mm was defined for the drilling operation to prevent chips clogging the hole, since depth of hole was three times larger than diameter of the hole.

Maximum BUE formation on the drill and adhesion/abrasion on the form taps were measured with a Keyence VHX 5000 digital microscope.

A.2. Results and Discussion

A.2.1 Cutting Force Results for Drilling test

Figure 30 shows that the maximum feed forces for the drilling process were lowest in the case of Hocut 795H and highest for sunflower oil-water emulsion. Figure 30 and 31 show that sunflower oil MWF was not effective in decreasing the thrust force and torque.

The reason is very high Aluminum adhesion to the tool, resulting in built-up edge (BUE) formation.

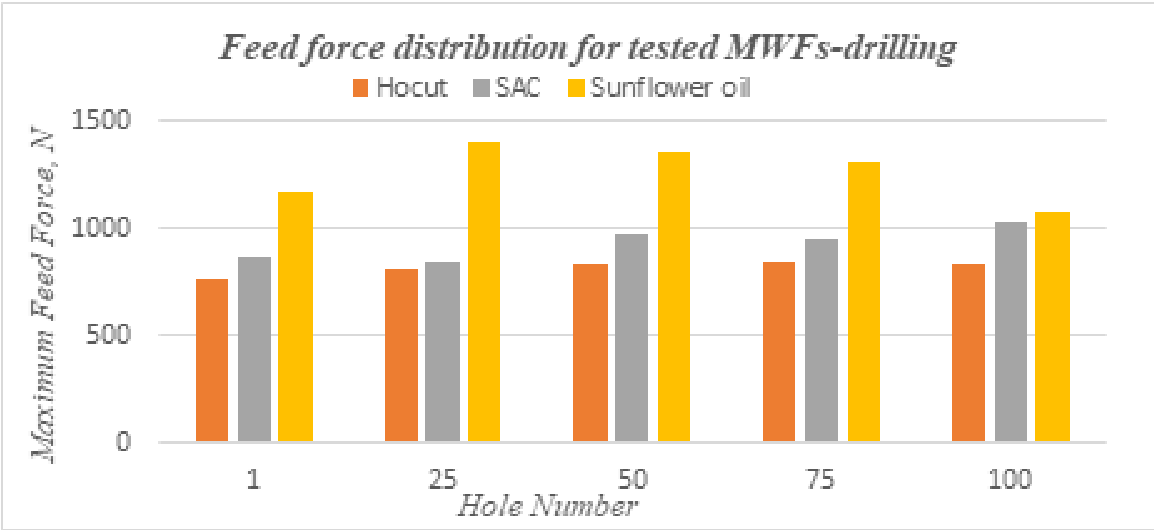

Figure 30 Maximum Feed Force distribution in drilling

The average BUE measured after 100 drilling holes at the cutting edge and chisel edge is shown in Figure 32. With the increase in BUE, the cutting tool geometry changes as the workpiece material adheres below the nose of the tool, causing more material removal per unit of time [70]. In fact, negligible flank wear was observed, which could not be related to higher feed forces. The feed force and torque results for the mineral oil and gel-based lubricants were comparable, but the mineral oil showed slightly lower forces. Hocut 795H is a commercial mineral oil with multiple chemical additives such as extreme pressure (EP) and anti-wear additives, which react with the tool surface and, according to [12], reduce the surface shear strength. Also, an EP additive forms a stable oxide layer that prevents metal to metal contact and enhances lubricity. Therefore, the tool experiences lower resistance compared to SAC and sunflower oil-based MWF. In order to prepare the SAC, semi-synthetic oil mixed with water was used, but because the amount of EP and other surface reactants were less than Hocut 795H, the amount of force increased to some extent. The existence of graphite nanoparticles in SAC decreases the frictional force which shows a gradual increase over time. This gradual increase of the frictional force indicated that up until 75 holes, the adhesion and BUE were very well controlled because the graphite and emulsion content of hydrogel particles reduces the temperature and friction between tool-chip and workpiece. It is also worth mentioning that during machining, thick casting products such as aluminum silicon present in the study material, in some cases are not homogeneous, and a porous structure consisting of micro holes is observed. Thus, lower thrust forces in Hocut 795H do not necessarily mean better lubrication conditions. This may be due to the cutting of those micro holes.

According to Figure 31, at the 25th hole the entire flute was clogged, and chips adhered to the surface of the flute of the drill. This adhesion increased the contact area between the tool and the workpiece and results in higher torque values. The inferior performance of sunflower oil could be because of its low thermal and oxidative stability [71].

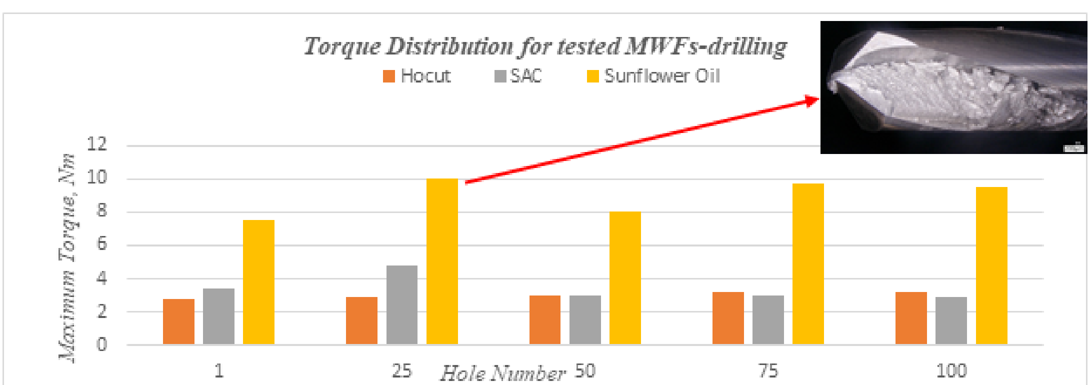

Figure 31 Maximum Torque distribution in drilling

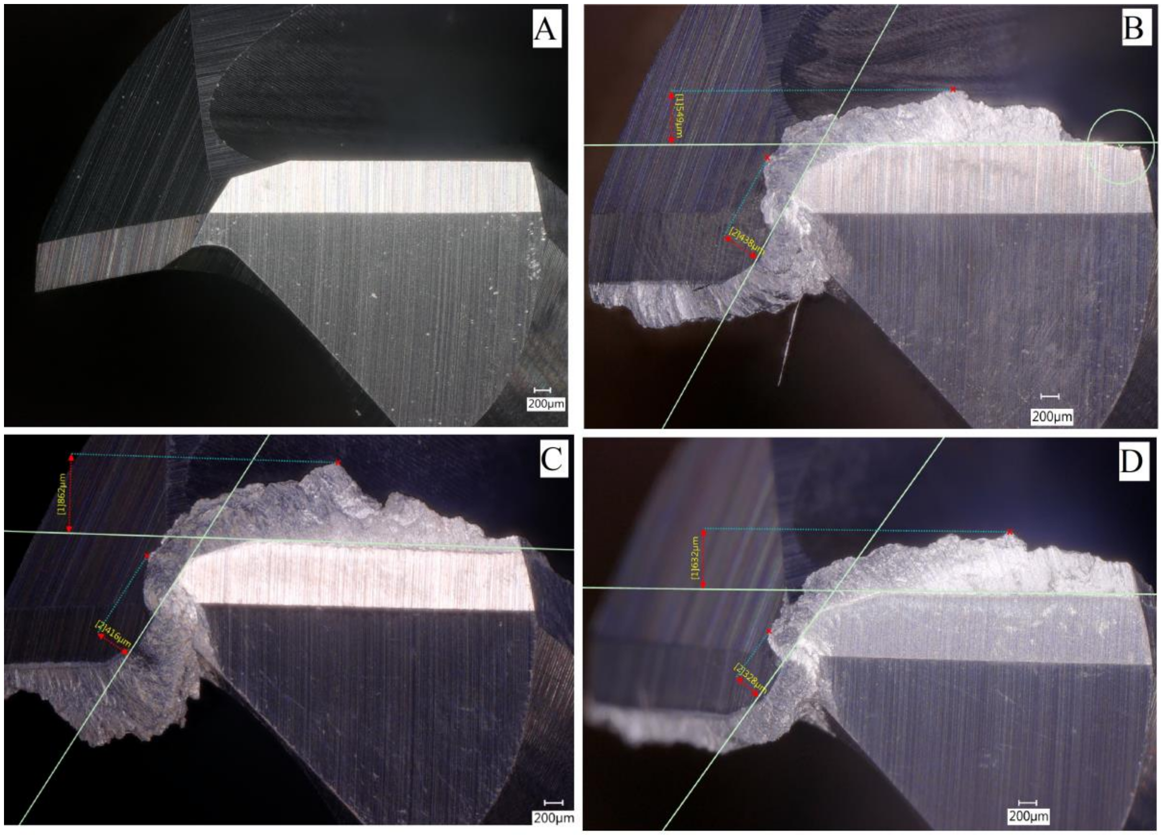

Figure 32 Optical images (50x magnification) of BUE on cutting and chisel edge of the uncoated carbide twist drill along the drill axis after drilling of 100 holes with A) at fresh condition of the drill B) Hocut 795H, C) Sunflower oil-water emulsion and D) SAC

A.2.2 Torque and Thread Profile Formation of the Tapping Test

Figure 33 shows the maximum torque recorded during the forward movement where the forming of threads in the workpiece is executed. The torque is initially higher for all the three lubricants and gradually stabilizes for the following holes. This is because the pre-tapped diameter of hole is initially tighter and becomes stabilized as the BUE on the drill grows constant. Hocut 795H results in the lowest torque, followed by SAC, and the sunflower oil has the highest torque during the forward movement of the tap. The sunflower oil has failed to withstand high stresses on the lobes of the last chamfered threads due to more strain hardening and higher penetration of the forming lobes into the workpiece, resulting in a higher formation torque.

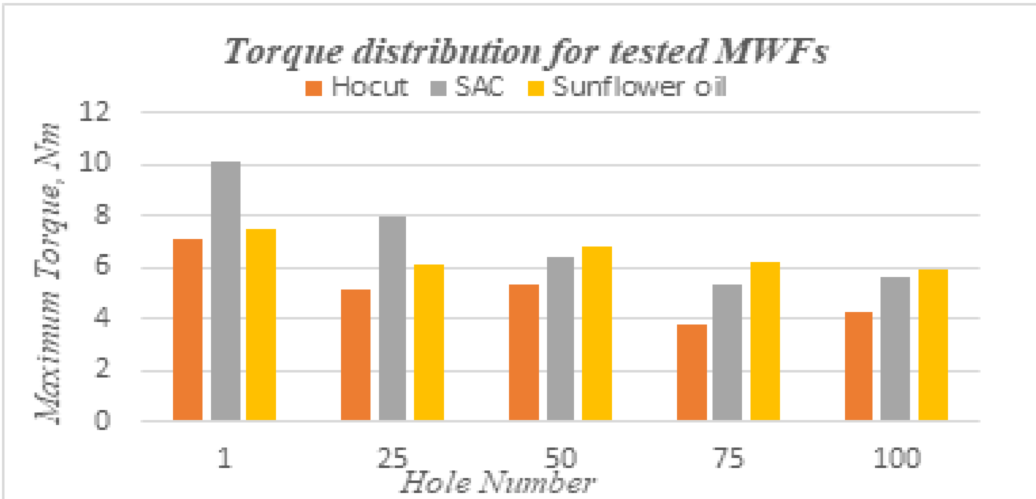

Figure 33 Maximum torque distribution for tapping test

The thread produced by roll form taps has a split crest, unlike threads machined by cut tapping. The split crest tends to weaken the overall strength of the thread, and the tips of the ridge may chip off during assembly or operation [72]. According to Figure 34, the thread produced using sunflower oil appears to be worst and the split crest is higher than the other two thread profiles. In this case, SAC has the smallest split crest and best thread profile, followed by Hocut 795H, and the thread profile is sharper than that of the sunflower oil.

Another reason for poor thread profiles in case of sunflower oil is the greater adhesion of Aluminum on the crest of the taps as evident in Figure 35. The tendency for adhesion to the uncoated tap was lower in case of SAC and Hocut 795H MWFs. During tapping with SAC, graphite nanoparticles reduce the friction and impediment between tool and workpiece as well as the contact and consequently the chance of adhesion, heat generation and BUE.

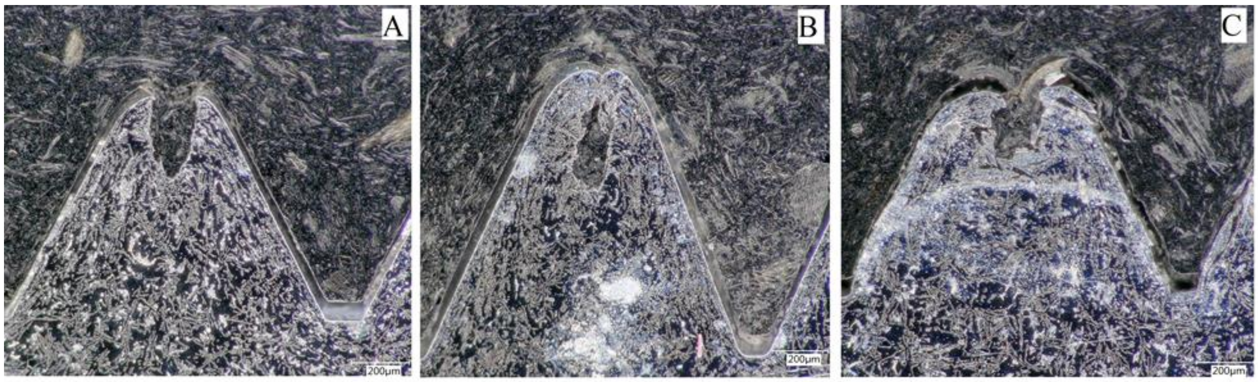

Figure 34 Thread profiles showing split crest formed during tapping with (A) Hocut 795H, (B) SAC and (C)Sunflower oil

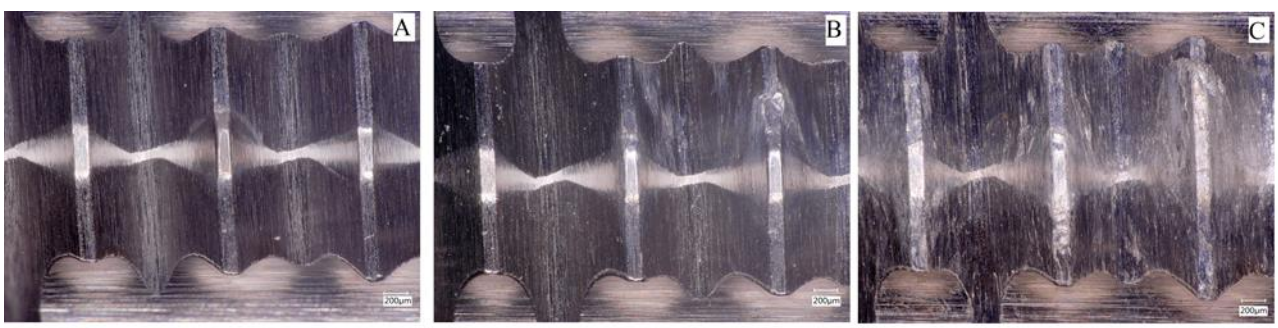

Figure 35 First three chamfered threads of uncoated roll form taps used with the (A) Hocut 795H, (B) SAC and (C)Sunflower oil

In conclusion, SAC with fewer chemical additives compared to Hocut 795H could provide comparable results in terms of feed forces and torque during drilling and in terms of thread profile, SAC exhibits better crest shape than the two other coolants.