An Investigation of the Impact of Selected Cooling Strategies on Milling of Difficult-to-Cut Materials with an Emphasis on Titanium Alloys and Hardened Steel

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Declaration

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Abstract

The aerospace- and automotive industries have an urgency to save space and reduce weight, as well as a need to increase fuel efficiency and reduce emissions. This has led to the use of lightweight structural materials, such as Ti6A14V alloy, which is the most widely used titanium alloy in the aerospace industry. This alloy has an exceptional strength-to-density ratio. The work also covers studies on tool steel 40CrMnMo7 that is used in applications in the tooling-, aerospace and automotive industry.

In the quest for improved performance new alternative methods of efficiently machining these materials are investigated. One of the important criteria during machining of these materials is their machinability. This study discusses current research in high performance machining strategies and techniques for advanced materials such as Ti6Al4V and 40CrMnMo7. The properties that make these materials advantageous for the use in the aerospace- and automotive industry also make them difficult to cut. The widespread application of Ti6Al4V in the aerospace industry has encouraged investigations into cooling strategies or -techniques to maintain and improve tool life. Ti6Al4V has a low thermal conductivity causing the heat generated during machining to accumulate on the cutting edge of the tool.

During various experiments the application of external compressed air blow cooling (dry cutting), flood cooling, high pressure through spindle cooling (HPTSC) and modifications thereof were investigated. The research project also evaluated the performance of a coating (TiAlN) and various coating treatments. The objectives of the HPTSC modifications were to improve the coolant stream impingement on the tool surface, effectively compressing the thermal barrier, and to reduce the chip-tool contact area. This would lead to a decrease in tool heating and wear.

The modified techniques failed to increase tool life but showed signs of increased heat removal capability under the given conditions. It was observed that air blow cooling (dry cutting) delivered the best results when considering cutting materials, coating, coating treatment and cooling strategies or –techniques throughout the experiments conducted.

Opsomming

Die Ruimte-en motor-industrie het 'n dringendheid om ruimte te bespaar en gewig te verminder, sowel as 'n behoefte om brandstofdoeltreffendheid te verbeter en emissies te verminder. Dit het gelei tot die gebruik van liggewig strukturele materiale, soos Ti6A14V Allooi , wat die mees gebruikte titanium allooi in die Ruimte is. Hierdie allooi het 'n uitsonderlike krag-tot-digtheid-verhouding. Die studie dek ook gereedskapstaal 40CrMnMo7 wat in die gereedskap, Ruimte-en motor-industrie aangewend word.

In die soeke na verbeterde prestasie word nuwe alternatiewe metodes om effektief bewerking van hierdie materiaal ondersoek. Een van die belangrikste kriteria tydens bewerking van hierdie materiaal is die bewerkbaar daarvan. Hierdie studie bespreek die huidige navorsing in hoë prestasie bewerking strategieë en tegnieke vir gevorderde materiale, soos Ti6Al4V en 40CrMnMo7. Die eienskappe wat hierdie materiaal voordelig maak vir die gebruik in die lug-en Ruimte-en motor-industrie, maak dit terselfdetyd moeilik om te sny. Die wydverspreide toepassing van Ti6Al4V in die lug-en Ruimte industrie moedig ondersoeke aan na koelstrategieë of -tegnieke om die instrumentlewe te handhaaf en te verbeter. Ti6Al4V het lae termiese geleidingsvermoë wat veroorsaak dat die hitte, wat gegenereer word tydens bewerking, versamel op die voorpunt van die instrument.

Tydens verskillende eksperimente was die toepassing van eksterne saamgeperste lugblaas-verkoeling (droë sny), vloed verkoeling, hoë-druk-deur-die-spil-afkoeling (HPTSC) en aanpassings daarvan geondersoek. Die navorsingsprojek het ook die prestasie van 'n bedekkingslaag (TiAlN) en verskeie bedekkingslaagbehandelings geëvalueer. Die doelwit van die HPTSC aanpassing was om die koelmiddelstroom beklemming op die instrument oppervlak te verbeter, en effektiewelik die termiese versperring saam te pers, asook die skerf-teenoor-instrument kontak te verminder. Dit sou lei tot 'n afname in die instrumentverwarming en -slytasie.

Die gewysigde tegnieke het daarin misluk om die instrumentlewe te verhoog, maar het tekens getoon van 'n toename in hitte verwydering vermoë onder die gegewe omstandighede. Dit is dus waargeneem dat lugblaas-verkoeling (droë sny) die beste resultate gelewer het in die oorweging van sny materiale, bedekkingslaag, bedekkingslaagbehandelings en verkoeling strategieë of -tegnieke wat regdeur die eksperimente uitgevoer was.

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Glossary

Attrition	Attrition consists of the formation of adhesion of workpiece material on the cutting tool surfaces, breaking away microscopic particles of the cutting tool material and dragging of these particles on the cutting tool surfaces, generally causing abrasion.
Built-up edge	This is a circumstance whereby the work piece material welds to the cutting edge of the tool.
Elastic modulus	The modulus of elasticity, Young's modulus, is the slope of a stress-strain curve within the elastic region known as Hook's law.
Fracture toughness	Fracture toughness is the ability of a material to resist failure from fracture by the propagation of a pre-existing crack.
Hardness	The hardness of a material is best described as the ability of a material to resist indentation or abrasion. The usual method of expressing hardness is the ratio of the applied load to indentation area. Hardness measurement techniques include Rockwell, Brinell, Knoop and Vickers hardness test.
Melting point	The temperature at which a pure metal, compound or eutectic solid phase changes to a liquid phase.
TRS	The stress required to break a specimen. Calculated from the flexural formula.
Thermal conductivity	Thermal conductivity is the property that characterises a materials ability to transfer heat. Thermal conduction is the phenomenon of heat transfer from a region of high temperature to a region of low temperature. The transfer of the thermal energy is purely by thermal means.
Thermal fatigue	This is the insert wear characterised by small cracks and fissures

	caused by temperature fluctuations. Thermal fatigue is also known as thermal cracking.
Thermal shock resistance	A materials ability to withstand sudden heating, cooling or both without the formation of cracks is termed its thermal shock resistance. The resistance to thermal shock is dependent on the magnitude of the change in temperature as well as the mechanical and thermal properties of the material.

Nomenclature

Symbol	Description	Units
K_{IC}	Fracture toughness	$MPa.m^{1/2}$
σ_f	Fracture strength	MPa
v_c	Cutting speed	m/min
f_z	Feed per tooth	mm/tooth
a_p	Axial depth of cut	mm
a_e	Radial depth of cut	mm
n	Spindle rotational speed (RPM)	rev/min
h_{eMax}	Maximum un-deformed chip thickness	mm
Ø	Tool diameter	mm
MRR	Material removal rate	mm^3/min
TL	Tool life	min
ρ_c	Density of cooling fluid	kg/m^3
$m_w + m_o$	Sum of the mass of water and the mass of oil	kg
V_c	Volume of cooling fluid	m^3
P_a	Tool supply pressure	kPa
g	Gravitational constant	m/sec^2
h_a	Coolant supply pressure head	m
v_a	Coolant supply velocity	m/min
Q_a	Tool supply flow rate	m^3/min
A_a	Area of the tool supply hole	m^2
D_a	Diameter of the tool supply hole	m
v_b; v_b’	Coolant outlet velocity	m/min
Q_b; Q_b’	Tool outlet flow rate	m^3/min
A_b; A_b’	Area of the outlet hole	m^2
d_b; d_b’	Diameter of the outlet hole	m

1. Introduction

1.1 Background

In the post 2000 advanced manufacturing arena, an urgency to save space and reduce weight in the aerospace and automotive industries has become the norm rather than the exception. This need, combined with a requirement for fuel efficiency and less emissions, has led to the use of lightweight structural materials at higher temperatures. In this study the focus is on the most widely used titanium alloy in aerospace, Ti6A14V. This titanium alloy has an exceptional strength-to-density ratio and has the ability to withstand high temperatures as well as severely corrosive environments while maintaining the characteristic of high strength.

The study also covers a high strength tool steel 40CrMnMo7. This steel is used in tooling applications as well as in high stress gears, piston rods and transmission shafts in the automotive industry. In the quest for improved performance, automotive and tooling industries are constantly investigating new alternative methods of effectively machining this new generation of hardened tool steels.

The lower density of titanium alloy Ti6Al4V, 4.43 g/cm^3, over hardened steel 40CrMnMo7, 7.85 g/cm^3, as well as its comparable ultimate yield strength, 935 – 977 Mpa and 992 – 1014 Mpa respectively, has given it consideration for aerospace and automotive industry components. The lower density and equal strength allows for the replacement of hardened steel in numerous applications. Typical examples where this titanium alloy offers favourable use is in turbo-machinery parts such as turbine blades and compressor impellers, complex shapes for heat transfer, cylinder heads/combustion chambers and structural components [1]. The, abovementioned reduces the overall weight of the aircraft/motor vehicle allowing for increased fuel consumption. However, the need for weight reduction is less of a concern in automotive industry and, more so, for the tooling industry. For this reason 40CrMnMo7 still has use in these industries. The common concern in the abovementioned industries is the machinability of the mentioned materials and the cost effectiveness of its application.

Machining has a major influence on the production cost. One of the important criteria during machining of materials is the machinability. Machinability entails the process used to cut the material, the difficulty to cut the material due to its properties, the material removal requirements and the selection of cutting parameters that meet these requirements. Better understanding of the *wear mechanisms* encountered will help improve tool performance and reduce tool costs. Titanium's machinability is considered to be poor, despite all of its positive characteristics. The heat generated during machining accumulates on the cutting edge of the tool, due to the low thermal conductivity of titanium, reducing the flow of heat away from the cutting zone [2]. Furthermore, the interrupted cutting process during milling causes *thermal and mechanical shock loading*.

Machinability could be regarded as a material constant, but in this text it is used in general logical sense. The requirement for improved machinability of Ti6Al4V and hardened steel has increased the demand on machining parameters. This has developed a need to improve on cooling strategies and techniques, as well as implementing the correct cutting tool material, combined with the inclusion of a suitable coating. Cutting tool materials that can withstand both the temperature and mechanical demands placed upon them have the potential to increase the material removal rate and material removed under the same machining time or less. Titanium alloy machinability can be improved by selecting a suitable cutting tool material and coating. Additionally, the cooling strategy or technique of application has the potential to improve tool life. The strategy chosen for the application of coolant can be described as the basic application method. A technique of applying cooling fluid should be regarded as a subdivision under a particular cooling strategy. The selection of a suitable cooling strategy and technique can reduce the thermal and mechanical demands on the cutting tool, increasing the tool life and shortening machining time.

It is important to understand the general terms High Speed Machining (or Cutting) and High Performance Machining (or Cutting). High Speed Machining (HSM) refers to machining applications where high spindle speed/cutting speed is the qualifying parameter. This includes conditions for moderate surface complexities, requiring smaller diameter cutters. The major benefit is then productive, fast, surface coverage through high axial feed rates. This allows the use of a small step-over that results in cost effective achievement of a high surface finish, often associated with a small depth of cut. High Performance Machining (HPM) is defined as the most productive means to achieve a high material removal rate (MRR). Cutting speed, feed rate and depth of cut are integrally optimised to achieve the best possible MRR. In the aerospace industry HPM is more applicable due to the high demand on integral parts which require a large percentage of the original material to be machined away.

1.2 Problem Statement

As the cost of crude oil soars, aerospace and automotive industries are under pressure to find innovative means to minimise fuel costs. Consolidation and a stressed operational environment have reshaped the aerospace and automotive industry, with fuel efficiency rising to be an influential business priority. The requirement of reduced emissions, in tandem with a need for increased fuel efficiency, has necessitated the reduction of weight and brought a requisite for efficient turbine engines and power generation components. Therefore, a necessity is created to use high strength-to-density ratio materials on a larger scale for airliners to achieve higher fuel efficiency with lower carbon emissions in order to reduce fuel consumption and the cost thereof. This need has created a trend towards carbon reinforced polymers (CRP) such as carbon fibre, requiring a major shift from aluminium to titanium, driven by CRP compatibility. Against the backdrop that it is a difficult-to-cut alloy, the result is that titanium manufacturing techniques, specifically machining, are a challenging subject that has become prominent lately.

The increased requirement for machining *titanium and hardened steel* has brought about high cutting speeds and eminent demands on the cutting materials and processes used during machining. The properties that make Ti6Al4V alloy and hardened steel 40CrMnMo7 advantageous also make them difficult-to-cut. Among the interesting characteristics are density, hardness, yield strength, modulus of elasticity and thermal conductivity. From the material side, titanium presents its most demanding challenges to achieve a high MRR. Although machining of titanium is not a unique area of expertise, it does however require special techniques and knowledge. Its relative toughness, high strength and low modulus of elasticity when compared to many steels are largely responsible for this. Due to Ti6Al4V alloy having a *low thermal conductivity* there is a larger portion of machining heat concentrated on the cutting tip rather than the chip, increasing the heat in the cutting zone [3]. This increase in thermal loading in the cutting zone and reduction of heat expulsion from this area results in destructive wear of the cutting tool surface reducing the tool life during machining, in some instances catastrophic tool failure can occur.

Therefore the predominant problem during machining is caused directly or indirectly by the heating of the cutting zone. For this reason, the heat generated during the machining of these difficult-to-cut materials plays a major role in determining the tool life.

1.3 Main Objectives

The research areas cover the high performance machining of light metals with an emphasis on the Ti6Al4V alloy. Developments in tool materials and coating have increased in the past century in the attempt to withstand cutting temperatures and mechanical forces brought about due to HPM of difficult-to-cut materials [2]. Cutting tools now require superior hardness and wear resistance, high strength and toughness as well as thermal stability when machining difficult-to-cut materials. The aforementioned has created a recent trend toward coated carbide systems [4]. Therefore, one of the objectives is to:

- *Determine* economically optimised machining conditions, tool material, coating, coating treatment and the effect of applying a cooling strategy or –technique to achieve satisfactory tool life.

Also, cooling fluid is conventionally used to reduce the cutting temperature as well as lubricate and flush chips out of the cutting zone, but can create problems in terms of employee health and environmental pollution. Since the facilitation of a cooling strategy or -technique providing an optimised solution for the relief of the consequences of the expansive machining demands, further removal of this heat generation factor promises to improve the efficiency of the machining process and increase tool life, which in turn will reduce the cost of machining [4]. Therefore rendering the objective to:

- Investigate various cooling strategies and -techniques along with the need to remove heat from the cutting zone.
- Make an innovative contribution to knowledge and develop an improved strategy or -technique of applying coolant during machining difficult-to-cut materials.

The overall aim is to optimise the machining process and establish how tool coating, coating treatment, and different cooling strategies or -techniques influence the cutting tool life during high performance machining of difficult-to-cut materials, with an emphasis on Ti6Al4V alloy and hardened steel 40CrMnMo7.

1.4 Research Approach

The understanding of tool demands and effective methods for milling difficult-to-cut materials, entails determining cutting parameters and cooling strategies that are appropriate for the machining process. The optimisation of these parameters effectively helps to reduce machining demands and make the machining process more efficient. Tool life depends on a number of variables, including cutting tool material, work material, cutting conditions and cooling strategies or -techniques.

Firstly, the demands on the machining process are studied. Once the demands are determined, the consequences of these demands are elaborated in the mechanisms of wear and the various wear formations. While tool wear is unavoidable, it can be reduced by fully understanding the failure mechanism and factors contributing to the wear formation. Therefore issues that influence heat generation, flow of heat, and the distribution of temperature in the cutting tool and workpiece material are investigated in this research.

Secondly, the significant machining parameters that lead to the shortening of the tool life are investigated. There is negligible theory to predict adequate understanding of the relationship between the tool life and cutting parameters, machining approaches as well as cooling and lubrication strategies. The thermal loading experienced increases the effect of mechanical loading causing untimely mechanical failure. For this reason cooling strategies and –techniques' ability to reduce the effects of temperature are investigated.

2. Machining of difficult-to-cut materials - a literature review

2.1 Introduction to difficult-to-cut materials

Developments in machine tools, the aircraft and motor industry, as well as in process technology have dramatically increased the industrial relevance of machining difficult-to-cut materials. There is a trend for the reduction of machining time and machining cost in the manufacturing industry in general. Outcomes from these demands consist of significantly higher cutting speeds, feed rates, cutting parameters and process temperature [5].

The assessment of a process encompasses economy, flexibility, ecology and quality as important criteria of evaluation [6]. The process of machining difficult-to-cut materials has increased costs of production and consumption of material resources, relative to the machining of other metals. One of the elementary methods of improvement of the cutting process is to develop an appropriate cooling application method. This has potential to increase the quality of the product and reduce the machining demands. The minimisation of cutting fluid use will help reduce waste, costs and lead to a more effective consumption of resources.

In the machining process, the machining parameters produce complex demands on both the cutting tool and machined material. These difficulties cause tool failure by mechanical or thermal means. The mechanisms that cause wear, as well as the wear formations that arise from these mechanisms, influence the tool life considerably.

2.2 Physical properties influencing machining of difficult-to-cut materials

The machinability of any material depends to a large extent on its physical properties. Table 1 (adapted from [7,8]) indicates some of the properties of Ti6Al4V alloy and hardened steel 40CrMnMo7. The low modulus of elasticity of Ti6Al4V alloy (114 GPa) and its high strength properties (935~977 MPa) increases the difficulty of machining this alloy at elevated temperatures. Additionally, the lower modulus of elasticity causes a substantial spring back after deformation under cutting load and leads to the movement of the titanium workpiece away from the cutting tool during machining [3]. The different chemical compositions of these materials make up their physical properties and give them the characteristic of being difficult-to-cut. Respectively, Table 2 and Table 3 shows the composition of the Ti6Al4V alloy and hardened steel 40CrMnMo7 used in this study [4,7,8,9,10,11]. Figure 1 gives the strength-to-density ratio of Ti6Al4V alloy and other metals over varying temperatures. From this graph, it can be seen that titanium has a high strength-to-density ratio, at relatively high temperatures. These properties, combined with a similar hardness to hardened steel, make this titanium alloy a favourable replacement material for hardened steel in a number of applications. However, since titanium is not favourable at temperatures above approximately 500 °C, hardened steel still maintains its application at temperatures exceeding 500 °C [1,12].

Table 1: The properties of Titanium Alloy (Ti6Al4V) and Hardened Steel (40CrMnMo7) [7,9,13]

Properties	Ti6Al4V	40CrMnMo7
Density	4.43 g/cm^3	7.85 g/cm^3
Hardness Brinell	334 HB	300 HB
Ultimate tensile strength	935~977 MPa	992 ~ 1014 Mpa
Yield Strength	880 Mpa	821 ~ 854 Mpa
Melting Point	1650 °C	1400 – 1540 °C
Modulus of Elasticity	114 Gpa	205 GPa
Thermal Conductivity	6.6 W/m°C	33 W/ m°C
Specific Heat	565 J/kg°C	460 J/kg°C

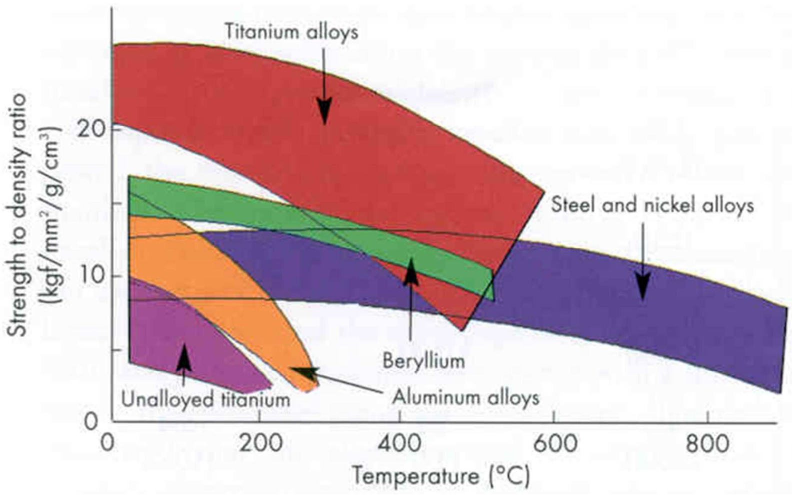


Figure 1: Strength-to-density ratio vs. temperature for various materials [1]

Table 2: Composition of Titanium Alloy (Ti6Al4V)

	Si	*Mn*	*Mo*	*Ti*	*Al*	*Ti+Al*	*V*	*Fe*	*Cu*
Composition %	0.02	< 0.01	< 0.01	BAL.	6.54	-	3.91	0.16	< 0.01

Table 3 : Composition of Hardened Steel (40CrMnMo7)

	C	*Cr*	*Fe*	*Mn*	*Mo*	*P*	*Si*	*S*
Composition %	0.41	2.00	BAL.	1.50	0.20	-	0.30	-

The fracture toughness, K_{IC}, is the critical stress intensity value or plane-strain fracture toughness, often used in design of structural members that utilise high strength materials, reflecting the resistance to fracture of the material. Figure 2 indicates the fracture toughness, K_{IC}, as a function of the fracture strength, σ_f, of titanium alloys. It can be seen that titanium alloys, can potentially replace hardened steel, in virtue of their similar fracture toughness and fracture strength characteristics. Titanium therefore shows considerable promise as a possible replacement for selected components made from hardened steel.

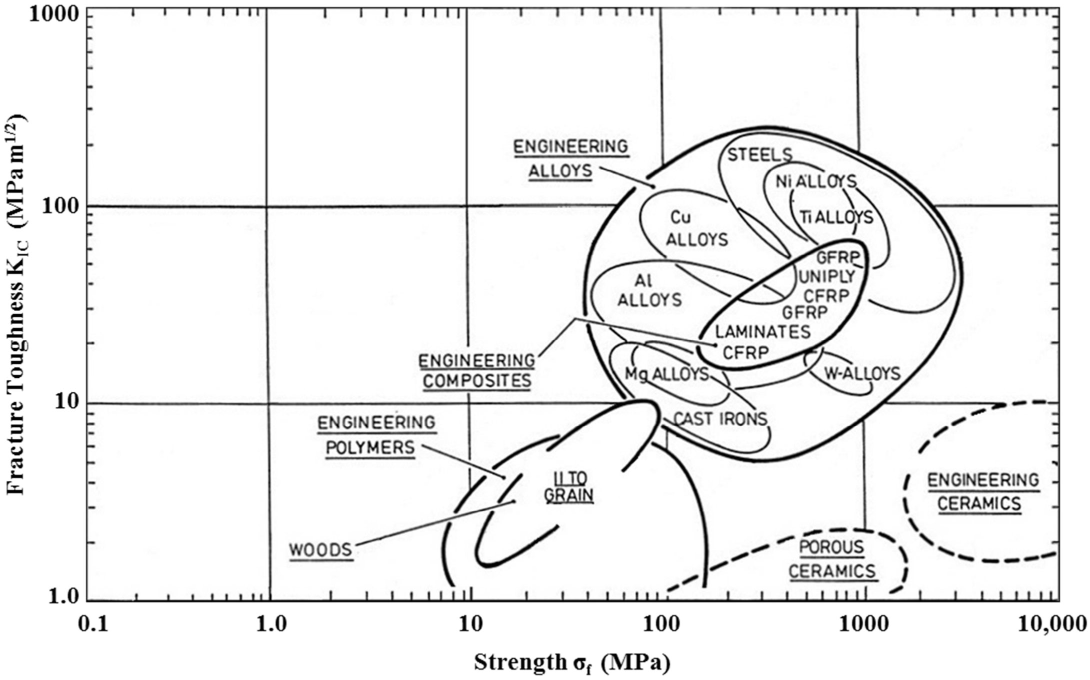


Figure 2: Fracture toughness vs. fracture strength (adapted from [14])

2.3 Demands during machining of difficult-to-cut materials

In any form of material removal there are forces, stresses, pressures and temperatures that occur due to the contact between the cutting tool and workpiece material. Depending on the cutting parameters, cutter body material and machined material used in the process, different machining challenges transpire determining the difficulty of machining. Therefore, understanding the mechanism of material removal is essential for process evaluation [15,16,17,18].

The key complications during machining difficult-to-cut materials are the thermal and mechanical loading demands. Figure 3 depicts the heat development in the cutting tool and workpiece, as well as the deformation zones in which the mechanical and the thermal demands develop. Heat and mechanical forces created by plastic deformation, generated in the primary deformation zone, are transferred to the workpiece and chip under formation by conduction. The secondary deformation zone transfers the heat and force to the cutting tool through conduction of the frictional heat caused by the chip/tool contact. The heat taken up by the chip is transferred through conduction or convection, depending on the cooling strategy applied, as well as radiation [19]. Machining difficult-to-cut materials produces excessive tool wear in the secondary deformation zone, resulting in low cutting speed, extension of machining time and a rise in manufacturing costs [20].

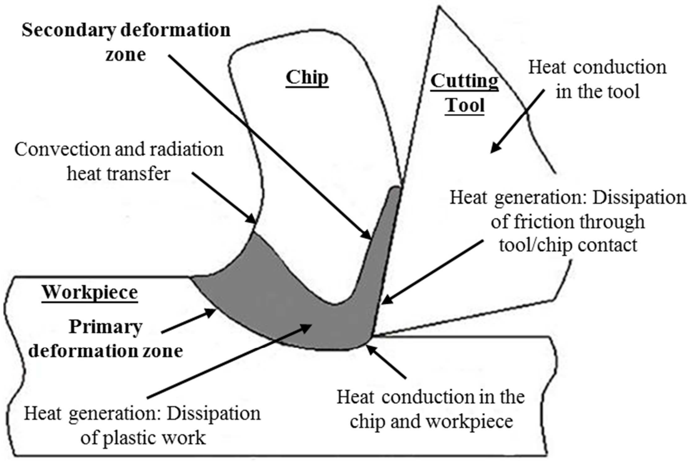


Figure 3: The distribution and flow of heat and deformation in the cutting zone [19]

In the milling process, the interrupted cutting intensifies the mechanical and thermal demands confronted by the cutting tool. The mechanical demands are largely influenced by the feed rate and the thermal demands exaggerated by cutting speed. These demands simultaneously apply load on the insert, often termed thermo-mechanical loading, mounting to varying modes of tool failure [15,16,17,18]. It is necessary to understand both thermal and mechanical demands on the cutting edge (see sections 2.2.1 and 2.2.2 below) when designing or developing an innovative strategy or technique in order to improve the machining of difficult-to-cut materials [20].

2.3.1 Mechanical demands

The mechanical demands are a combination of the workpiece chip load on the cutting edge, otherwise known as mechanical load (h_{emax}), and the machining vibrations. The h_{emax} is represented by the maximum thickness of the un-deformed chip which is the foundation of the major mechanical load, as depicted in Figure 4 (*i*). The mechanical load is a function of the tool diameter (Ø), the feed rate (f_z) and the radial immersion (a_e).The f_z is the most influential cutting parameter on h_{emax} followed by a_e. The line *a-b* denotes h_{emax} and *c-d* indicates $h_{emax'}$ in

Figure 4 (*i*) and (*ii*) respectively. The change in magnitude in h_{emax} and $h_{emax'}$ demonstrates the influence of f_z and a_e on the maximum un-deformed chip thickness [21].

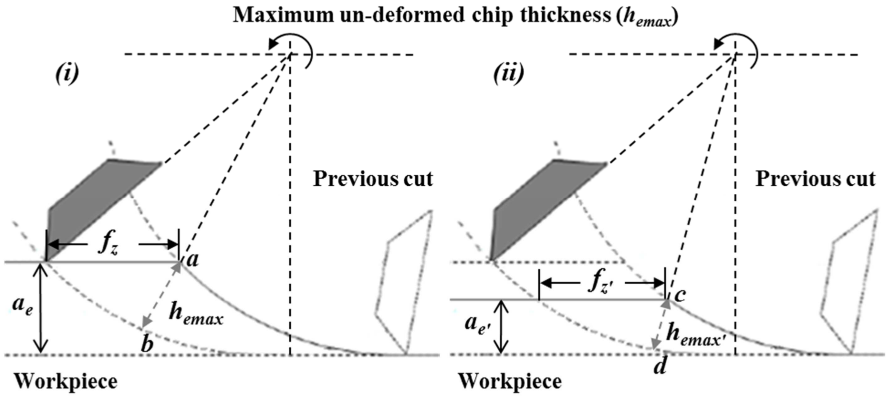


Figure 4: Contributing parameters on mechanical loading (h_{emax}) during milling (adapted from [21])

Catastrophic tool failure, due to mechanical overload, is caused by self-excited chatter and forced vibrations, owing to a formation of shear localisation during chip generation and fluctuating frictional phenomena between the cutting tool and chip. The phenomena of friction between the workpiece and forming chip is formed in the primary and secondary deformations zones highlighted in Figure 3 [19,22,23,24]. The wear formation that occurs due to mechanical loading is often characterised by coating delamination, chipping, abrasion and mechanical fatigue [18,24,25]. In the case of difficult-to-cut materials, their mechanical and physical characteristics encourage chatter and workpiece movement away from the cutting tool, resulting in high cutting temperatures, tool vibration and decreased tool life [26,27].

2.3.2 Thermal demands

In the milling process, the machined material is subject to high strain and plastic deformation. The deformation zones and heat generation are illustrated in Figure 3. The portion of plastic deformation is miniscule in proportion to the total deformation, and for this the assumption is that all energy is transformed into heat [28]. The cutting tool temperature is a function of the cutting speed (v_c) and exposure time to the thermal load generated [8,29]. During the milling process, the cutting tool is heated on entry and during cutting, and then cooled on its exit of the cutting zone. This causes temperature variations, which result in periodic expansion and contraction of the cutting tool, leading to the formation of thermal cracks. This process of thermal cracking is also known as *thermal fatigue* which often leads to rapid tool wear [10,18]. Thermal wear formations are classified by adhesion, plastic deformation, thermal fatigue and chemical reaction [25].

Thermal conductivity is an important physical characteristic. Titanium has a low thermal conductivity in comparison to hardened steel, resulting in a greater concentration of heat in the cutting zone [20]. The concentration of heat at the cutting edge is a result of the heat not dissipating with the forming chip. Higher cutting speeds yield increased cutting temperatures and followed by arbitrary cooling can result in premature tool failure, due to the formation of thermal cracks [28,30]. This is justified by the fact that temperature fluctuations are the main cause of thermal fatigue [10,18]. In the case of difficult-to-cut materials, the major proportion of the heat generated is concentrated at the cutting edge of the tool, which leads to rapid tool wear [8,16,29].

2.4 Tool failure modes

Cutting tools fail under gradual and progressive wear of the cutting edge or due to plastic deformation, enforcing loss of tool geometry and reduction in the cutting tools' efficiency [16]. The initiation of tool failure can consist of one or a combination of wear modes. These modes, at advanced stages, lead to overloading or -fatigue and catastrophic tool failure [15,24]. Uniform wear occurs under optimised machine cutting parameters. These parameters vary from process to process and from material to material.

The modes of failure determine the mechanisms of wear and wear formations, ultimately influencing the cutting tool life. In the context of tool failure, the importance and occurrence of these modes of failure can be classified by temperature failure and fracture failure, represented by Figure 5 [31]. It should be noted that adhesion is an outcome of both thermal and mechanical loading [25].

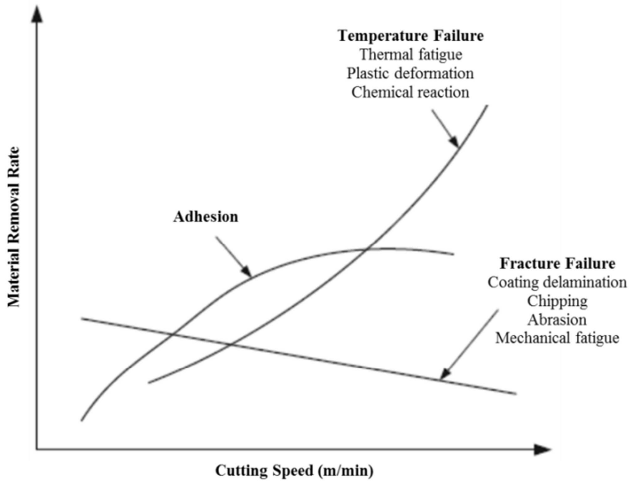


Figure 5 : Tool failure modes vs. cutting speed (adapted from [31])

2.4.1 Fracture failure

Fracture failure occurs when cutting tools fail abruptly, by brittle fracture, when cutting forces at the tool edge become exceptionally large [16,32]. This mode of failure originates when the applied load is greater than the fracture toughness of the machined material [33]. Fracture toughness is characterised as a material's resistance to brittle fracture due to the applied load causing the propagation of an existing crack.

2.4.2 Temperature failure

Under the extreme conditions which occur when high cutting speeds are used when machining difficult-to-cut materials, high cutting temperatures are experienced. When temperatures become too high for the cutting tool material, it causes the tool cutting edge to soften, leading to plastic deformation and blunting [16]. When machining titanium, temperatures reach above 500 °C, and this becomes considerably problematic. Titanium becomes chemically reactive at such high temperatures, and has a strong affinity to cause adhesion and diffusive wear on the cutting tool surface under these conditions [15]. Therefore, temperature failure has the potential to change both the cutting tool and workpiece material composition having the characteristics of a chemical reaction.

2.5 Mechanisms of tool wear

The execution of removing material by milling processes generates high forces and temperatures [16,29]. The generation of the mechanical and thermal loading are represented in Figure 6. The mechanical loading is divided into two main force components: cutting force (F_C) and normal force (F_N). The F_C and perpendicular F_N arises from the cutting speed, feed rate, depth of cut, radial emersion and shear localisations, which form segmented or continuous chips.

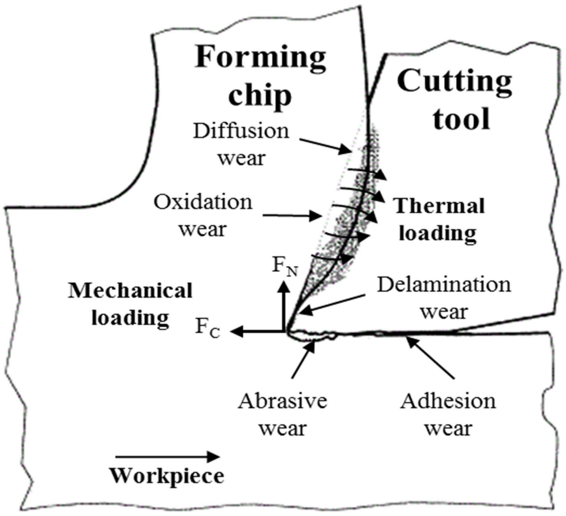


Figure 6: Mechanisms of tool wear during machining (adapted from [34])

Thermal loading occurs due to friction between the chip, workpiece and cutting tool interfaces and the transfer of heat focused in the area of contact, particularly in the case of titanium machining. High temperatures cause softening of the tool material, increasing the probability of tool failure. When cutting forces become too great, tool fracture becomes more eminent [16]. Figure 6 shows the frequent wear locations and formations situated in the cutting zone. Some of the common wear mechanisms are diffusion, oxidation, abrasion and adhesion, described in the sections below for a basic understanding of the mechanisms of tool wear [10,30,35].

2.5.1 Abrasion

Abrasion is a mechanical wearing action whereby hard particles contained in the work material are dislodged and abrade the cutting tool. In effect, chips and grooves develop because of the displaced particles' abrasive action on the cutting tool. This mechanism of wear causes significant deterioration of the cutting tool surface and is present in both flank and crater wear formations [36,37,38,39].

2.5.2 Adhesion

Under high pressure and temperature, two materials forced into sliding contact with each other can cause the materials to adhere or weld together. These conditions are present in the contact between the chip and rake face of the tool. The chip passing over the rake face causes small fragments of the tool to detach from one surface and attach to the other surface [16,37,40]. These fragments can be continually transferred, back and forth between the two surfaces, or develop into detached wear particles. The temperature at which adhesion occurs varies with the different combinations of cutting tool and work material [40].

2.5.3 Diffusion

Atoms within a crystal lattice of high concentration move to regions of low concentration. The exchange of these atoms during machining materials occurs at the boundary of the tool/chip interface. This depletes the tool surface hardness by the removal of atoms responsible for hardness, creating a surface susceptible to abrasion and adhesion. Crater wear is believed to be mainly caused by diffusion. Diffusion is a process that is highly dependent on temperature [7,16,37].

2.5.4 Oxidation

Chemical reactions can occur on the cutting tool edge due to the tool/chip interface contact. The oxidisation layers are softer than the tool material and are therefore easily removed to expose new clean surfaces on which oxidation layers form without difficulty [16,40]. This process of the oxidisation layers forming and being removed is continually and periodically repeated, especially under high temperatures. This form of wear is commonly called oxidation wear [41].

2.6 Wear formations on the tool

Wear is apparent on two principal locations on the cutting tool, namely the rake face and the flank face. To completely understand the advantages and limitations of the cutting tool materials, knowledge of the different wear mechanisms that the material is subjected to is important.

2.6.1 Flank wear

The rubbing of the newly machined surface on the clearance face results in flank face wear. During milling, flank face wear has been observed to be prominent [30,35]. The degree of flank wear can be measured by the average width of the wear scar (V_B), otherwise known as the wear band or wear land. In most cases, flank face wear is an indicator for the tool life expectancy. Figure 7 exhibits flank face wear [39].

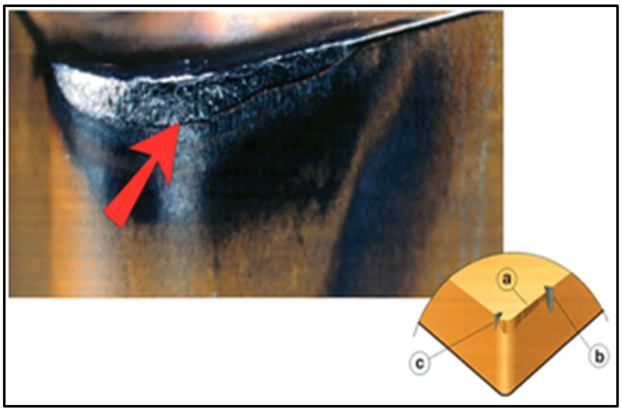


Figure 7: Flank face wear [39]

2.6.2 Crater wear

Crater wear, formed by the chip sliding across the tool rake face, creates a concave section, as shown in Figure 8 [39]. High cutting forces and temperature are contributing factors to the formation of crater wear [16,42]. The depth or area of the wear scar determines the extent of the crater wear [37].

The maximum depth of crater wear occurs at the apex of the insert. This is caused by the contact of the chips on the tool face. Crater wear can be exaggerated by chips that have a short contact length with the insert and focused on the apex of the tool, exposing the tool to severe stresses and temperatures [16].

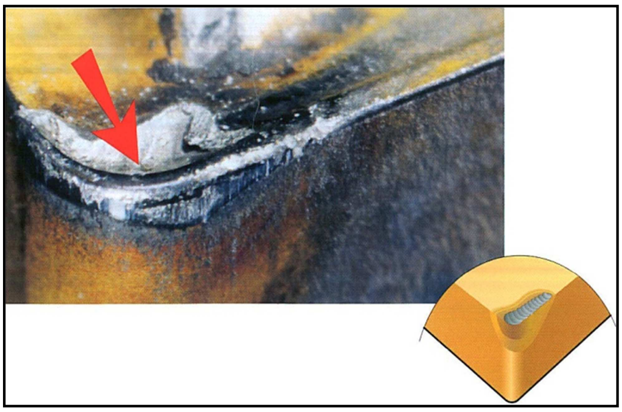


Figure 8: Crater wear [39]

2.6.3 Plastic deformation

Plastic deformation is another mechanism of wear of the cutting edge. The cutting forces present on the tool edge are subject to high temperatures, causing the edge to deform plastically, as a consequences of compressive stress on the cutting edge [8], the results of which can be seen in Figure 9 [39]. This leaves the tool surface exposed to abrasion and is the predominant cause of flank wear [16].

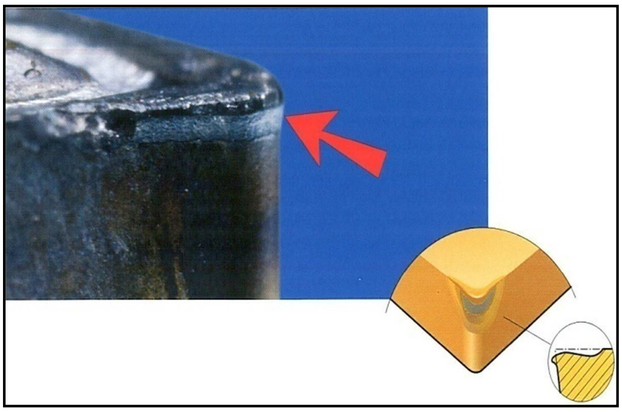


Figure 9: Plastic deformation [39]

2.7 Parameters effecting tool life

The machining parameters contribute to the characteristics of the failure modes and mechanisms of wear, concerning the tool insert. In the machining of parts, quality of the final product is specific to the customer requirements. Damage of the cutting tool is influenced largely by the stress and temperature experienced at the tool surface. The damage of the tool is dependent on factors such as any changes in cutting parameters, ranging from feed rate, cutting speed, axial immersion (depth of cut) and the presence of cutting fluid with the inclusion of tool geometry. The surface finish is a major indicator of the surface roughness and influenced mainly by the cutting conditions [43].

2.7.1 Cutting speed and feed rate

Cutting temperature and force resulting from milling at high cutting speeds and high feed rates are the main cause of tool failure and heat generation [4]. Increased cutting speeds encourage diffusion wear because of the high temperatures between the workpiece and cutting tool interface [44,45]. Cutting speed (v_c) and radial immersion (a_e) are the factors that most affect the tool life (*z*), followed by the feed rate (f_z) and axial immersion (a_p), illustrated in Figure 10 [21]. The feed rate has a larger influence on the chip load in comparison to the cutting speed due to the establishment of increased mechanical forces, presented in Figure 4 (*i*) demonstrates the mechanical loading h_{emax} in section 2.2.1 [8,24,32,35,46].

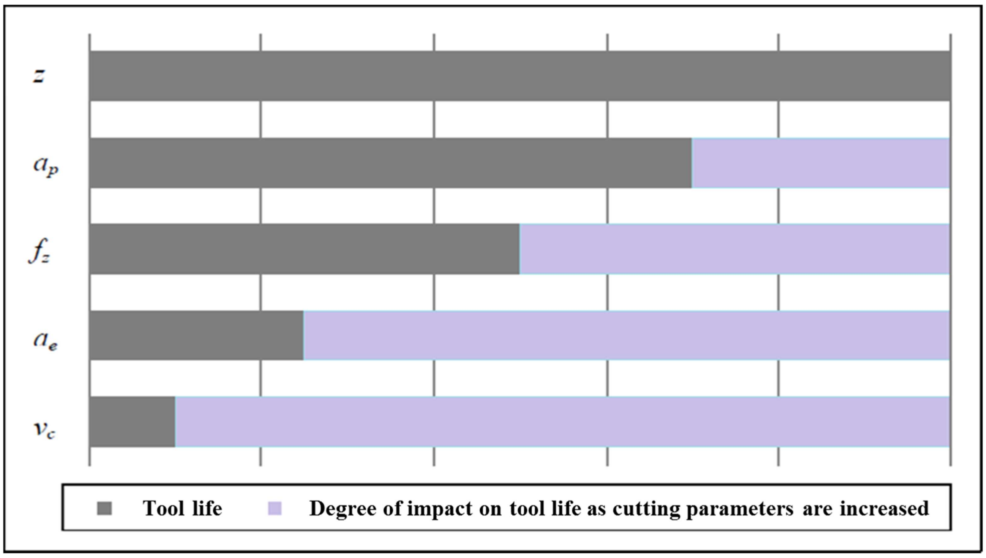


Figure 10: Influential cutting parameters that reduce tool life during milling (adapted from [21])

Figure 11 shows a typical tool-life chart giving cutting speed versus tool life at varying feed rates [29]. From the graph, it is evident that cutting speed and feed rates are inversely proportional to the tool life of the inserts. This is also clear inFigure 10, which clearly shows that an increase in cutting speed or feed rate decreases the tool life substantially, with particular focus on the cutting speed. Li Anhai *et al* confirmed that cutting speed and feed have a prominent impact on the tool wear progression and tool life [25].

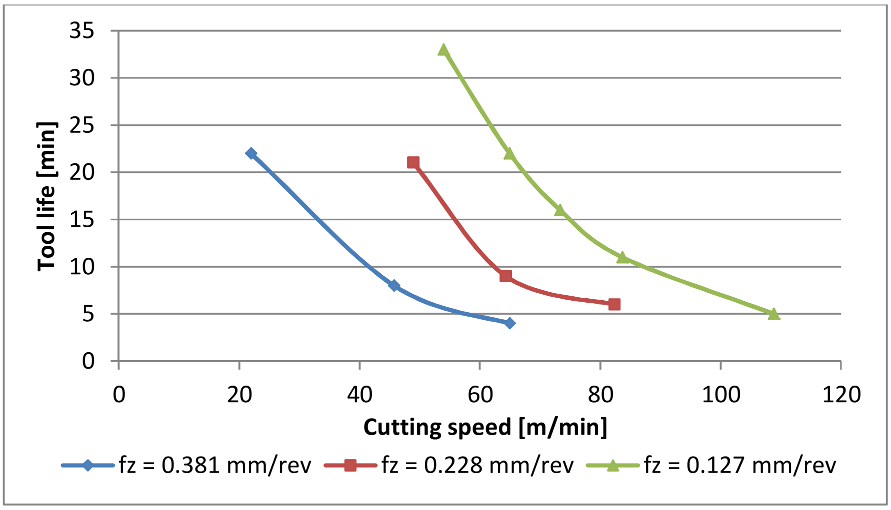


Figure 11: Effect of cutting speed and feed rate on tool life in turning Ti6Al4V with C-2 (883) Carbide [29]

2.7.2 Effects of axial immersion and radial immersion

The Sandvik technical guide (D) states that axial immersion (a_p) has minimal effect on the tool life. The a_p has an impact on the machining strategy implemented, which is determined by the material removal requirement, more so than that of the tool life [21,47]. In order to prevent chatter, it is vitally important that cutting stability be maintained during machining, as well as rigidity of the tool/workpiece interface [21]. According to Li Anhai *et al,* [25] a_p should not change the progression of average flank face wear. The a_p and h_{emax} values demonstrated in Figure 12 indicate the working cross sectional cut area and the material removal characteristics for indexable milling tools with an entry angle of 45° and 90°.

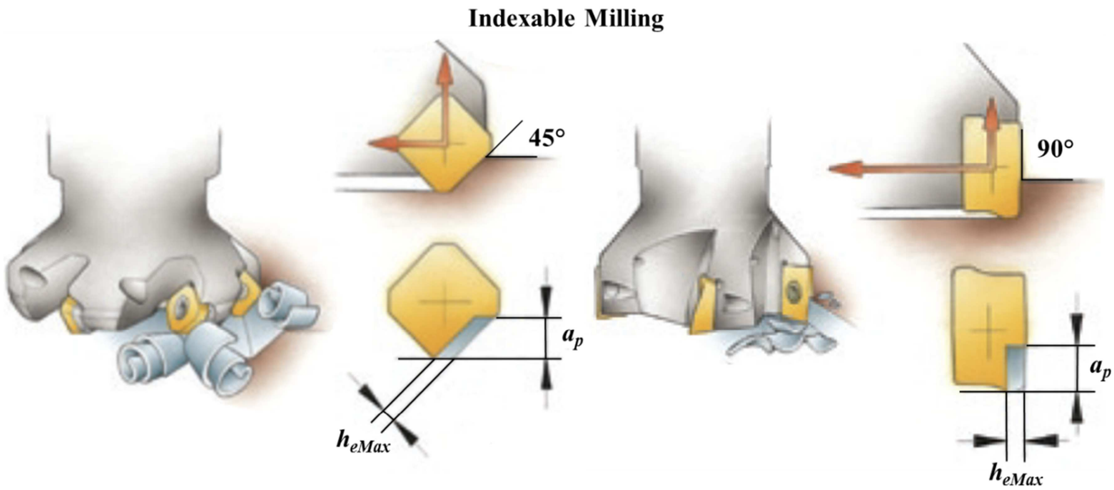


Figure 12: Cutter body entry angles, cutting force effects and axial immersion [47]

Radial immersion (a_e) is highly dependent on the cutting speed. The a_e defines the period the tool is in contact with the heat generated at the cutting edge [33]. This and the fact that the a_e causes an increase in the h_{emax}, seen between the difference in Figure 4 (*i*) and (*ii*), both contribute to the mechanical and thermal demands experienced when machining. Therefore, a_e coincides with Figure 10, indicating the impact of a_e on tool life. For an economical tool life and material removal rate, Sandvik recommend an a_e in the region of 30 - 40% of the diameter of the cutting tool for rough milling [47].

2.8 Cutting tool materials

Cutting tool materials must possess resistance to the resulting mechanical and thermal demands, wear and deformation. These materials should be rigid, with adequate power and toughness [6,43]. The cutting material should have resistance to factors such as the heavy impact typically resulting from abrasive particles in the microstructure of the workpiece material causing grooves to form in the cutting tool combined with indentation resilience, attributed to the exposure of the cutting tip to deformation in the tool-workpiece contact area [6].

The energy resulting from the cutting forces, transformed almost completely into heat, generates high cutting temperatures. Since the cutting insert experiences the full extent of the mechanical and thermal loading, cutting materials that can withstand these criteria are required. An overview of the mechanical and thermal properties of cutting tool materials commonly used during machining difficult-to-cut materials are given in Table 4 [6].

Table 4 : Different cutting tool material properties [48,49,50,51,52,53,54,55]

Properties		Units	Cemented Carbide	Ceramics	PCBN	PCD
Mechanical	Hardness Vickers	Gpa	≈ 1.8 – 2.1	≈ 1.9–2.3	≈ 2.7 – 3.8	≈ 7 - 8
	Young's Modulus	Gpa	520 - 630	300 - 380	580 – 680	776
	Fracture Toughness	Mpa/m^2	≈ 10 - 17	3.5 - 6.5	≈ 3.7 – 7	≈ 6 - 10
	Transverse Rupture Strength	Gpa	≈ 2.0 – 2.8	≈ 0.5 – 0.8	≈ 0.8 – 1.3	≈ 1 – 1.5
Thermal	Thermal Conductivity	W/(K m)	≈ 70 - 100	30 - 40	44 – 100	≈ 520
	Thermal Expansion Coefficient	$10^{-6}K^{-1}$	≈ 4.5 – 5.3	7.5 – 8	4.6 - 4.9	4.2

The hardness of the material expresses the materials resistance to abrasion or scratching. The greater Young's modulus gives an indication of the stiffness of the material and the larger fracture toughness expresses the material's resistance to sudden mechanical loading. The resistance to fracture of the cutting tool material is represented by the transverse rupture strength (TRS). The thermal conductivity shows the materials ability to take up heat. The expansion of the volume of the cutting material is given by the thermal expansion coefficient.

From Table 4 it can be seen that polycrystalline diamond (PCD) has superior hardness and stiffness. Although PCD has a good fracture toughness, its low resistance to fracture by mechanical loading is unfavourable in machining processes where mechanical demand is the major contributor to failure as is the case in milling operations. However, PCD has a high thermal resistance and low expansion coefficient, making it favourable where temperature is the main difficulty. Polycrystalline cubic boron nitride (PCBN) has a relatively high hardness and stiffness but low rupture strength, thermal conductivity and a high affinity for expansion. These properties are not progressive in milling difficult-to-cut materials. Cemented carbide has the best opposition to mechanical loading due to its high fracture toughness and transverse rupture strength in addition to its moderate stiffness, recommended in interrupted cutting for its resistance to mechanical failure. Unfortunately, cemented carbide has poor thermal conductivity and moderately high expansion under high temperatures. This leaves it susceptible to failure because of thermal demand.

Both high temperature and mechanical loading are prevalent in machining of difficult-to-cut materials, particularly in the interrupted milling process. Cemented carbide and PCD both possess the sought-after properties to withstand these mechanical and thermal conditions. However, due to the high cost of PCD and high diffusion ability of carbon in ferrous materials [6] the latest cemented carbide was used in this study. Cemented carbides are also cheap and utilised extensively in industry.

2.8.1 Cemented carbides

There are two categories of carbide tool materials available for commercial machining application, namely straight and mixed carbides. Straight carbide grades usually consist of 6 wt.% Co and 94 wt.% WC with a cobalt composition ranging from 5 – 12 wt.%. The mixed grade carbides have titanium carbide (TiC), tantalum carbide (TaC) or niobium carbide (NbC) and other rare-earth elements added to the base composition of the straight grade [17]. The most commonly employed cutting tool material is cemented carbide. Tungsten carbide (WC) inserts display superior wear performance in comparison to other cutting tool materials when cutting in interrupted processes [36,56]. Carbides may be coated or uncoated, depending on their application during machining. In the case of coated carbides, the most popular coating is PVD TiAlN [10,36]. Coated cemented carbides have a high tensile strength, fracture toughness and improved resistance to temperature fluctuations [6,37,45].

The prevailing mechanism of wear is dependent on cutting conditions, tool and work materials [37]. In previous studies, results have shown that when uncoated carbides are used at low cutting speeds, abrasion and adhesion are the responsible mechanisms for the tool flank wear, where diffusion and abrasion is dominant in coated carbide tools. The diffusion and abrasion mechanisms of wear are the main causes of crater wear forming on the flank face edge [8,10,30,44]. The cracks formed on the cutting edge are due to the characteristic interrupted milling process causing the fluctuating mechanical and thermal demands [44].

2.8.2 Ceramics

Ceramics are very hard and refractory materials that are able to withstand temperatures in excess of 1500°C with no chemical decomposition. These characteristics allow for their use in machining materials under high cutting speeds and in dry cutting conditions. Their fragile nature renders them unfavourable for use in milling processes, which typically subject them to continuous impact and high risk of chipping and tool failure [55]. Pure ceramic cutting tool materials reveal no specific benefit during machining of difficult-to-cut materials and are unsuitable under high pressure cooling conditions. High pressure coolant has the tendency to cause excessive nose wear and chipping or fracture of the cutting edge [6,9].

Ceramic cutting tools are primarily based on alumina (Al_2O_3), silicon nitride (Si_3N_4) and sialon (combination of Si, Al, O and N). Alumina tools can contain titanium, magnesium, chromium or zirconium oxides distributed homogeneously in the matrix to improve toughness [55]. Al_2O_3 ceramic tools have a high chemical stability and hardness but low resistance to fracture. Consequently, the tool fails due to micro chipping on the cutting edge. Although silicon nitride ceramics have higher toughness in comparison to aluminium nitride ceramics, its hardness and chemical stability is lower. For this reason, a combination of the two ceramics merges the benefits of the two cutting tool materials. SiC-whisker and TiC-whisker reinforced ceramics display similar wear behaviour to aluminium oxide ceramics. The ceramic material that has the highest potential in the cutting of hardened materials is TiC-reinforced Al_2O_3-ceramics, due to their comparatively lower flank wear rate combined with a high resistance to chipping of the cutting edge [6,57].

2.8.3 PCBN/CBN

CBN tools are manufactured from hexagonal boron nitride crystals under high temperature and pressure conditions. They are the hardest tool materials available after diamond and used mainly in the cutting of hardened steels [17]. PCBN cutting tool materials are often used in hard turning and face-milling operations. PCBN has a high hardness and temperature stability. This allows the material to resist the mechanical and thermal loading experienced during hard machining. PCBN possesses both a high fracture toughness, which is favourable during interrupted cutting, and high thermal conductivity combined with low thermal expansion coefficient, which is favourable for hard machining [6].

Theses cutting materials exhibit the longest tool life, but composition influences the mechanism of wear. The content of cubic boron nitride (CBN), grain size and distribution along with the type of binder phase used, which can be ceramic or metallic, impacts the properties of the material. In the process of machining difficult-to-cut materials, ceramic binders are preferred over metallic binders. A high CBN content increases the hardness and a low content of CBN demonstrates the advantage of having a lower thermal conductivity and higher toughness. The main type of wear in these tools is flank wear [6,44].

2.8.4 PCD

The increased focus on productivity and cost reduction requirements for cutting tools have led to the implementation of superhard materials in order to machine previously un-machinable materials. PCD has significant advantages in hardness compared to conventional tool materials and targets machining of non-ferrous materials [58]. PCD is available in coarse, medium and ultra-micro grain size. Medium grain sizes are used for general purpose cutting tools, due to their balance between high wear resistance and surface finish. Ultra-micro grains are preferred when high surface finish is required [55].

Due to the high sensitivity of diamond derivative tools for machining difficult-to-cut materials, selection of correct cutting conditions is paramount. PCD is mainly used in finishing processes, due to its susceptibility to fracture caused by mechanical shock [36]. When machining materials that are difficult-to-cut, high temperatures are experienced. This restricts PCD to machining materials where the cutting temperature does not exceed 700°C and that have no affinity with carbon if diffusion wear occurs [6], despite its encouraging temperature stability.

2.9 Influence of coating preparation and treatment on cutting tool

The contact conditions between tool and workpiece are determined by the tool geometry. Different tool geometry causes the development of either mechanical and thermal loading or a combination of the two demands, influencing the wear mechanisms on the cutting tool surface [6,43]. Furthermore, common practice in industry is to chamfer the cutting edge of the insert. The chamfer reduces the propensity of the tool tip chipping, thereby extending tool life. However, this is accomplished at the expense of tool performance. It leads to crater wear, usually because of its ploughing effect on the workpiece and the chip changing direction. A recent development, called Engineering Micro-Geometry, utilises a defined round shape cutting edge instead of the chamfer. With this geometry, the negative effects of chamfering are eliminated, but this geometry has not been proven to protect against normal cutting edge failure [2].

Coated tools can significantly improve the tool performance when using appropriate substrate and coating treatment. Coated tools have compound material structure, consisting of the substrate covered with a hard, anti-friction, chemically inert and thermal isolating layer. Therefore, coated tools diminish friction, tool-chip interface interaction and improve wear resistive in a wide range of cutting temperatures [4].

The mechanical and thermal loads acting on the cutting edge during the material removal can give indication of the better cutting performance of coated tools. The maximum temperature encountered using coated inserts amounts to approximately 266 °C. This compares favourably with a maximum of 658 °C in the case of an uncoated tool. The comparatively higher temperature retention of the uncoated tool translates to thermal energy transferred into the cutting tool, during the same chip contact time, leading to a significant increase of cutting tool temperature. In interrupted cutting, depending on the chip contact time, the maximum tool temperature is commonly lower than the corresponding steady state temperature of continuous material removal processes [4]. The cutting performance of coated tools is significantly improved through adapting coating properties applicable for specified cutting requirements [13].

2.9.1 Substrate mechanical treatments

The coating adhesion and subsequent cutting performance of coated cemented carbide tools depends significantly on the applied mechanical pre-treatment. A method of improving the coating's adhesion is by micro-blasting of ground or polished substrates.

The effects of micro-blasting on ground carbide substrates can be seen by the morphology of the surface, presented in the Figure 13. After micro-blasting, superficial residual stresses occur because of the Co-binder deformation and an increase in micro-roughness (Rt) results. This reveals individual cobalt (Co)-free tungsten carbide (WC) particles due to the Co-binder being removed from the cemented carbide surfaces. In this way, the assumption can be made that coating deposition nucleation rate of potentially formed transient junctions are increased, such as TiAlN coating on Co-free WC surfaces. Hence, an adhesion improvement between the substrate and the PVD film occurs, since the less adhesive Co-region on the substrate surface decreases [4].

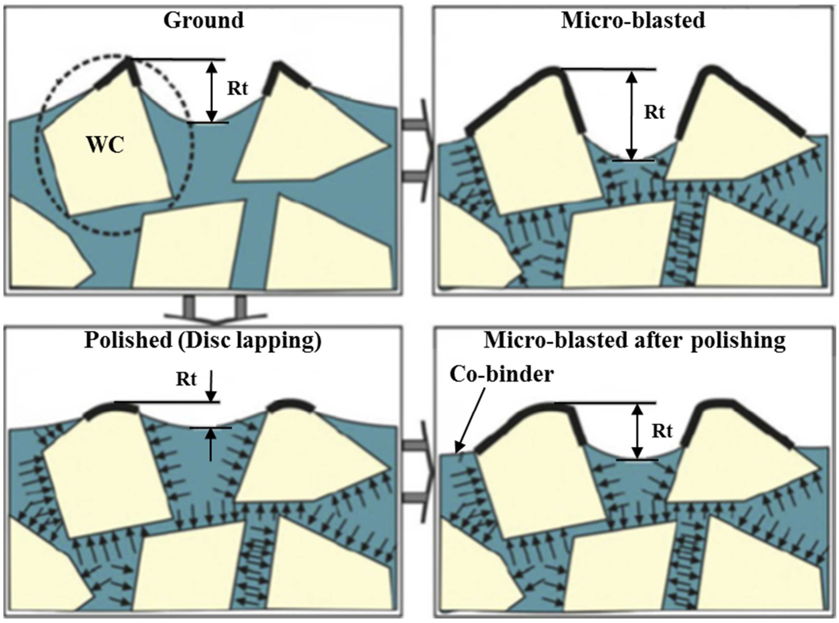


Figure 13: Micro-blasting of ground and polished cemented carbide [4]

If the cemented carbide is polished by disc lapping the Co free WC particles are rounded, restricting the surface exposure of the Co free WC surfaces. Thus, increasing the Co-region and deteriorating the film adhesion. The advantages of micro-blasting can be restored by micro-blasting the polished surfaces again. In addition, the Co free WC is now better embedded in the Co-binder. This can be noted by the reduced micro-roughness (Rt) in comparison to ground substrates and ground and micro-blasted substrates. Hence, micro blasting of ground or lapped substrates contributes to a coating adhesion improvement and a cutting performance increase [4].

2.9.2 Coating mechanical post-treatments

It is often practised in industry to grind sharp cutting edges of small diameter tools. This action stabilises the tool edge improving the cutting performance. The round cutting edges distribute the cutting stresses evenly between the flank and rake face of the cutting tool. Unfortunately, the increase of the cutting radius in the cutting region also leads to a heat flux growth into the substrate. This may cause deterioration of tool performance under higher cutting speeds [59].

With reference to Bouzoukis, K.D. *et al* (2009) [59], AlTiN PVD coated cutting tools with varying cutting edge sharpness were investigated. The cutting edge roundness was classified in three groups, namely: as deposited (as dep.), slightly ground (SG) and intensively ground (IG). The average radium and minimum film thickness are exhibited in Figure 14, depicting that with an increase in the edge radius ρ_C the minimum coating thickness $t_{\rho min}$ decreases.

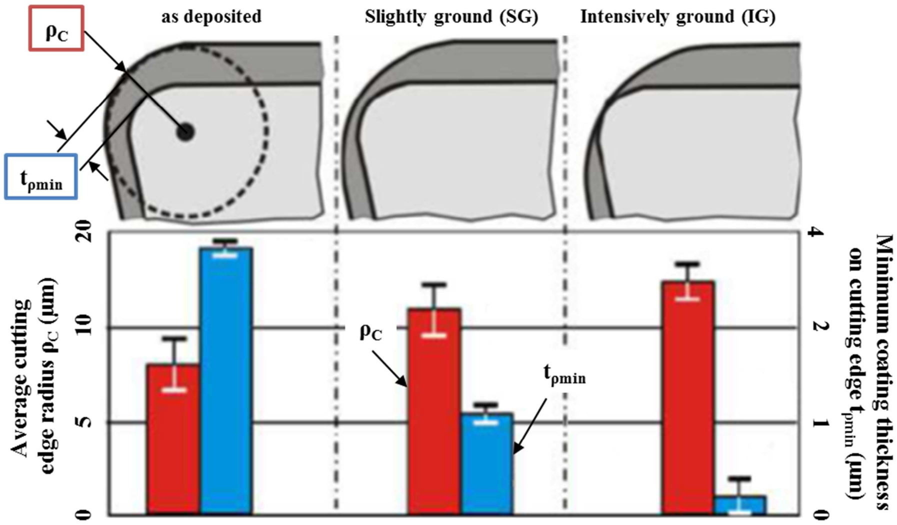


Figure 14: Average cutting edge radius (ρ_C) and minimum coating thickness ($t_{\rho min}$) for ground inserts [59]

After investigating the cutting edge roundness cases, it was found that as deposited (as dep.) coated tools achieved the best results. The increased cutting roundness decreased the performance of the cutting tool, however, even in the worst IG tool case the flank wear developed at a slower rate when compared to uncoated inserts, depicted in Figure 15 [59].

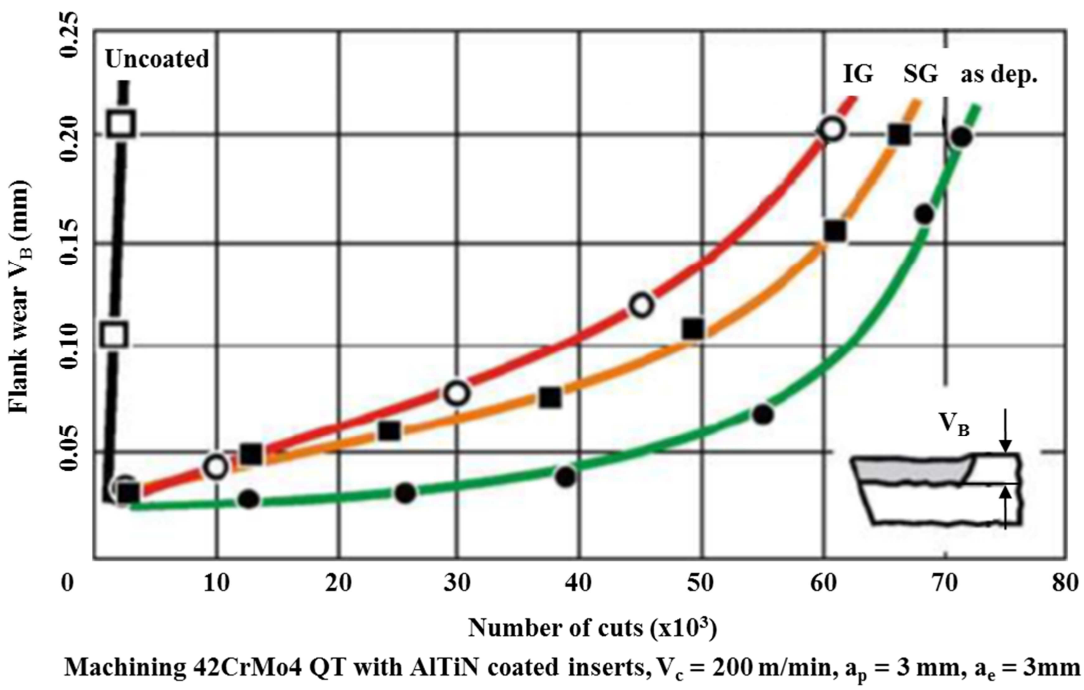
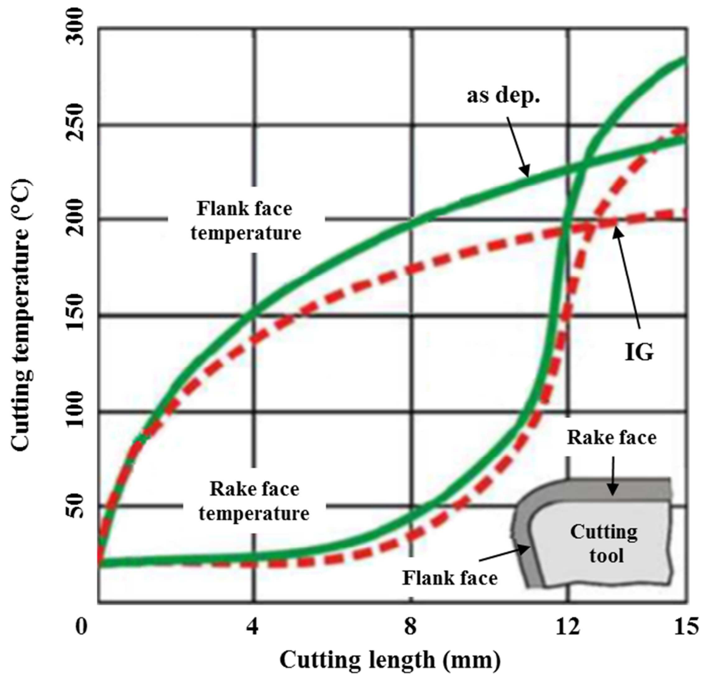


Figure 15: Flank wear development against the number of cuts in milling with various ground cutting edges [59]

When the cutting temperature for as dep. and IG coating cases were investigated at specific points on the cutting tool, as indicated in the bottom right corner of Figure 16, it was found that in the early stages (1mm) of material removal, both cases were heavily stressed. Simultaneously, the flank face possesses an enhanced impact resistance due to the developed film temperature. Furthermore, the rake face experiences a slightly lower temperature at the end of the cutting process in the case of IG cutting edge, as explained in Figure 16. This means that the thinning of the coating thickness, due to the rounding of the cutting edge, allows for a portion of heat to flow into the substrate. In this way, the cutting heat distribution is over a wider cutting area, reducing the temperature. Therefore, the thermal loading is not responsible for the greater wear rate on the IG inserts in comparison to the as-deposited ones and attributing the wear to cutting mechanical loading [59].

The increased cutting radius decreases the coating stresses, as in the IG insert case compared to the as-deposited tools. This indicates the IG cutting tool substrate is placed under higher mechanical loading above its yield strength in its transient region, reducing the tool life compared to milling with as-deposited coated tools [59]. Nowadays, a large majority of carbide cutting tools are deposit-coated using either CVD or PVD techniques [3].



Machining 42CrMo4 QT with AlTiN coated inserts, V_c = 200 m/min, a_p = 3 mm, a_e = 3mm

Figure 16: Development of cutting temperature versus cutting length on critical positions of various ground cutting edges [59]

2.9.3 Physical vapour deposition

The first commercial physical vapour deposition (PVD) coating was titanium nitride (TiN) and since then, most of the industrial coatings have been based on nitrides. The most extensively investigated coating system is the (TiAl)N, due to the ease of deposition parameters and materials contents manipulation, as well as its potential to increase the cutting performance of tools. PVD covers a broad range of vacuum coating processes in which the employed material is physically removed from a source by evaporation or sputtering. Then it is transported by the energy of the vapour particles and condensed as a film on the surface of appropriately placed parts under vacuum [4].

PVD-prepared coated tools have the benefit of high intrinsic hardness and compressive stresses. These properties aid the constraining of crack growth in tool material. Additionally, PVD deposition produces no chemical interaction with the substrate, maintaining the substrate's physical properties. These coated tools are used in machining processes where finish operations are required [4].

2.9.4 Chemical vapour deposition

Chemical vapour deposition (CVD), unlike to PVD vacuum processes, is a heat-activated process based on the reaction of gaseous chemical compounds with suitably heated and prepared substrates. Primary reactive vapours can be either metal halides (chloride, bromide, iodide, or fluoride), metal carbonyls, M(CO), or hydrides and organometallic compounds [4].

CVD coated tools are preferred in operations where high material removal is required. It is suited for this function due to its ability to produce thick coating layers by increased deposition rates. Its downfall is the coatings interaction with the substrates, occasionally producing brittle carbides at the interfaces [4,13].

2.10 Conclusion

With the aforementioned literature, there is now an appropriate understanding of the machining demands, modes and mechanisms of tool failure or wear, influencing cutting parameters, cutting tool materials, coating preparation and treatment of cutting tools. From this it can be deduced that it is important to identify strategies to reduce or eliminate the outcomes or drawbacks of these demands and tool failure modes. Therefore, the most common procedure is to apply a cooling strategy during machining so that cutting temperatures and cutting forces experienced between the cutting tool/workpiece and cutting tool/chip interfaces can be reduced.

3. Application of cooling during milling

This chapter focusses on different cooling strategies and techniques currently utilised in aerospace and automotive industries. Greater cutting parameters encourage increased productivity, but involve an increased risk of deteriorated surface quality and reduced tool life. Heat generation becomes intensified when machining difficult-to-cut materials, particularly when the thermal conductivity of these materials is very low. When machining these difficult-to-cut materials under conditions requiring high standards of both safety and quality, the efficiency of the machining process is constrained in comparison to conventional production technology [1]. One of the most practical and effective methods of raising productivity in cutting these types of materials is to dissipate heat as quickly as possible during cutting. Any reduction in the cutting temperature will increase the tool life. Cutting fluid is used to lubricate the tool and alleviate heat from the cutting tool/workpiece interface. It also helps flush chips. It is important to note that the lubrication role is more significant at lower cutting speeds and the cooling effect is more consequential at higher cutting speeds, due to heat generated by the chip removal process at higher cutting speeds [8,9,10,22,23].

An improved cooling strategy or technique presents a solution to meet these demands with the possibility of improved surface quality, tool life, and a reduction in costs and production time. The cooling strategy reduces the thermal loading in the cutting zone and the lubrication action decreases mechanical forces. This prevents the cutting tool from exceeding its critical temperature range beyond which tool softening occurs and the tool begins to wear rapidly [28].

3.1 Designated cooling strategies and techniques

In order to ensure reasonable cutting tool life during machining difficult-to-cut materials an efficient cooling strategy and technique should be employed to reduce cutting temperatures at the cutting interface [45]. The cooling strategy forms the base of the cooling method and can be defined as the most basic system of applying coolant. The technique of application can be seen as a subdivision of the cooling strategy itself and supplies a method for a more specific application of coolant. The trend of recent research institutes and researchers has fallen into one or more of the following categories of cooling strategies or -techniques:

- Flood cooling
- Air blowing cooling (dry cutting)
- Minimal quantity lubrication (MQL)
- High pressure through spindle cooling (HPTSC)

These strategies form the focus of this study. The various benefits of the cooling and lubrication strategies during the milling process are examined, as illustrated in Figure 17. This was a necessary step in order to design a new cutting tool cooling technique, incorporating as many benefits as possible into a single strategy. To obtain a satisfactory cooling technique design, tool wear needs to improve while maintaining a practical material removal before the insert fails. The cooling techniques should not be excessively costly or complicated. This is to avoid extensive upgrading of the existing cooling apparatus or system.

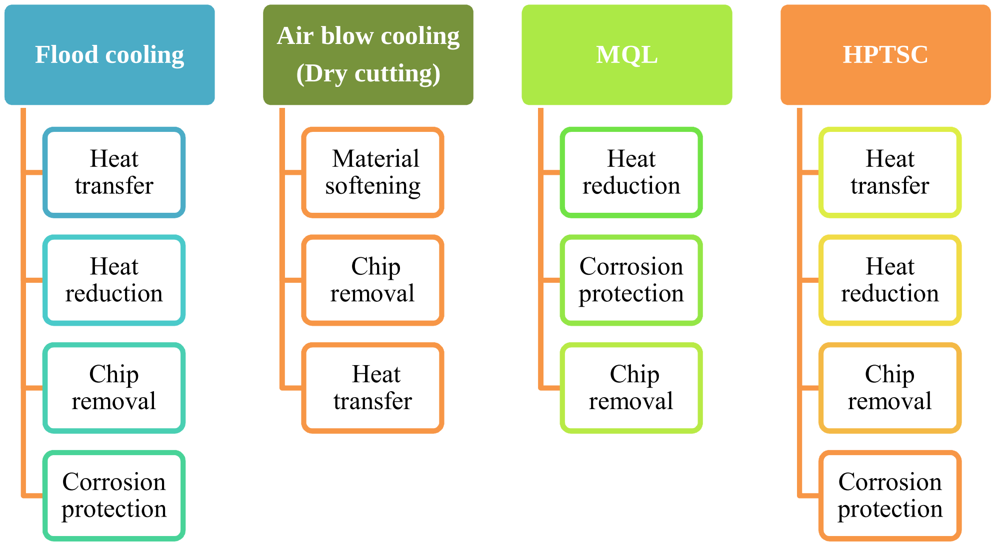


Figure 17: Benefits of cooling and lubrication strategies in the milling process

Figure 17 relates the main attributes of each cooling and lubrication strategy. Flood cooling and HPTSC show the best potential for heat transfer and heat removal, with added benefits of chip removal and corrosion resistance in the cutting zone. The main advantage of high pressure cooling is superior performance at higher cutting speeds and feed rates. Air blow cooling (dry cutting) has the benefit of softening the workpiece material as well as the removal of chips from the cutting zone. MQL also reduces the heat by using a low quantity of lubricant applied in an airstream, but its main benefit is to help with tool corrosion.

3.1.1 Flood cooling

Flood cooling could be best described as an uninterrupted flow of an abundant quantity of coolant, thus flooding the cutting zone. Chips are removed by a flushing action, thermal shock on milling tools minimised and the ignition of chips eliminated, particularly during grinding actions. When this strategy is used, the orientation of the nozzle direction can be changed to clear the cutting surface so as to reduce flank wear at low cutting speeds [29]. This method is the benchmark for all experiments, as it is the most widely used in standard machining.

3.1.2 Air blow cooling (dry cutting)

Dry cutting involves reliance on the natural environment for cooling, such as radiation and air convection. There is no use of cooling fluid or lubrication. Dry cutting supplemented by an external supply of compressed air is also common practice, this is known as air blow cooling (dry cutting). Compressed air delivered under pressure, directed into the cutting zone, yields favourable conditions for machining operations. The main reason for air blow cooling (dry cutting) is the benefit to the environment, low cost of maintenance and reduction of operator health risk [60].

3.1.3 Minimum quantity lubrication

Minimum quantity lubrication (MQL) is an economical technique of applying coolant, also known as near dry machining. This method applies small quantities of oil, which is usually vegetable oil or a synthetic ester, mixed with compressed air fed onto the cutting edge as an oil mist [61]. Due to the low amounts of oil used, MQL is an environmentally friendly alternative to flood cooling when dry cutting is not feasible. The effects of oil volume and air pressure on cutting performance when applying MQL necessitate particular attention and consideration when utilising this cooling strategy [61]. MQL can be applied in two different mixing methods, namely inside-nozzle mixing and outside-nozzle mixing. Inside-nozzle mixing combines the pressurised air and lubrication in a mixing device inside the nozzle, whereas outside-nozzle mixing takes place in a device positioned in a specific tank, outside the nozzle. The pressurised air forms the cooling action and the lubricant performs the lubricating action [62]. The performance of MQL is highly dependent on the nozzle positioning, coolant velocity, number of pulses, quantity and diameter of fluid particles in each pulse [45].

3.1.4 High pressure through spindle cooling

HPTSC is the delivery of coolant at high pressure, directed at tool-workpiece and tool-chip interfaces. The coolant under high pressure causes discontinuous chips, that are small and easy to dispose, and hydraulically forces the chip away from the tool. The improved penetrating effect of the high pressure coolant additionally lubricates the contact area, thereby reducing tool wear [29,46]. This leads to a reduced seizure region, lowering the friction coefficient, which results in a decrease in the cutting temperature and cutting forces. Under high pressure cooling, the effects of welding of the tool and chip or built-up edge are eliminated, improving the tool life and surface finish [28].

In the case where coolant is applied to the cutting zone where high temperatures are present, the evaporation thereof causes a thermal barrier to be created on the surface of the workpiece material. This thermal barrier has a lower thermal conductivity than that of the coolant and therefore reduces the heat removed, causing accumulation of heat in the cutting zone. High-pressure coolant has the potential to impinge on the thermal barrier and reduce cutting temperatures and diffusion wear rate [8,17].

3.2 Evaluation of selected cooling strategies

Friction and heat generated in the cutting zone can cause complex difficulties during machining. The cooling strategy utilised should perform both high efficiency cooling and chip removal simultaneously [45]. Separate research renders results of cooling strategies that have many dependent factors that vary from researcher to researcher. Examples of these factors are tool and workpiece geometry, cooling fluid properties, tool properties, cutting conditions and workpiece material properties. In order to capture a basic understanding and combine the findings of the cooling strategies researched, a rating system of excellent, good, average, fare and poor was implemented for each cooling strategy criterion. The selected cooling strategies where evaluated in terms of the performance of heat removal, chip removal, lubrication and economic and environmental friendliness (E & EF). This evaluation is illustrated in Table 5.

Table 5: Selected cooling strategy evaluation criteria for machining hard-to-cut materials under HPM

Criteria	Cooling and Lubrication Strategies			
	FC	ABDC	MQL	HPTSC
Heat removal	◐	◔	◔	●
Chip removal	◔	◐	◔	●
Lubrication	◔	○	◐	◐
E& EF	◔	●	◐	◔

●Excellent; ◕ Good; ◐ Average; ◔ Fare; ○ Poor
FC: Flood cooling; ABDC: Air blow cooling (dry cutting);
MQL: Minimum quantity lubrication; HPTSC: High pressure through spindle cooling

The *heat removal* indicates the potential the cooling strategy or -technique has to remove the heat generated in the cutting zone. Different mechanisms of heat transfer, such as conduction and convection, vary in potential for heat transfer/removal. A change in phase occurs when an adequate amount of heat has been transferred to it. An example of this change of phase is that of a liquid, the coolant in this case, to a vapour. From this, vaporisation has the most potential to remove heat from the cutting zone and is therefore the favoured means of transferring/removing heat in cooling applications. The forming chips retain and remove a portion of the heat generated on the cutting zone and the remaining heat is conducted into the cutting tool and workpiece. Additionally, re-cutting of chips that remain in the cutting zone cause unwanted wear. For this reason, *chip* *removal* is vital for the improvement of tool life. The *lubrication* of the cutting zone can help lessen the friction between the cutting tool and workpiece, thereby reducing the temperature on the cutting edge. Finally, the *economic and environmental friendliness* of the cooling strategy entails the cost of the constituent components (water, oil etc.), machinery or system cost, operator safety and disposal of waste. This also entails attention to issues relating to environmental problems, fluid disposal, toxicity, filterability, misting, staining and indirect cost involved while using coolant during the machining process.

From Table 5 it is observed that flood cooling has excellent heat transfer capability, yet under HPM conditions, the heat removal capability is reduced. Flood cooling displays no further motivating criteria due to its inability to penetrate the heat-affected cutting zone and has a high maintenance cost. HPTSC has the best potential to remove chips and penetrate the cutting zone to increase lubrication as well as reduce the cutting temperature. Unfortunately, there are complications in the system setup costs, running and equipment costs, and environmental factors. Since environmental concerns are fast becoming a necessity of consideration in the machining industry, dry cutting and MQL provide possible alternatives to the application of cooling fluids.

MQL has a good capability to transfer heat, but under HPM of titanium it is found that this proficiency is reduced substantially. The reduced heat removal in MQL is mainly due to lubrication not penetrating the cutting zone and temperatures increase the tool wear process. Dry cutting, on the other hand, is very economic and environmental friendly. A brief overview of the literature used to select a cooling strategy for machining difficult-to-cut materials is discussed in Table 5 with the criteria evaluation proceeding in this chapter.

3.2.1 Heat removal

Heat removal is dependent upon fluid properties, geometry and material properties of the workpiece [61]. The predominant form of heat transfer is through vaporisation, which has the added potential of heat removal compared to that of convective heat transfer [45].Coolant has the potential to effectively remove heat from the cutting zone and offers lubrication between the chip-tool and work-tool contact interface [63].

Flood cooling – flood cooling heat transfer occurs mainly due to *convection* of the soluble oil constituent. With the increase of the cutting speed, cutting temperatures rise and the cooling effect reduces [45]. This is due to the tendency of flood coolant to vaporise under temperatures above 400°C in the cutting zone, resulting in a thermal barrier between the cutting tool and workpiece surfaces. This barrier influences the full penetration of the flood coolant into the cutting zone, resulting in similar characteristics as dry machining, as the coolant does not access the chip-tool interface. In fact, the heat conducted is retained in the cutting zone, reaching undesirable temperatures. Additionally, flood cooling has the tendency to harden the workpiece material surface, due to the irregular cooling tending to produce similar effects to rapid quenching [45,63].

Air blow cooling (dry cutting) – the main form of heat transfer of the air stream depends on forced convection. Cold air cooling capacity is limited, due to its low heat transfer coefficient [45]. Cutting force are reduced under dry cutting conditions due to the heat generated in the cutting zone softening the workpiece material, this is more apparent when cutting speeds are high. The inclusion of air-cooling is commonly practised in order to reduce the flank wear, increasing tool life. Therefore, the *forced convective* heat transfer of the air stream is more effective when higher cutting speeds are used. Furthermore, during interrupted cutting of difficult-to-cut materials, air blow cooling (dry cutting) has potential to improve the tool life over the application of coolant where the cutting tool is subjected to thermal shock loading [64].

MQL – in the application of MQL, the characteristics of importance are lubrication and *vaporisation* cooling, being the favoured method of heat transfer [45]. Air pressure and velocity having a greater significance on the *vaporisation* heat transfer than the quantity of oil. MQL does not fully replicate the cooling ability of flood cooling. When machining, it is important to be able to control the cutting temperature, particularly when machining difficult-to-cut materials [61]. The temperature experienced under higher cutting speeds becomes too great for MQL cooling applications. It is therefore found that the application of MQL is not recommended for the machining of titanium [46].

HPTSC – HPTSC produces significant reduction in temperature at the cutting zone, aiding the maintenance of the tool cutting edge geometry for longer periods, under higher cutting speeds and feeds [63]. This is attributed to HPTSC's enhanced *forced convective* heat transfer. A good penetration of the thermal barrier produced during machining can be obtained by the impingement effect of HPTSC. The high velocity penetration into the cutting zone and vaporisation under high temperatures effectively enhances the heat removal of the cooling strategy [45].

3.2.2 Chip removal

Flood cooling – this strategy delivers a large quantity of fluid and flushes the chips if sufficient volume is applied. Unfortunately, the fluid may not reach the tool workpiece interface because of nozzle direction or chip formation when higher cutting speeds are used. This can cause the tool to run wet and then dry, leading to thermal shock loading [65].

Air blow cooling (dry cutting) – compressed air has the ability to remove the cutting chips from the cutting zone and acts as a chip breaker. The cutting temperature at the cutting zone increases during dry machining, deformation and shearing of the chip becomes easier, improving the tool life particularly in the case of machining with coated carbides [28].

MQL – MQL applies droplets of oil at high velocity that are able to penetrate through the thermal barrier formed. The droplets contact the cutting tool directly, promoting plastic flow on the backside of the chip to relieve compressive stresses, curling the chip away from the cutting edge and reducing the chip contact length. These benefits of MQL are only experienced under low cutting speeds and not satisfactory under machining of difficult-to-cut conditions for increased productivity [28].

HPTSC – HPTSC delivery offers efficient cooling characteristics and reduces the tool wear. Further, the high pressure coolants penetration into the cutting zone reduces the contact between the chip and tool rake face. This hydraulic action lifts the chip and curls it away from the cutting edge [45,66]. HPTSC not only has the ability to remove the heat in the cutting zone, it has an efficient chip removal and acts as a chip breaker [57].

3.2.3 Lubrication

Flood cooling – aids the lubrication of the contact zone between the cutting tool and the workpiece but is more applicable at lower cutting speeds. This cooling strategy is not suited for the machining of difficult-to-cut materials, particularly the machining of titanium [67].

MQL – in the application of MQL to the rake face of the inserts, there is little or no influence on the tool life. There is no trace of chemical compounds on the insert, verifying that lubrication does not reach the cutting surface. On the other hand, traces of lubrication were found when MQL was applied to the flank face of the insert under the same cutting conditions. Furthermore, the flank face application consistently outperformed dry cutting and flood cooling [45].

HPTSC – the water vapour under high pressure can penetrate into the chip-tool interface, acting like a hydro-dynamic lubricant. It will greatly reduce the friction heat, seizure of the chips to the cutting tool and also improve the temperature-induced wear of the cutting tool efficiently [45,46].

3.2.4 Economic and environmental friendliness

Flood cooling – is effective but costly, due to the plant infrastructure necessary to accommodate the coolant, maintenance, disposal and the cost of the coolant. Economic and environmental concerns have motivated researchers to look for alternatives to flood cooling [61].

Air blow cooling (dry cutting) – this method of cooling does not cause any pollution of the atmosphere or water. The swarf comprises of metallic chips, metallic dust and small metal pieces, which is recyclable in dry cutting applications. There is no danger to the health of the operator because it is non-injurious to skin and is allergy free. Air blow cooling (dry cutting) can save related coolant costs due to the abundance of air as a coolant and a saving in the amount of equipment required [64].

MQL – can reduce machining floor space, coolant testing, coolant treatment, coolant disposal and machining cost, due to the small lubrication quantity. MQL generates more cutting fluid aerosol because of the splash mechanism associated with the mist application. Therefore, ambient air quality conditions need to be maintained and guaranteed during the application of MQL, where the oil particles are harmful for the operator's health [45].With proper fluid carrier gas selection, cost reductions per cut can be achieved when compared to the combined cost of fluid, fluid disposal and a continuous fluid management of conventional systems [28].

HPTSC – the application of HPTSC is becoming more attractive. The effective application of this cooling strategy without pollution of the environment is becoming a necessity [63]. HPTSC is often employed for machining difficult-to-cut materials, to obtain better surface quality, an improved machining efficiency and lower production costs. HPTSC often requires a high pressure supply above 10 MPa and a large mass of coolant with a flow rate as high as or higher than, 10 l/min [45].The cost of facilitating a high pressure system requires large overhead costs of coolant delivery systems, pumps and filtration systems [28]. In the majority of the current milling machinery, the application of HPTSC is built-in, yet the filtration and pump systems are still required separately.

3.3 Selection ofcooling strategy, cutting tool material and coating

As discussed in section 3.2, the application of MQL is not recommended for machining difficult-to-cut materials, particularly in the case of titanium. MQL is further excluded from the study. Although flood cooling is not preferred in the literature research when machining difficult-to-cut materials at high cutting speeds, it has been included for its extensive use in the industrial environment. This leaves air blow cooling (dry cutting) and HPTSC, with the inclusion of flood cooling as a benchmark. Therefore, the following study discusses the application of the abovementioned cooling strategies, emphasising the HPM of titanium Ti6Al4V alloy.

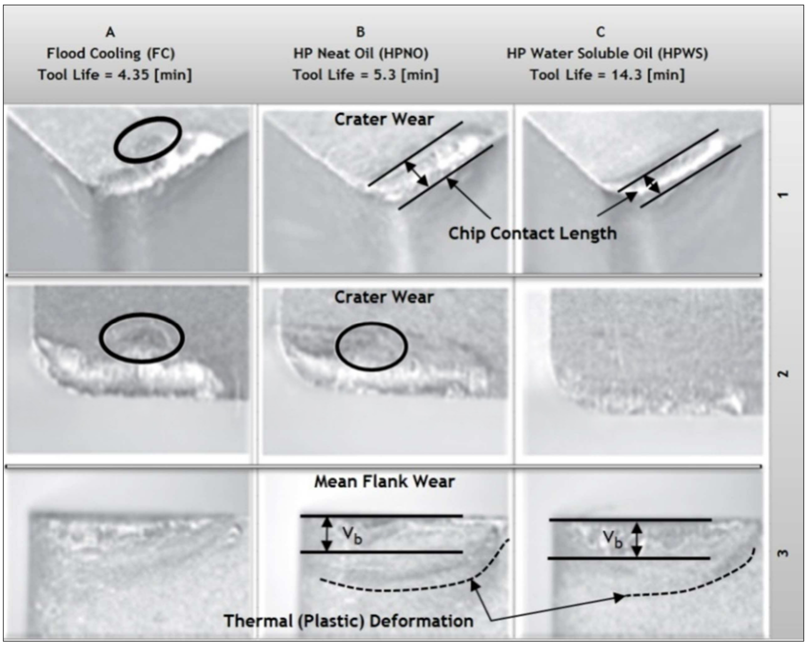
The cutting tool material and inclusion of coating has little influence on the tool temperature during machining. However, the control of this temperature plays a dynamic role in the process concerning tool life. Coating applications increase the hot strength, wear resistance, temperature stability and resistance to oxidation, while also providing lubrication properties [57]. Furthermore, the selection of the correct cutting tool material and coating for HPM of difficult-to-cut materials, more specifically titanium Ti6Al4V alloy, needs to be determined.

3.3.1 Cooling strategy

HPTSC

Experiments done by M.C. Gowrishankar *et al* (2009), conducted under flood cooling (FC), cooling using high pressure neat oil (HPNO) and cooling using high pressure water soluble oil (HPWS), revealed superior heat transfer under HPWS conditions when machining Ti6Al4V, as illustrated in Figure 18. The experiments were conducted using uncoated microcrystalline ISO grade K20 inserts with a nose radius of 0.8 mm. The HPNO and HPWS both show significant reduction in chip contact length, attributed to the chip curling under the hydraulic action of the high pressure coolant. The presence of welding or built up edges reduces, chip removal is improved and tool life enhanced throughout the experiments under HPWS [46].

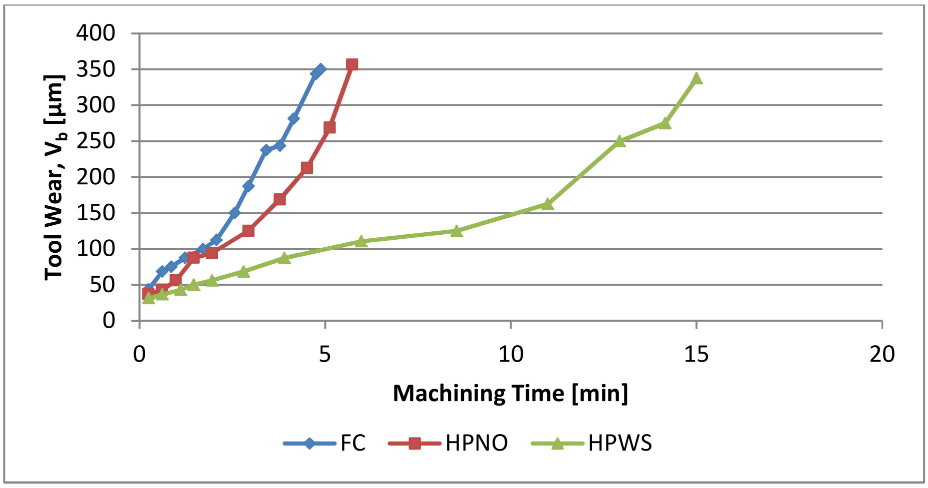
It was further noted that crater wear is significantly reduced under high pressure conditions. The HPWS demonstrated the best improvement in flank and rake face wear, which attributes to the greater thermal conductivity, higher momentum and superior convective heat transfer of the water-soluble constituent of the coolant in this case. The geometry and integrity of tool is preserved for a comprehensive period when using high pressure coolant [46].



v_c = 100m/min, f_z = 0.20mm/rev, p = 100 bar and d_n = 0. 8mm

Figure 18: Cutting edge of a uncoatedmicrocrystalline ISO grade K20 inserts machining Ti6Al4V [46]

The relationship between the flank face wear, v_b, and machining time is compared in Figure 19. It is observed that the HPWS has a superior ability to reduce the wear on the flank face during machining. This indicates that high pressure coolant reduces the effects of thermal and mechanical loading caused by high contact pressures and temperature gradients when machining titanium, particularly when using HPWS [46].



v_c = 100m/min, f_z = 0.20mm/rev, p=100 bar and d_n = 0.8mm

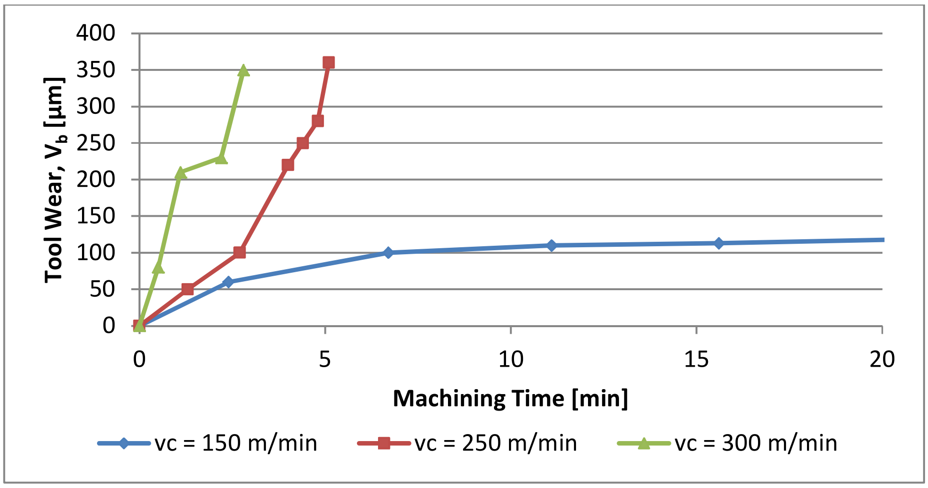
Figure 19: Growth of tool wear while turning Ti6Al4V alloy under conventional wet, high-pressure neat oil and high-pressure water-soluble oil [46]

Air blow cooling (dry cutting)

In some of the cases dry machining using compressed air encourages the improvement of surface finish, reduction in tool wear and cutting forces. Compressed air is an environment friendly gas, making it favourable as a cooling medium when applied under pressure during dry cutting. Environmentally friendly cooling techniques give promising results with a large number of tool materials, particularly with coated carbides [28].

In a study done by Li Anhai *et al*, [25] dry cutting was compared under varying cutting speeds and feeds. The cutting tool used was a SECO 25 mm diameter end mill and during experiments, a single insert was mounted on the cutter. The insert was a tungsten carbide coated with a CVD Ti(C, N)-Al_2O_3 coating with a 0.8 mm corner radius. Remarkable tool life was recorded at cutting speeds of 150 m/min when compared to speeds of 250 m/min and 300 m/min. The progressive flank wear over machining time for varying cutting speeds is shown in Figure 20.

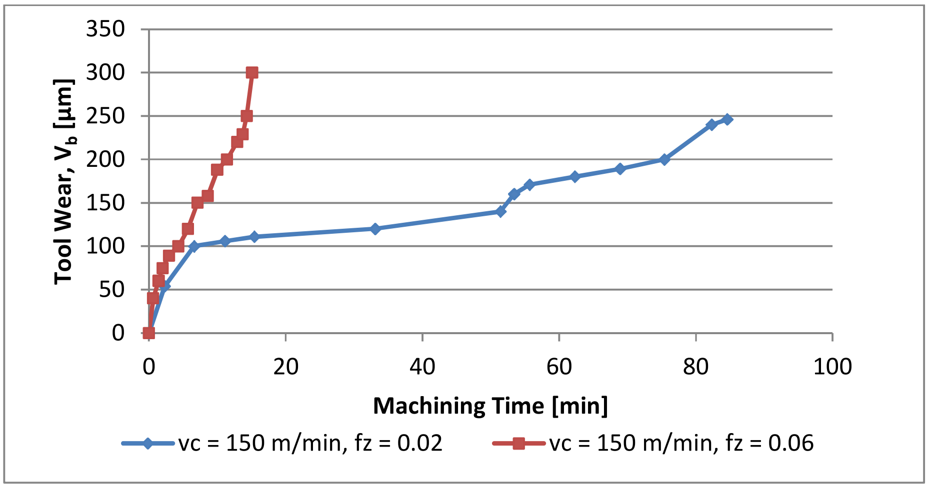
Over extended periods of machining time, the flank wear increases gradually. From this graph, it is obvious that the increase in cutting speed accelerates the progression of wear. Tool life at speeds of 150 m/min exceed 90 min before 300 µm flank face wear is reached, whereas at 250 m/min and 300 m/min only 5 min and 3 min, respectively, is reached. This indicates a drastic decrease in tool life when the cutting speeds are increased over 150 m/min. After a certain period of time, chipping on the cutting edge was noticed and thereafter flank wear and chipping intensified till failure [25].



(a_e = 5 mm, a_p = 1 mm, f_z = 0.02 mm/z)

Figure 20: Progression of average flank wear vs. machining time with varying cutting speed for coated carbide machining Ti6Al4V under dry cutting conditions [25]

Figure 21 shows the tool wear progression corresponding to varying feed rates over machining time. In the application of larger feed rates, the wear development is greatly increased. It should be realised that it is difficult to clearly define the factors that influence the tool wear under varying feed rates [25].



(a_e = 5 mm, a_p = 1 mm)

Figure 21: Progression of average flank wear vs. machining time with varying feed rates for coated carbide machining Ti6SAl4V under dry cutting [25]

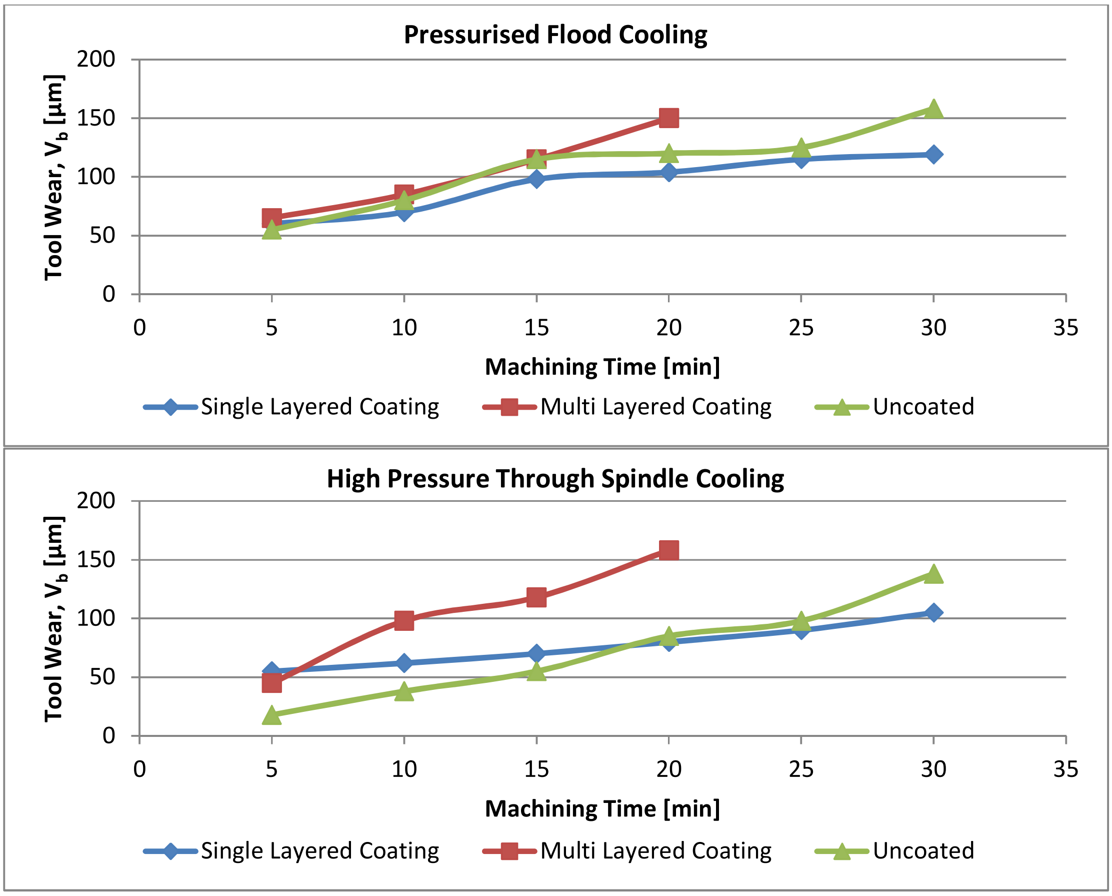
The aspects that should be considered from Figure 20 and Figure 21 are the increase in speed at constant feed rates causes drastic decrease in tool life. Meantime, when the cutting speed is constant and feed rate augmented the identical consequence is realised. It is therefore evident that there exists an optimal cutting condition for machining difficult-to-cut materials with coated carbides under air blow cooling (dry cutting).

3.3.2 Cutting tool material

It is established that the cause of both the wear and failure mechanisms developed in cutting tools is primarily the influence of temperature [63]. Difficult-to-cut materials subject the cutting tool to extreme thermal and mechanical loading close to the cutting edge, often leading to plastic deformation and accelerated tool wear. Cutting tools used in machining difficult-to-cut materials should possess adequate hot hardness to withstand elevated temperature generated at high speed conditions. In the tooling industry, HPM of difficult-to-cut materials is generally carried out with coated carbide tools, ceramics and PCBN tools [17].

When machining difficult-to-cut materials PCBN tools are not popular in industry. This is mainly due to the tool cost and extreme hardness, making PCBN tools susceptible to fracture and chipping, particularly when machining at greater depths of cut [17]. E.O. Ezugwu *et al,* [56] found that, when comparing tool life of different grades of PCBN tools to uncoated carbide tools under flood cooling and high pressure cooling, PCBN tools' displayed lower levels of performance in all conditions. However, under high pressure cooling, there where improvements in tool life for both uncoated carbides and PCBN.

When coated tungsten carbide cutting tools are used, improvements in flank wear during the application of HPTSC are recognised, as shown in Figure 22. Experiments indicated that the multi-layered coating performance was the worst and showed no relative benefits when compared to pressurised flood cooling or HPTSC. However, the single-layer coated insert performed better than the other inserts, both under pressurised flood cooling as well as HPTSC. In the case of the single-layer coated insert, the coating contributes towards a more robust process where the influence of cooling technique is not as prominent as with uncoated tools [7,58,68]. Andriya Narasimhulu *et al,* [3] found that coated carbides are suitable for machining titanium under dry cutting conditions when the process parameters are selected correctly.



(70 Mpa) (Vc = 120 m/min, fz = 0.076 mm/z, ap = 1 mm, ae = 10 mm)

Figure 22: Performance of single-layered coated, multi-layered coated, and uncoated inserts [69]

When PCD cutting tools are implemented for HSM machining Ti6Al4V flood cooling is the suggested cooling strategy [57]. PCD has received comprehensive attention and application due to its high hardness, high compressive strength, and excellent thermal conductivity and wear resistance. Li Anhai et al confirm this in a study of PCD cutting tools, obtaining considerable tool life performance under HSM conditions while machining titanium under flood cooling [31,70].

Although PCD displays better performance under flood cooling, the application of HPTSC has a detrimental effect on the tool life. Their study compared coated carbides and PCD under flood cooling, dry cutting and HPTSC. The deduction from their research is shown in Figure 23, where PCD tool life decreases slightly under HPTSC at pressures of 40 bar and 80 bar. PCD is also shown to perform poorly under dry cutting conditions [15].

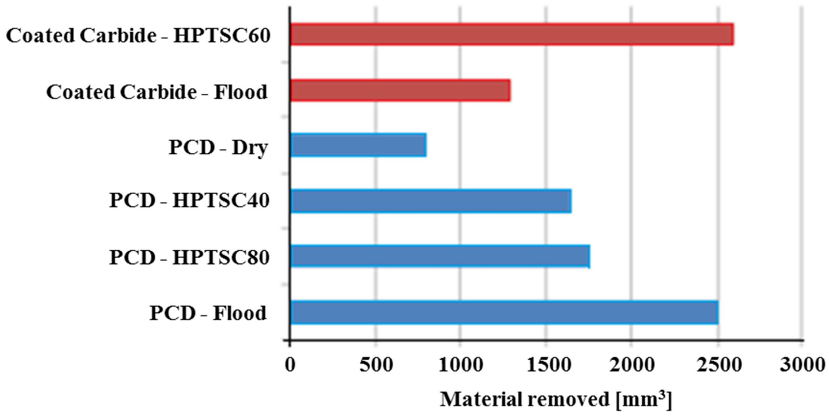


Figure 23: Performance of different lubrication strategies for finish milling [15]

In order to apprehend the findings of the researched cutting tools, a rating system of excellent, good, average, fare and poor was implemented. The selected cooling strategies where evaluated in terms of the tool life performance of each cutting tool under flood cooling, air blow cooling (dry cutting) and HPTSC. This evaluation is illustrated in Table 6. Therefore, from the overview, it can be seen that coated carbide inserts produce the greatest potential for increased tool life under the selected cooling strategies. Furthermore, uncoated carbides, PCBN and ceramics are not as favourable for cutting difficult-to-cut materials under HPM conditions.

Table 6: Selection of appropriate cutting tool material with reference to the selected cooling strategies for HPM of difficult-to-cut materials

Cutting Tool		UC	CC	PCBN	PCD	C
Cooling Strategy	Flood Cooling	◔	◔	○	◔	○
	Dry Cutting	○	◕	○	○	○
	HPTSC	◔	●	◔	◑	○

●Excellent; ◕ Good; ◑ Average; ◔ Fare; ○ Poor

UC: Uncoated carbide; CC: Coated carbide; C: Ceramics

3.3.3 Cutting tool coating

Since CVD and PVD films are very hard and brittle materials, properties such as fatigue, toughness, residual stresses and adhesion are essential for cutting with coated tools. The evolution of TiAlN, by adding aluminium to the TiN base composition, provided higher hardness, inertness and remarkably high temperature strength resistance up to approximately 900 C, contributed to pivotal cutting condition enhancements. The composition of this coated carbide is shown in Figure 24 [4]. Speeds of up to 150 m/min are attained when machining with WC-

Co coated carbide tools. It is noted that tool wear accelerates once the substrate is exposed to the work material. Therefore, the coating delays the accelerated wear of the substrate [17].

Figure 24: Fractograph of a coated cemented carbide with a layer of TiN bonding layer combined with a TiAlN top layer

The coating technique that was found to be most prevalent throughout the research literature was TiAlN [57]. This coating can be applied in a number of different layers of varying proportions from company to company, but the main constituents remain the same. An example of the layering of TiAlN is illustrated in Figure 24. The tools used in this study where produced by SECO using their standard preparation techniques. The exact preparation techniques, however, are not disclosed to the users. The techniques can therefore be one or a combination of that discussed above. For these reasons, the TiAlN coating technique was selected for the following experiments.

3.4 Conclusion

Coated carbides are practical under HPTSC and also show promise under air blow cooling (dry cutting) conditions. Additionally, coated carbides are cost-effective and readily available. With recent developments in coatings, coated carbides have been making advances in temperature capabilities, force resistance and, in some cases, lubrication.

Since HPTSC and air blow cooling (dry cutting) conditions are favourable, under HPM with coated carbides, further investigation into the benefits of these cooling strategies are grounded through experimentation of the influence of each cooling strategy on the tool life during the machining of Ti6Al4V. The tool life as a function of the machining time will give indications of the effectiveness of the separate cooling strategies. The results of these experiments will be benchmarked to the results of flood cooling under the same cutting conditions.

4. Design of experiments

The present experiment's aim is to compare the performance of cooling application methods on coated carbide inserts in milling of Ti6Al4V alloy and hardened steel 40CrMnMo7. Inserts possess a limited tool life because of wear or tool failure. The common method of determining the threshold is by a predetermined value of cutting tool wear. For this reason, it is evident that the cutting tool and workpiece materials have a role to play in the length of the tool life. There is much of interest in the interaction of the materials in question. The main objectives are:

(1) To evaluate the performance of various cooling strategies and techniques in terms of the tool life and tool wear, when machining with coated WC inserts.
(2) To evaluate the performance of new techniques of applying HPTSC.
(3) To investigate the performance of these strategies under different cutting speeds and feed rates.

4.1 Experimental Setup

Milling experiments were conducted on a computer numerical control machine centre (CNC Hermle C40U Dynamic), shown in Figure 25 in its idle position. The CNC machine is capable of supplying HPTSC at a maximum pressure of 80 bars and flood cooling from an external filtration system. There are many technologically advanced cutting fluids and lubricants in the market. These coolants or -lubricants have been specifically designed for isolated machining applications. In this study the chosen coolant emulsion covers the machining of titanium and hardened steel. For this reason Rocol ULTRACUT EVO 260 high performance cutting fluid was selected and mixed in a ratio of 30:1. This cutting fluid is designed for a wide range of cutting conditions and includes the machining of titanium and hardened steel. The technical data is given in Table 7.

Table 7: Technical data for high performance cutting fluid

Rocol ULTRACUT EVO 260	
Appearance	Clear amber liquid forming a white emulsion when mixed with water
Odour	Mild
pH	9.4 at 25:1
Density at 20 °C	990 kg/m^3

The materials machined are Ti6Al4V and 40CrMnMo7. The dimensions for both the Ti6Al4V and 40CrMnMo7 plates are 330 x 253 x 48 mm. The chemical composition and mechanical properties are given in Table 1 and Table 2. A CNC machine vice was used to clamp the workpiece in position, where the machining experimental setup is shown in Figure 26.

Figure 25: Hermle 5-Axis milling machine

Machining was done using a Mitsubishi 25 mm diameter end mill tool holder fitted with a VP15TF coated carbide insert (code: Mitsubishi XPMT13T3PDER-M2) and a 50 mm diameter SECO 45° milling cutter tool fitted with a SECO SEAN1203AFTN-M14 insert. The SECO SEAN1203AFTN-M14 inserts are coated with a TiAlN layer (2 µm thick) and a TiN layer (approximately 0.2µm thick) over the top, with each insert having a different cutting edge treatment.

The various coating edge treatments used in this study are abrasive blasting (AB), abrasive flow machining (AFM), brushing (B), honing (H), laser machining (LM) and magneto-abrasive machining (MAM). Graphical representations of the various coating edge treatments mentioned are indicated in Appendix A. Each experiment, under the Mitsubishi and SECO tool holders, is conducted with a single insert mounted on the tool holder. In the case of the Mitsubishi tool holder modifications, the insert is interchanged between each flute depending on the technique used in the experiment.

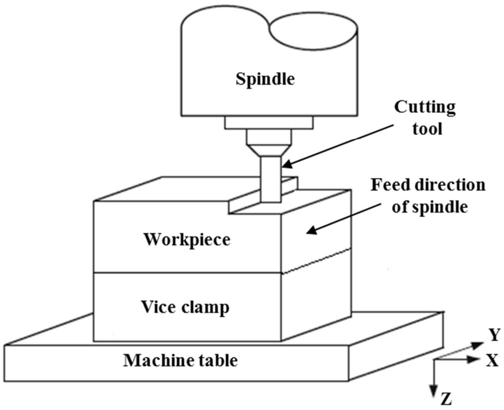


Figure 26: Schematic of the experimental machining setup

As discussed in the Chapter 3, HPTSC releases the chip from the cutting tool and reduces the chip/tool contact length, penetrates into the cutting zone and relieves the extreme temperatures experienced, while also decreasing the cutting forces experienced by the cutting insert. This, combined with a high velocity, leads to more efficient cooling of the cutting edge [68]. There is little comprehensive research concerning HPTSC, and there is much room for investigation and design of new techniques under this application method. The following chapter discusses new designs for HPTSC, where three innovative techniques are developed.

4.2 Design of focused high pressure through spindle technique modifications

In addition to environmental concerns, industries also require economic viability through technological benefits in terms of product quality, tool life and savings in energy. One possible method to meet these demands is by the application of HPTSC. Therefore, the study of HTSPC has become essential in terms of cutting temperature reduction, chip removal, cutting force, tool wear, tool life and surface quality of the product in machining. This is particularly true in the case of machining material, where high cutting temperature is cause for the foremost trepidation.

The intention of the new design is to improve the chip removal rate and reduce cutting temperatures in order to enable higher cutting speeds. Directing the nozzle at a particular location plays a vital role in machining with HPC. Since high pressure cooling provides desirable benefits, the application of a focused high pressure through spindle cooling (HPTSC) technique was explored. The Mitsubishi BAP3500 cutter body is able to accommodate HPTSC and the following designs are based on this cutter body. The ability for the HPC to penetrate the thermal barrier and reduce the temperature depends highly on the velocity of the cutting fluid encountering the cutting zone. Therefore, in the new design a reduction in the original hole diameter is presented in Figure 27.

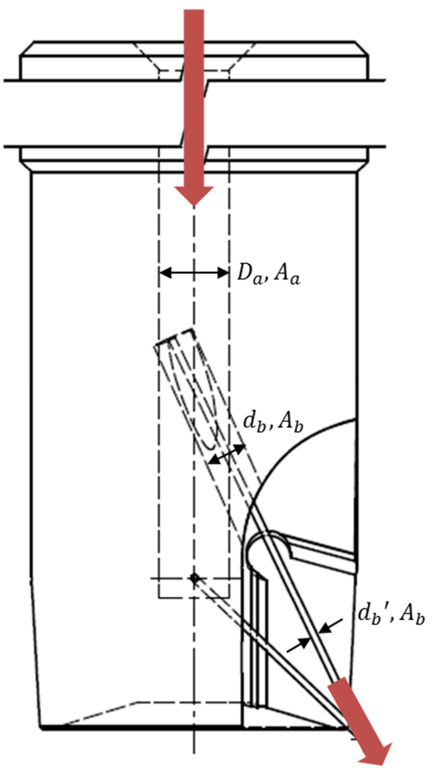


Figure 27: Schematic of the change in diameter and conservation of the volumetric flow rate for the Mitsubishi BAP3500 indexable cutter

From Figure 27, it can be seen that the supply pressure P_a and diameter holeD_a determine the supply flow rate Q_a of the HPC supply. From the regulated pressure source of the HPTSC system, the supply flow rate can be calculated using Eq. 2. Firstly the density of the coolant needs to be determined using Eq. 1, where ρ_a is the density of the coolant, $m_w + m_o$, the sum of the mass of water and the oil constituents of the coolant and V_c volume of the coolant supply. Followed by the calculation of the flow rate in Eq. 2, where P_a is the supply pressure, ρ_c density of the cooling fluid emulsion mixture, g is the gravitational constant, h_a supply pressure head, v_a the supply fluid velocity in the tool holder, A_a the supply hole area and Q_a the supply flow rate.

$$\rho_c = \frac{m_w + m_o}{V_c} \qquad \textbf{...Eq. 1}$$

$$P_a = \rho_c g h_a \qquad \text{determine } h_a$$

$$v_a = \sqrt{2gh_a} \qquad \text{determine } v_a$$

$$Q_a = A_a v_a \qquad \textbf{...Eq. 2}$$

The conservation of mass can be expressed as a volumetric flow for steady state flow and the velocity of the output can be calculated, indicated in Eq. 3, where A_b and A_b' are the outlet areas and v_b andv_b' are the outlet velocities, as indicated in Figure 27.

$$Q_a = Q_b = Q_b' \qquad \text{volumetric flow}$$

$$A_a v_a = A_b v_b = A_b' v_b' \qquad \textbf{...Eq. 3}$$

The conceptual design is given in Figure 28, indicating the vertical guide hole that allowed access for the new focused HPTSC hole into the HPTSC main supply. The vertical guide hole was plugged after completing the new focused HPTSC hole. Both the adjusted and new focused HPTSC techniques have a focus point to which they are directed. Figure 29 gives a (a) vertical side and (b) top view of the positioning of the insert and focus point. The focus point is located 0.2 mm from the cutting edge of the insert, indicated in Figure 29 (a) vertical side view, aimed in the direction of the cutting tip, as shown in the zoom of Figure 29(b) vertical top view. A detailed positioning of the focus point is given in Appendix B under cutter point.

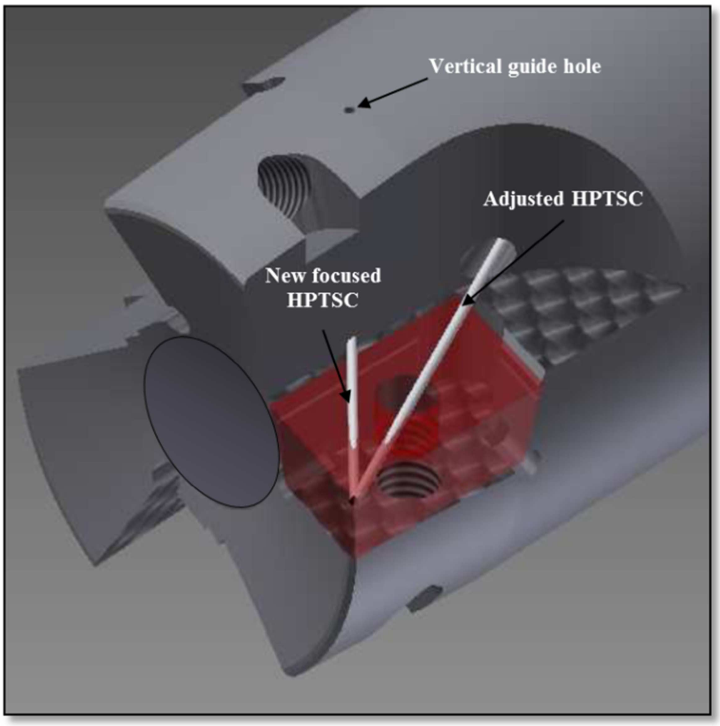
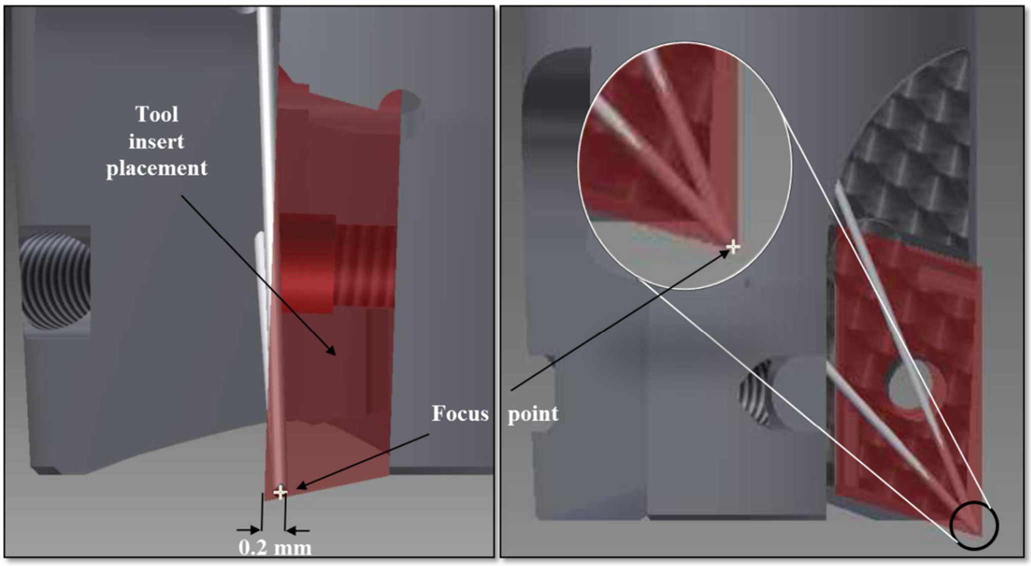


Figure 28: Conceptual design of the adjusted HPTSC and new focused HPTSC jets

(a) Vertical side view

(b) Vertical top view



Focus point depth from cutting tip

Focus point alignment to insert cutting tip

Figure 29: Placements of the focus point for the HPTSC designs

The focus point is below the cutting tip of the insert to ensure the HPC coolant contacts the cutting tool before the tip, curling upwards under the forming chip, as depicted in Figure 30 by the chip flow, forcing the chip away from the heat zone, ultimately reducing contact and breaking the chip sooner. The breaking action causes discontinuous chips that constrain the contact between the insert and chip as well as reduce the possibility of continuous chip entwinement, causing unnecessary wear or damage to the workpiece or cutting edge.

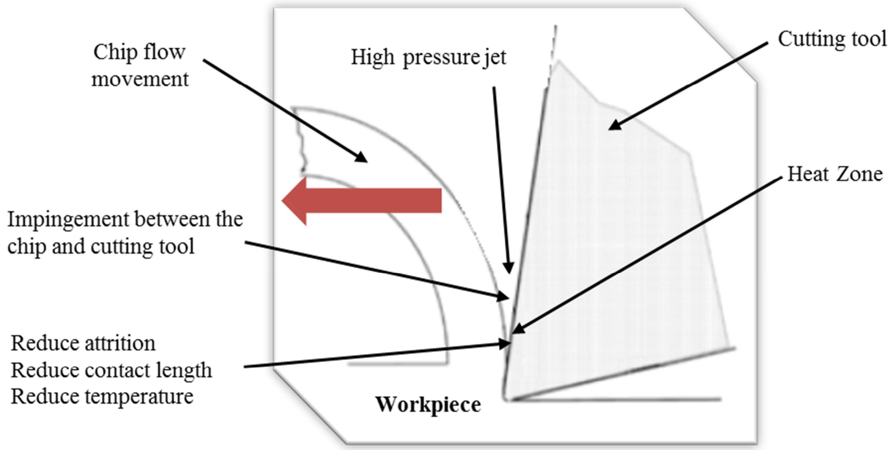


Figure 30: Jet contact with insert and formed chip

The first step in the design of the HPTSC techniques was to develop a 3D model of the Mitsubishi cutter body, drafted from the basic measurements available. This model then needs validation, accomplished by means of reverse engineering and CAD programs, before further design modifications can be incorporated.

A comprehensive 3D design model was drawn using Autodesk Inventor 2010, creating a part file (*.ipt). The original tool holder was then inspected using a Mitutoyo Bright 710 CMM machine together with a Cosmos (version 2.9) software package. The analysis process digitised the physical object in order to obtain computed data points. The data output gives a 2D/3D vector graphics format based on the initial graphics exchange specification (*.igs) which is used in CAD programs. In order to validate the conceptual solid body, the *.igs vector data points and *.ipt part files were exported into Delcam PowerSHAPE (*.psmodel) and oriented about the centre axis of the tool and referenced to the base of the cutter body, as seen in Figure 31. The inaccuracies were determined and corrected using PowerSHAPE surface modelling capabilities to obtain an accurate representation of the original cutter body. The *.psmodel was then exported back into Autodesk Inventor *.ipt format and the focused HPTSC techniques were integrated into the drawing directed at the focus point. The redesigned Mitsubishi BAP3500 indexable milling cutter with the compound angles and dimensions are given in Appendix B.

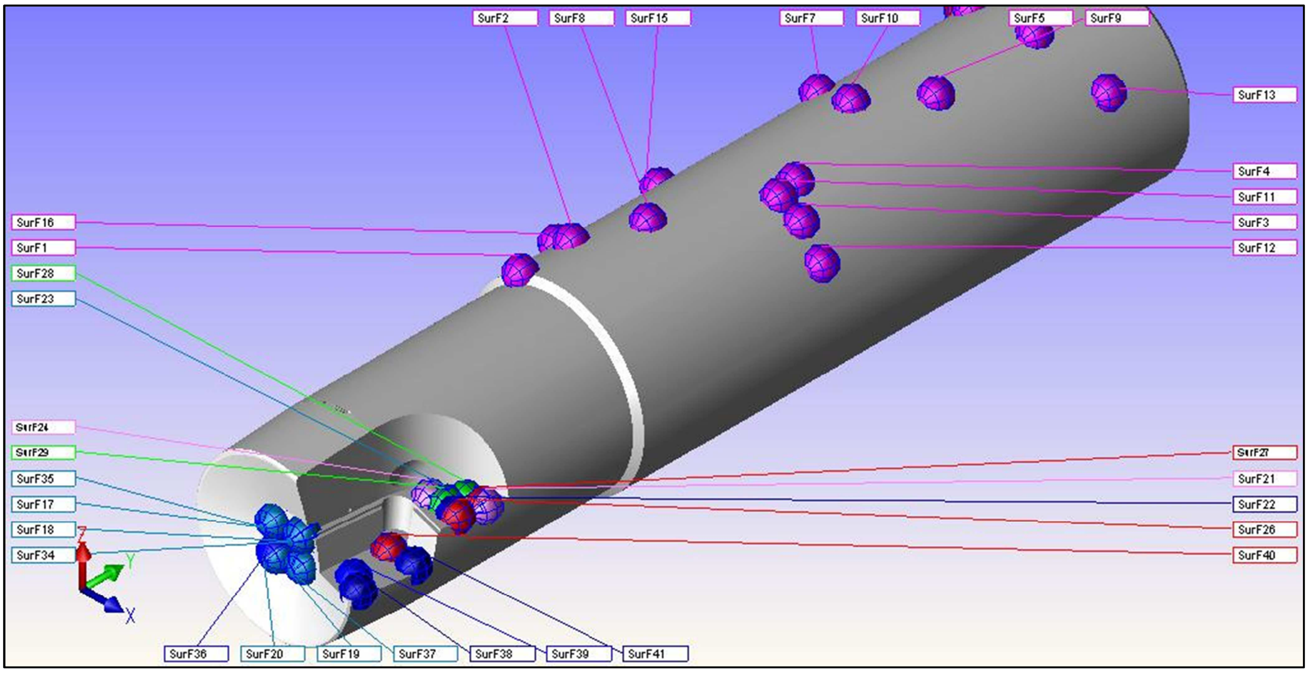


Figure 31: Surface analysis using a Mitutoyo Bright 710 CMM machine

There are three flutes on the Mitsubishi BAP3500 cutter body and three HPTSC techniques, namely adjusted HPTSC, focused HPTSC and combined adjusted and focused HPTSC. Therefore, since only one inset is used for each experiment and there is a technique assigned to each flute on the cutter, the cost of purchasing multiple cutters is reduced. Furthermore, all three experimental procedures can be accomplished using one cutter body. The three HPTSC techniques are described below.

In order to increase the velocity of the cutting fluid being exposed to the cutting zone, the outlet diameter d_b of the HPTSC needs to be decreased. For this reason, the original hole diameter has been decreased from 3 mm to 0.5 mm and directed at the focus point. The reduced outlet diameter velocity, $v_b{}'$, as indicated in Figure 27, can be calculated from Eq. 3. It was taken into account that four exit holes are present on the modified cutter body, due to the combined adjusted and focused HPTSC technique housing two holes on a single flute. The calculated velocity for the original cutter body and modifications are given in Table 8.

Table 8: Supply and outlet conditions for the original and modified HPTSC Mitsubishi BAP3500 indexable milling cutter body

HPTSC coolant supply conditions				
P_a	ρ_c	D_a	A_a	v_a
7 MPa	997.94 kg/m^3	5 mm	19.63 mm^2	118.44 m/min

HPTSC coolant outlet conditions			
Original HPTSC	d_b	A_b	v_b
	3 mm	7.07 mm^2	109.67 m/min
HPTSC Techniques	$d_b{}'$	$A_b{}'$	$v_b{}'$
Adjusted HPTSC	0.5 mm	0.20 mm^2	2961.10 m/min
New focused HPTSC	0.5 mm	0.20 mm^2	2961.10 m/min
Combined HPTSC	0.5 mm	0.20 mm^2	2961.10 m/min

Assumptions: All frictional losses can be ignored, supply is constant, coolant temperature is approximately 20 ºC, the coolant fluid water and oil $(m_w + m_o)$ emulsion ratio remains constant at 30:1

The procedure followed to reduce the original hole was to plug the original HPTSC hole and spark erode the 0.5 mm hole through the plug. The compound angle for the adjusted HPTSC design is shown in Appendix B under cutter hole angle 1. The drawing indicating the coolant stream follows the original HPTSC stream centre line, but is then angled to come into contact with the focus point, contacting the insert before the forming chip as discussed previously. The adjusted HPTSC diameter reduction and coolant stream travel is shown in Figure 32 under the horizontal top and side view.

Adjusted HPTSC

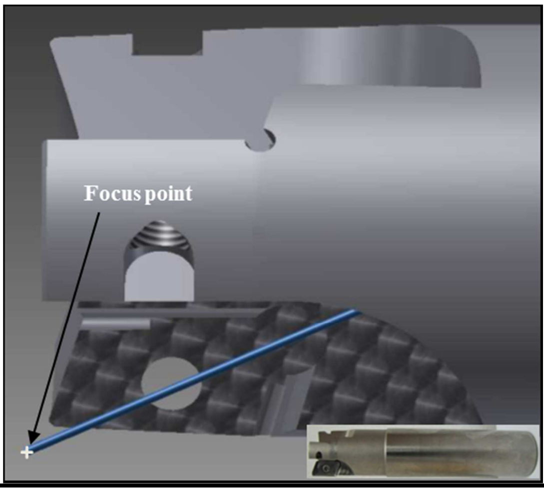
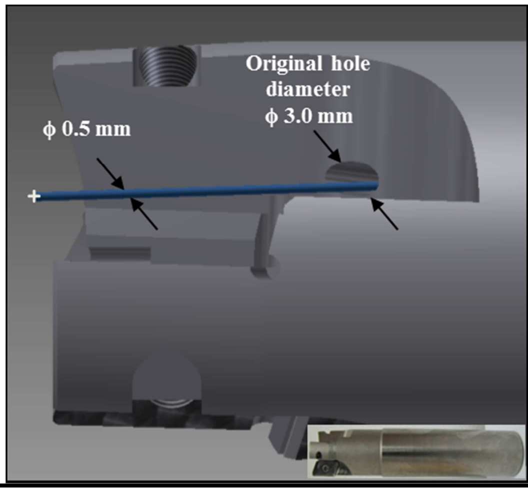
Horizontal top view	Horizontal side view
	

Figure 32: Adjusted HPTSC technique reduction in diameter and coolant stream travel

The new focused HPTSC coolant stream is spark eroded in a designated direction from the focus point through a point 0.2 mm above the flute land, until it reaches the vertical guide hole, indicated in Figure 33. A detailed drawing of the compound angles and positioning is given in Appendix B under cutter hole angle 2. Once this has been completed, the vertical guide hole will be plugged as deep as possible to prevent the HPTSC escaping away from the cutting zone.

New focused HPTSC

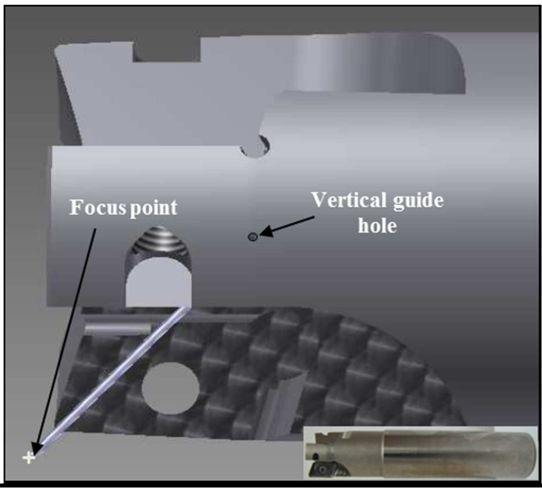
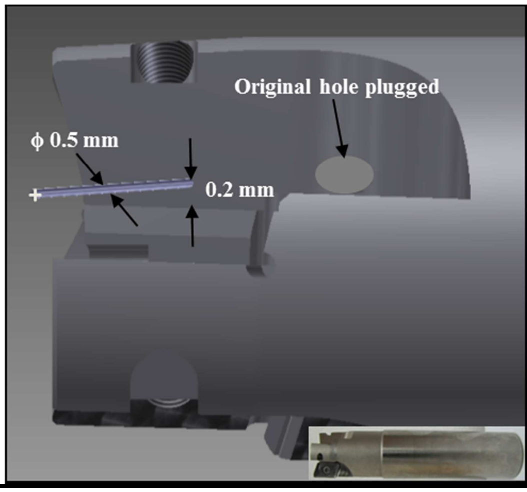
Horizontal top view	Horizontal side view
	

Figure 33: New focused HPTSC technique positioning and design

The design of the new focused HPTSC reduces the travel distance of the coolant stream. The shorter distance reduces the expansion of the coolant stream, intensifying the focus of coolant on the cutting zone with the intent of increasing the cooling capacity and flushing ability. The variations in the travel distances are easily visible in Figure 34 horizontal top view, where the adjusted and new focused HPTSC coolant stream designs are combined in the attempt to incorporate the benefits of both techniques.

Combined adjusted and new focused HPTSC

Horizontal top view | **Horizontal side view**

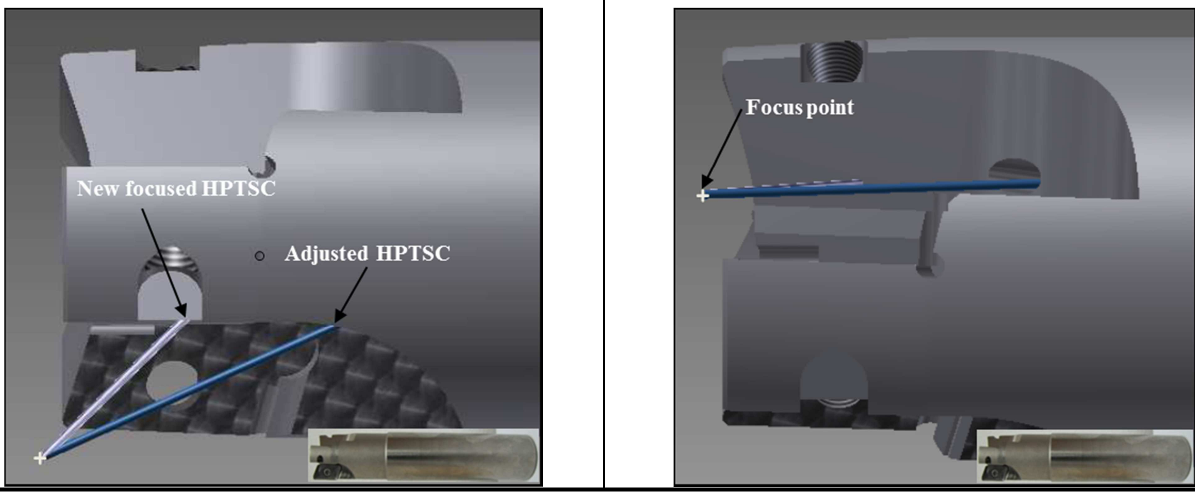


Figure 34: Combined adjusted and new focused HPTSC technique

The adjusted HPTSC stream diameter of contact will be greater than that of the new focused HPTSC, allowing for greater flushing of chips. In contrast to the adjusted HPTSC, the new focused HPTSC concentrates the cooling capacity of the coolant stream onto the cutting zone. Both the flushing and focused cooling attributes of the adjusted and focused HPTSC techniques are favourable and a combination of the two techniques appropriate. A graphical representation of the combined HPTSC techniques is given in Figure 34.

4.3 Experimental procedure

The machining experiments were carried out in the type down milling operation along the shoulder of the workpiece material. Two separate experimental cutting parameters were compiled for both the SECO and Mitsubishi cutting tool holders, assembled in Table 9 and Table 10 respectively. The cutting parameters were derived from CIRP-Collaborative Project and comply with international standards [71]. The material removal parameters were kept constant throughout all experiments.

At the beginning of each experiment, a new cutting insert was mounted onto the tool holder. Since tool wear is the most important limiting factor concerning tool life, the employment of the most aggressive cutting parameters was selected for these experiments. The flank face wear band width (V_b) gives an indication of the effect of the chip contact and cooling effect on the cutting edge. For this reason, in each experiment, the wear scar measurement was on the flank face of the insert. Tool flank wear was measured under an optical microscope periodically and the edge surface examined for clear wear mechanisms contributing to tool failure. Once the tool wear parameters were measured, the tool was remounted and the procedure repeated until consistencies of the experimental values were obtained. The tool rejection criteria were as follows:

1. Average flank wear $V_b = 200\ \mu m$
2. Maximum flank wear $V_{bmax} = 350\ \mu m$
3. Excessive chipping or catastrophic fracture of the cutting edge

Experimental procedure was stopped on reaching any of the above criteria. As determined in literature, the requirement for increased productivity when machining difficult-to-cut materials and the harsh temperature conditions that form consequently, require adequate cooling strategies. Therefore, under each experimental procedure different cooling strategies were integrated with the intent to investigate their influence on the tool life of the inserts and their reduction of the severe temperature conditions. As previously discussed under Chapter 3, the cooling strategies are flood cooling, air blow cooling (dry cutting) and HPTSC. Each experimental parameter accommodates variations in cooling strategies and techniques. These are discussed as follows.

Table 9: Experimental parameters for milling with Ø50 mm SECO milling tool holder

Material	Cutting speed v_c (m/min)	Feed per tooth f_z (mm/z)	Axial depth of cut a_p (mm)	Radial depth of cut a_e (mm)
Ti6Al4V	150	0.375	2	0.65
40CrMnMo7	250	0.485	3	4.7

The SECO tool experiments were carried out under a flood cooling benchmark, together with air blow cooling (dry cutting) application. The cutter body was mounted with type SEAN SECO inserts with the described insert coating treatments in section 4.2. The insert dimensions and tolerances are given in Appendix C1 and the SECO Ø50 mm tool holder specifications are detailed in Appendix C2. Since this tool holder has no HPTSC capability, no modification techniques were applied in this experimental procedure. The experimental parameters and cutter body are given in Table 9. The main objective of the SECO experiments was to determine the effect of the coating treatment and the cooling strategy on the tool life of coated carbide inserts.

Table 10: Experimental parameters for milling with Ø25 mm Mitsubishi BAP3500 tool holder

Material	**Cutting speed v_c (m/min)**	**Feed per tooth f_z (mm/z)**	**Axial depth of cut a_p (mm)**	**Radial depth of cut a_e (mm)**
Ti6Al4V	150	0.375	2	0.65
40CrMnMo7	250	0.485	3	4.7

The Mitsubishi BAP3500 tool holder was mounted with Mitsubishi inserts with dimensional specifications indicated in Appendix D1. The experimental parameters and original cutter body are given in Table 10. The cutting parameters described were conducted under a flood cooling benchmark together with air blow cooling (dry cutting), HPTSC and the HPTSC modifications described above. The specifications for the Mitsubishi BAP3500 Ø25 mm indexable milling tool holder are given in Appendix D2. The Mitsubishi experiments compared the focused HPTSC techniques and cooling strategies on tool life of coated carbide inserts.

5. Results and discussions

The results of the experiments are compiled into graphical representations of tool flank wear V_b as a function of machining time. The deductions of the various coating treatments and cooling strategies effect on tool life are discussed as below.

5.1 General considerations

The results are separated into two components of titanium and hardened steel; both materials machined under the SECO and Mitsubishi tool holder experimental parameters. The experiments begin with the observed wear on various coating treatments of carbide inserts mounted on the SECO tool holder under flood cooling and air blow cooling (dry cutting) conditions. The conclusions of the experiments give the performance, in terms of tool life/machining time, of the coating and coating treatments under different cooling conditions with reference to the wear rate of the inserts.

The experiments then continue with the Mitsubishi tool holder fitted with a coated carbide insert, where the wear under the focused modifications are discussed. The results from the focused modifications are then compared to the outcomes experienced under flood cooling and air blow cooling (dry cutting) conditions. In conclusion, an examination of the tool life/machining time as derived from the wear rate gives a strong indication of the performance of the cooling strategies and techniques on coated carbides.

5.2 Machining titanium (Ti6Al4V)

The results discuss the effects of various coating treatments on TiAlN coating, as described in section 4.1, and the effects of the application of cooling strategies and techniques, as well as modifications to an existing HPTSC strategy, covered in section 4.2.

5.2.1 SECO insert cooling strategy performance under different coating treatments

The tool life of various coating treatments under flood cooling and dry cutting while machining with the SECO tool holder are presented in Table 11. The average time taken to reach the tool wear criterion was taken as representing total tool life/machining time for each coating treatment. The results obtained from the machining experiments clearly show that the tool life increases under dry cutting conditions. Detailed results of each coating treatment, for the various cooling strategies, are given in Appendix E1 and Appendix E2.

Table 11: Effect of various coating treatments on tool life during HPM Ti6Al4V using SECO inserts

Cooling strategy	Type of coating treatment						
	U	***AB***	***AFM***	***B***	***H***	***LM***	***MAM***
	Tool life (min)						
FC	10.7	9.6	12.1	9.4	12.8	10.7	9.4
ABDC	119.9	125.2	127.3	111.4	132	134.6	157.3

Cooling strategy : Flood cooling : FC; Air blow cooing (dry cutting) : ABDC

Coating treatment: Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM; Magneto-abrasive machining : MAM

Firstly, the results of the coating treatments under flood cooling conditions are given in Figure 35. It is noted that the wear gradients for untreated (U), abrasive blasting (AB), abrasive flow machining (AFM), brushing (B), laser machining (LM) and magneto-abrasive machining (MAM) are practically linear. This indicates that under flood cooling conditions the various coating treatments wear at a constant rate up to 200 µm in a predictable manner. The wear rates under abrasive flow machining (AFM) and honing (H) treatments yield favourable tool life in comparison to the aforementioned treatments. The coating treatment performances are described briefly, followed by a more detailed account of the best performing coating treatment thereafter.

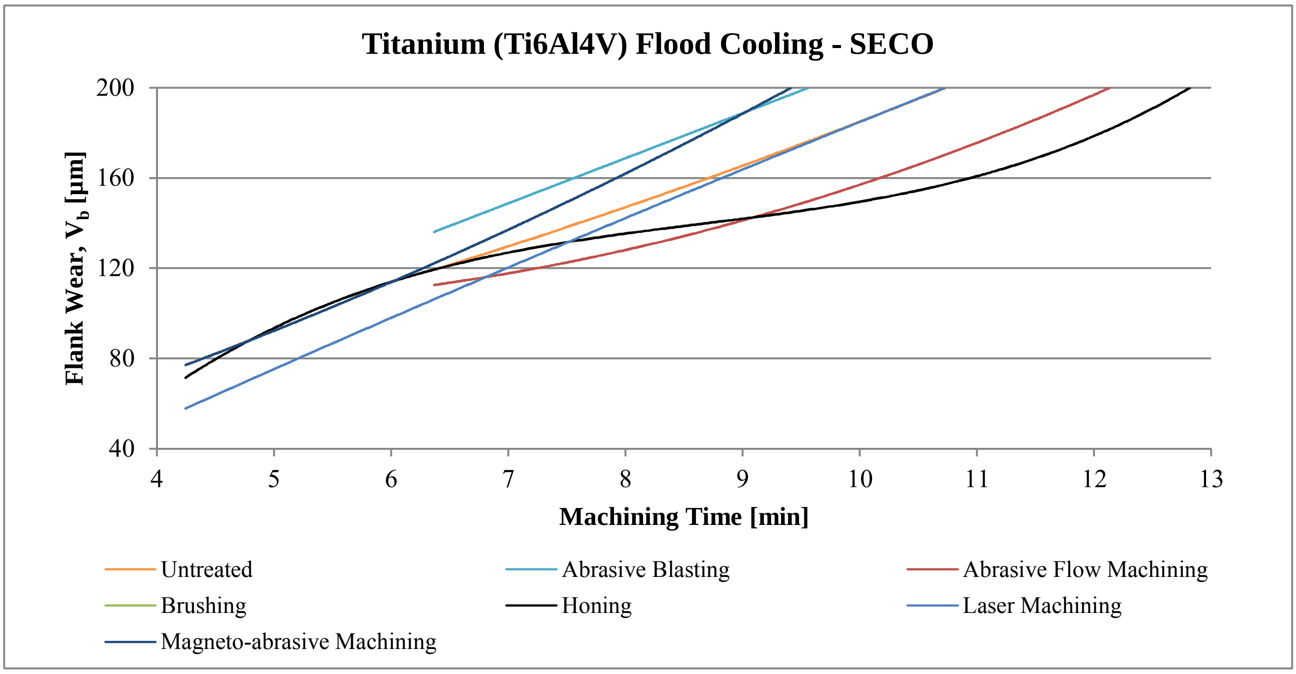
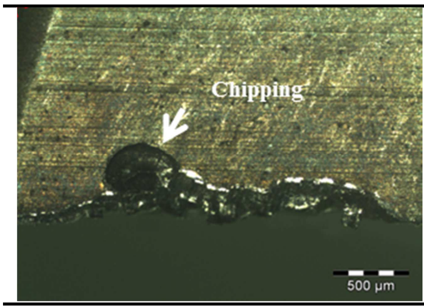
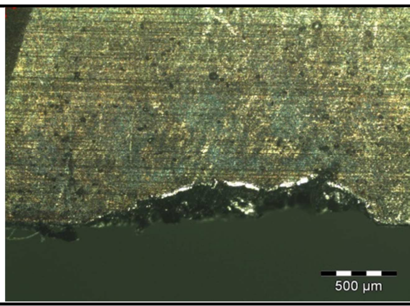
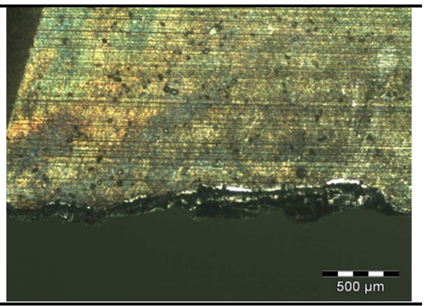
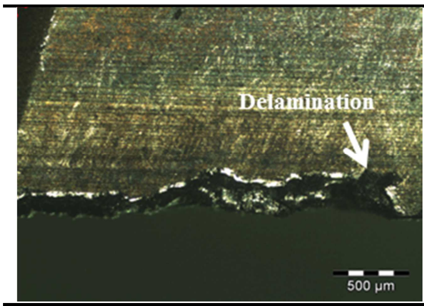
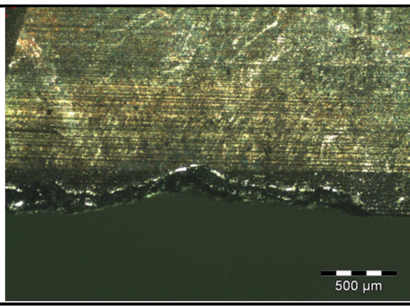
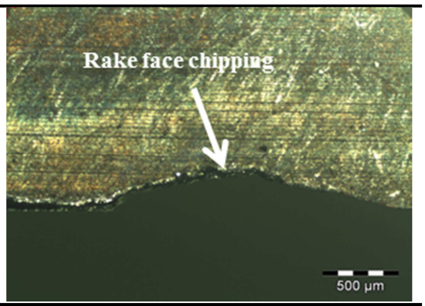


Figure 35: The tool life of flood cooling on various coating treatments, machining Ti6Al4V with SECO inserts

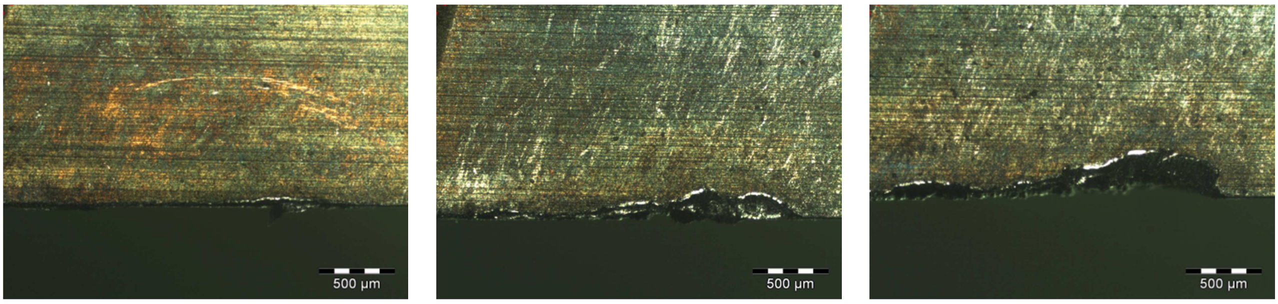
In the case of the U, AB, AFM, B, LM and MAM coating treatments, the tool life and tool wear are presented in Table 12. Notch wear was experienced throughout all experiments, which decreased the tool life, and in certain cases, caused chipping and tool failure. It is noted that under U and B coating treatments, adhesion, abrasion, chipping and delamination occurred towards the end of the tool life. Similar outcomes were experienced under MAM coating treatment but caused severe chipping and catastrophic failure on the rake face, removing a section of the flank face in the process. Under flood cooling, B and MAM coating treatments obtained the shortest tool life.

Table 12: Tool wear and tool life for coating treatments under flood cooling, machining Ti6Al4V with SECO inserts

U	AB	AFM
		
Wear after 10.7 min	**Wear after 9.6 min**	**Wear after 12.1 min**
B	**LM**	**MAM**
		
Wear after 9.4 min	**Wear after 10.7 min**	**Wear after 9.4 min**

Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Laser machining : LM; Magneto-abrasive machining : MAM

The coating treatment which obtained the longest tool life before reaching the average wear criterion was the coated insert with H coating treatment. In the initial stages of machining, tool wear is relatively high until approximately 7 min machining time. The flank wear scar progressed evenly over the cutting edge during this period and can be seen in Figure 36. Hereafter, the wear stabilises and increases gradually until 11 min machining time, from which the wear accelerates until 200 µm flank wear, reaching a tool life of 12.8 min under the presented cutting parameters. In this experiment, the formation of notch wear became significant after the initial stages of machining, seen in middle Figure 36, and was the reason for the accelerated wear. This notch wear was significantly lower than that of the previous coating treatments. Therefore, honing is the preferred coating treatment under flood cooling conditions.



Wear after 4.2 min **Wear after 8.9 min** **Wear after 12.8 min**

Figure 36: Wear scar progression for honing coating treatment under flood cooling conditions, machining Ti6Al4V with SECO inserts

Although honing and abrasive flow machining coating treatment show positive results in terms of increasing tool life under flood cooling in comparison to untreated coatings, the investigation includes the application of the same coating treatments under dry cutting conditions. Therefore, it is important to compare the tool life under dry cutting machining conditions with the coating treatments, as given in Figure 37.

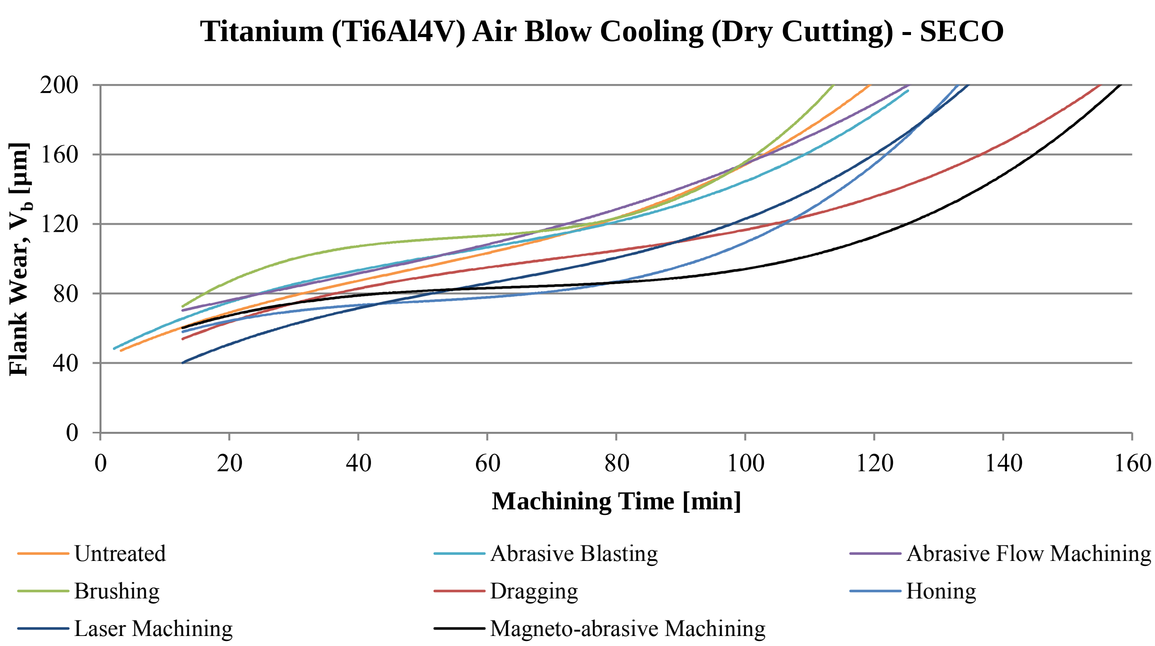
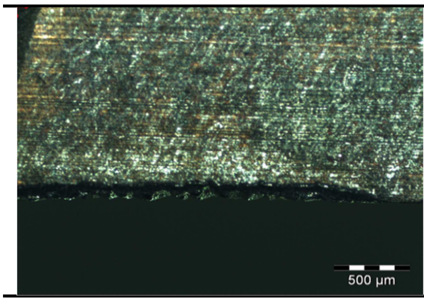
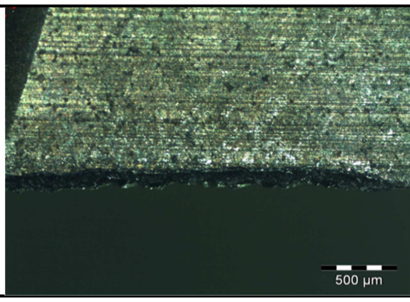
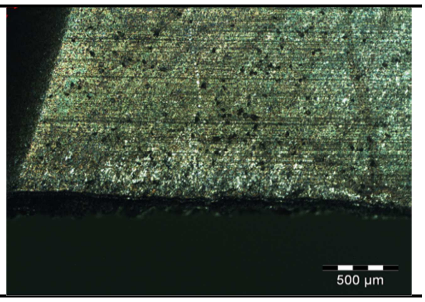
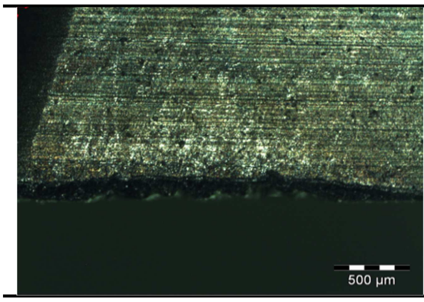
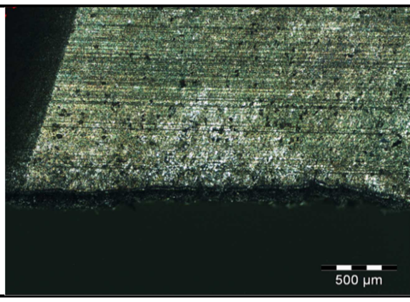
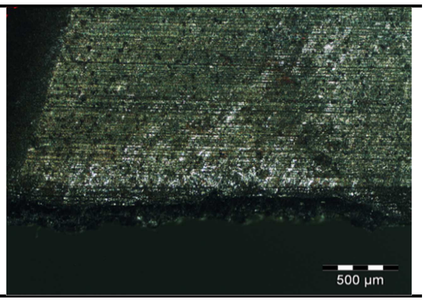


Figure 37: The tool life of air blow cooling (dry cutting) on various coating treatments, machining Ti6Al4V with SECO inserts

Under dry cutting conditions U, AB, AFM, B, H, and LM, coating treatments wear suddenly at entry but quickly reach linear wear after 20 min machining time, with the wear only reaching between 45 – 100 µm, as seen inFigure 37. At this stage of machining, the dry cutting has already produced longer tool life than flood cooling and it is reasonable to say that the coated tools perform better under dry cutting conditions. Nevertheless, the wear continues in a linear fashion, increasing marginally but in a consistent manner up until approximately 70 – 80 min machining time and then accelerating up to 200 µm. The respective tool life and tool wear for each of the various coating treatments are given in Table 13, showing a relatively constant wear over the cutting depth of the insert for all the coating treatments. What is important to note is that the machining time for each coating treatment, other than that of B, is greater than that of U. This gives reasonable evidence to a coating treatment preference under the given conditions.

Table 13: Tool wear and tool life for coating treatments under air blow cooling (dry cutting), machining Ti6Al4V with SECO inserts

U	**AB**	**AFM**
		
Wear after 119.9 min	**Wear after 125.2 min**	**Wear after 127.3 min**
B	**H**	**LM**
		
Wear after 111.4 min	**Wear after 132 min**	**Wear after 134.6 min**

Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H;
Laser machining : LM

Furthermore, it is clear in Figure 37 that MAM outperformed the other coating treatments. The wear development of MAM is similar to the other coating treatments, reaching a constant linear wear rate in the initial stages and increasing noticeably after 100 min machining time. The main difference is the period of linear wear, which runs for an extended machining time. The progression of the wear is shown in Figure 38, where the wear only starts to increase prominently after 114.6 min machining time, accelerating until the 200 µm wear limit after 157.3 min machining time. The tool life for MAM is considerably higher under dry cutting, showing significant potential for increasing tool life of coated carbides under the given cutting parameters.

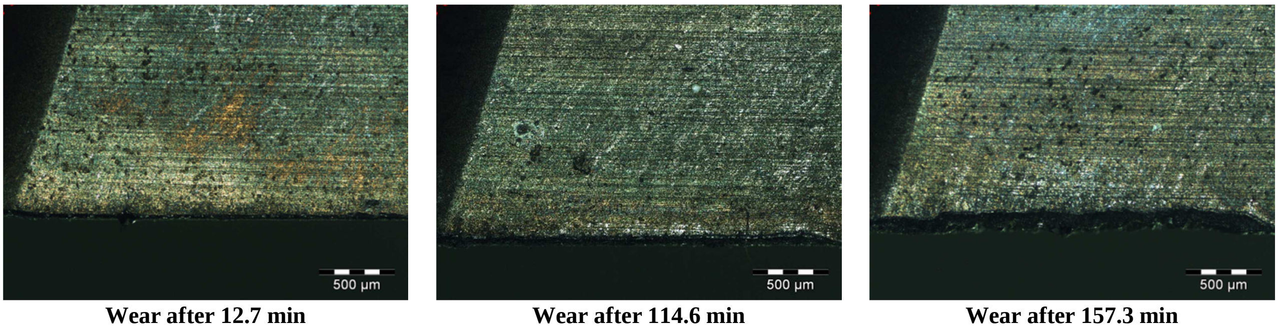


Figure 38: Wear scar progression for magneto-abrasive machining coating treatment under air blow cooling (dry cutting) conditions, machiningTi6Al4V with SECO inserts

The best tool life/machining time for the coating treatments under flood cooling and dry cutting conditions, MAM (dry cutting) and H (flood cooling), are compared in Figure 39 in order to highlight the benefits of the coating treatments under the selected cooling strategies. Thus it is clear, dry cutting Ti6Al4V with MAM coating treatment yields favourable tool life/machining time under the given experimental conditions and cooling strategies.

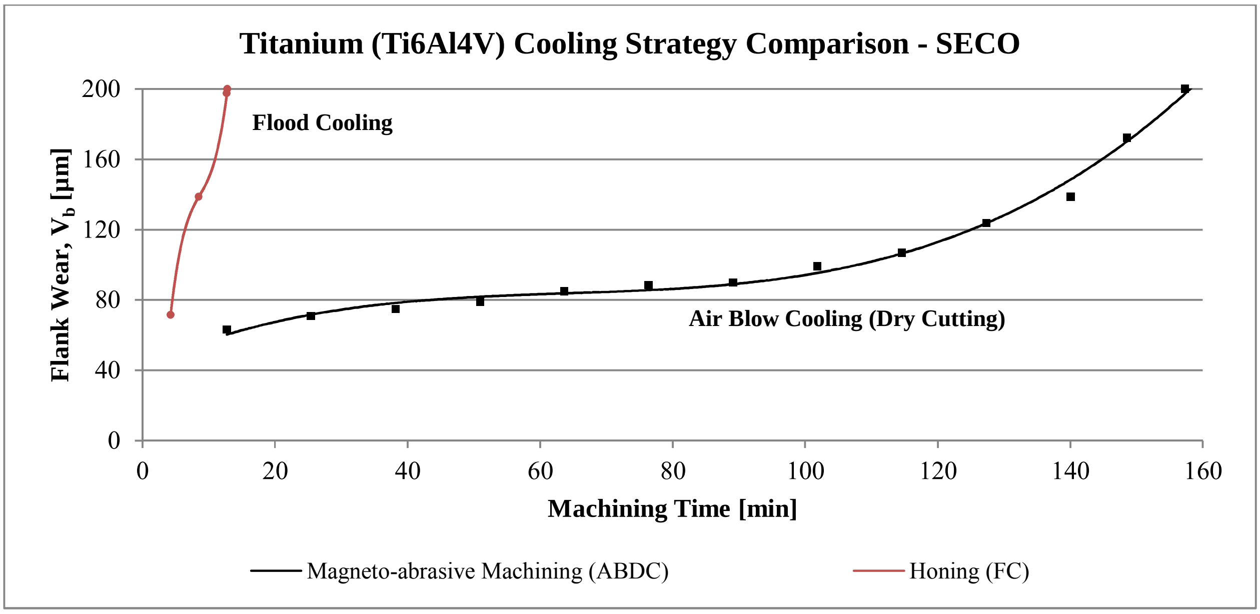


Figure 39: A comparison of the best performing coating treatments under flood cooling and air blow cooling (dry cutting), machining Ti6Al4V with SECO inserts

5.2.2 Performance of the Mitsubishi BAP3500 HPTSC strategies and techniques

Tool life of the various cooling strategies and modification techniques for machining titanium with the Mitsubishi tool holder are given in Table 14. The performance of the cooling strategies and techniques is measured by the ability of the cooling strategy or technique to increase the tool life of the inserts under the given cutting conditions (Table 10). The experimental cooling strategies and techniques are dry cutting, flood cooling (benchmark), HPTSC and the focused HPTSC modifications. The Mitsubishi tool holder has the ability to accommodate HPTSC, and therefore it was decided to incorporate inclusion of the focused modifications, described in more detail under section 4.3.

Table 14: Effect of various cooling strategies and techniques on tool life during HPM Ti6Al4V using Mitsubishiinserts

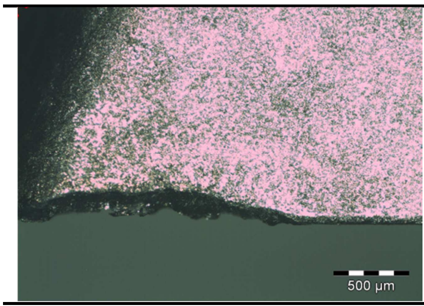
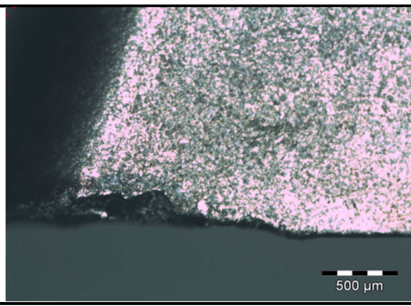
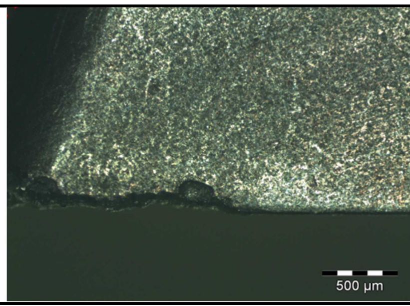
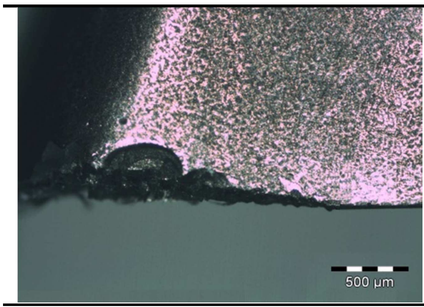
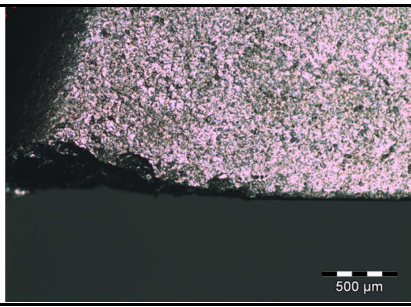
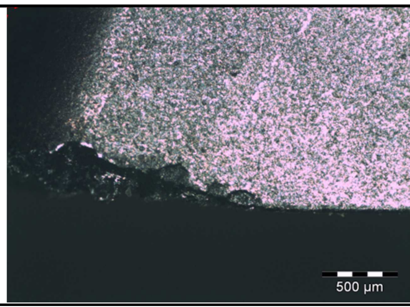
Material	Cooling strategies and techniques					
	ABDC	FC	MI	MII	MIII	MIV
	Tool life (min)					
Ti6Al4V	15.9	3.5	3.4	3.3	2.2	2.1

Air blow cooling (dry cutting) : ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

In this section the aim of the experiments was to determine the tool life/machining time of the cooling strategies and techniques on coated Mitsubishi inserts. The coating of the inserts is similar to that used in the SECO experiments, being TiAlN coated cemented carbide. This was chosen in order for the results to be further comparable. The relative performances of all the cooling strategies and techniques are given in Table 15, giving the graphical representation of the wear scar after reaching 200 µm wear and the machining time up to this point. It is evident that from Table 15, the application of fluid cooling strategies and techniques induce mechanical and thermal shock loading on the insert. This is visible by the increased plastic deformation and chipping on the cutting edge, particularly under the HPTSC modification techniques. The dry cutting produces a gradual increase in wear over the machining time and improves the tool life dramatically in comparison to the flood cooling and HPTSC techniques. The outcome of this strategy is discussed in further detail following the discussion of the HPTSC modification results.

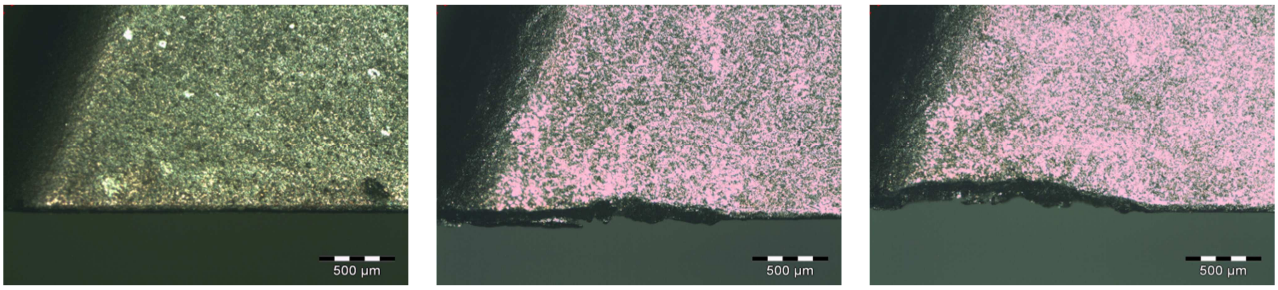
Since titanium has a low thermal conductivity, concentrating the heat into the cutting zone, there is a dramatic decrease in the temperature under the application of the HPTSC techniques. This, together with the fluctuating temperature conditions promote mechanical and thermal loading. Therefore, the deduction can be made that the focused HPTSC modifications increase the capacity to reduce the temperature and penetrate the cutting zone to shorten the chip contact with the cutting tool. Although these are favourable attributes, in the case of machining titanium, the modification techniques prove to have an adverse effect on tool life. It is therefore understood that the reduction of the contact length increases the concentration of the heat onto a smaller area on the tool surface and an increase in thermal demand on the cutting edge. The cyclic concentrated heating and focused cooling caused significant fracture, chipping and thermal fatigue, decreasing the tool life of the inserts.

Table 15: Tool wear and tool life under the various cooling strategies and modification techniques, machining Ti6Al4V with Mitsubishi inserts

ABDC	FC	MI
		
Wear after 15.9 min	**Wear after 3.5 min**	**Wear after 3.4 min**
MII	**MIII**	**MIV**
		
Wear after 3.3 min	**Wear after 2.2 min**	**Wear after 2.1 min**

Air blow cooling (dry cutting) : ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

Once again, the tool life/machining time performance of dry cutting has surpassed the other cooling strategies and techniques. The wear progression for dry cutting is given in Figure 40. The wear is evenly distributed over the cutting edge in the initial stages, after 3 min machining time, and distributed more to the depth of the cut at a later stage of machining, after 8.9 min machining time. After reaching 200 µm wear at 15.9 min machining time, it was noted that the wear was distributed more to the body of the cutting edge and the cutting tip maintained. There is also evidence of adhesion of chips to the cutting edge during the later stages of machining, which can be seen in Figure 40 after 8.9 min and at 15.9 min machining time.



Wear after 3 min | Wear after 8.9 min | Wear after 15.9 min

Figure 40: Wear scar progression under air blow cooling (dry cutting) conditions, machining Ti6Al4V with Mitsubishi inserts

When considering the coated cemented carbide insert, the coating counteracts the influence of the temperature and the substrate the mechanical loading. Due to the combination of these two parameters, tool life is prolonged by combating both temperature and mechanical loading simultaneously. The heat that is generated in the cutting zone helps to soften the material being machined, therefore reducing the mechanical loading on the insert. The application of an air stream helps to reduce the cyclic heating slightly, but has the purpose of removing the forming chip from the cutting zone. The flood cooling, HPTSC and focused HPTSC modification techniques are compared to the duration of the tool life under dry cutting in Figure 41. This gives a broad overview of the decrease in tool life of the flood cooling, HPTSC and focused HPTSC modification techniques. A detailed representation of each cooling strategy and –technique on Mitsubishi inserts is given in Appendix F1.

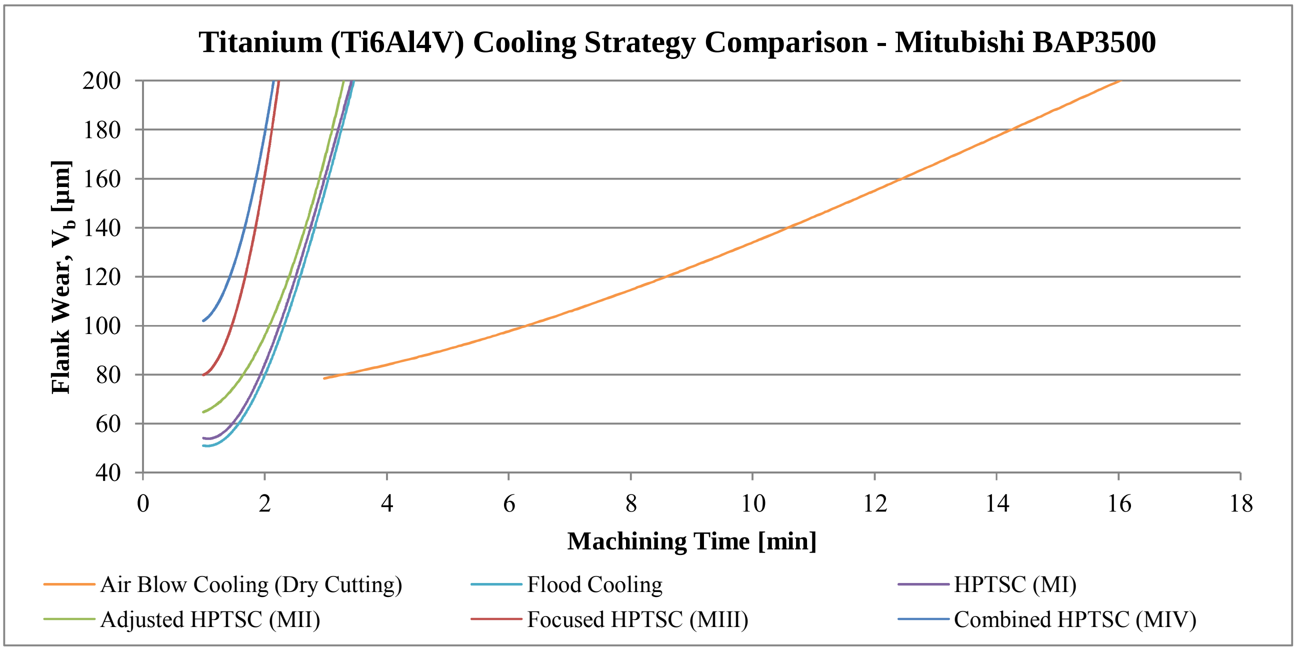


Figure 41: The tool life performance of air blow cooling (dry cutting), flood cooling, HPTSC and the HPTSC modification techniques, machining Ti6Al4V with Mitsubishi inserts

5.3 Machining hardened steel (40CrMnMo7)

Hardened steel is used extensively in the tooling, aerospace and automotive industries and the trend for the reduced machining time and machining cost has brought about higher cutting speeds, feed rates, cutting parameters and process temperatures. It is therefore important to investigate the influence of cooling strategies and techniques on the increased demands on machining this difficult-to-cut material. Similarly to the experiments using titanium, different coatings and coating treatments have been implemented to reduce or lessen the temperatures produced during machining. The discussion below explores the various coating treatments, as described in section 4.1 and the effects of the application of cooling strategies and techniques, including the effects of modifications to an existing HPTSC strategy, section 4.2.

5.3.1 SECO insert cooling strategy performance under different coating treatments

The effects on tool life for various coating treatment applications, machining hardened steel 40CrMnMo7, are given in Table 16 for flood cooling and dry cutting conditions. The average machining time before the wear criterion is reached is determined and indicates the tool life of the cutting tool. It is evident in Table 16 that dry cutting, again, outperforms the application of flood cooling under a number of coating treatments. The outcomes for flood cooling and dry cutting are investigated further as follows. Detailed graphs of each coating treatment, for the various cooling strategies, are given in Appendix G1 and Appendix G2.

Table 16: Effect of various coating treatments on tool life during HPM 40CrMnMo7 using SECO inserts

Cooling Strategy	Type of coating treatment						
	U	***AB***	***AFM***	***B***	***H***	***LM***	***MAM***
	Tool life (min)						
FC	13.7	13.3	12.7	14.3	12.9	13.4	21.2
ABDC	27.6	26.5	30.7	37.5	21.6	15.0	47.2

Cooling strategy : Flood cooling : FC; Air blow cooing (dry cutting) : ABDC

Coating treatment : Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM; Magneto-abrasive machining : MAM

Since flood cooling is the benchmark for all the experiments, it is discussed first. Figure 42 indicates the tool life for the various coating treatments under flood cooling, machining 40CrMnMo7. AFM, B, H and LM coating treatments wear in a similar manner, the wear increasing steadily throughout the machining time until 200 µm wear. The U and AB coating treatments have a similar tool life at 200 µm wear, but it was observed that, in the initial stages of machining, the wear rate was higher. The rate of wear reached a stable state with very little wear over the period between 4–7 min machining time. U and AB then experienced the lowest wear compared to the remaining coating treatments between 7–9 min machining time. Thereafter, the wear increased dramatically until the failure criteria were reached. This gives reasonable indication that U and AB coating treatments are not recommended when machining hardened steel under flood cooling conditions.

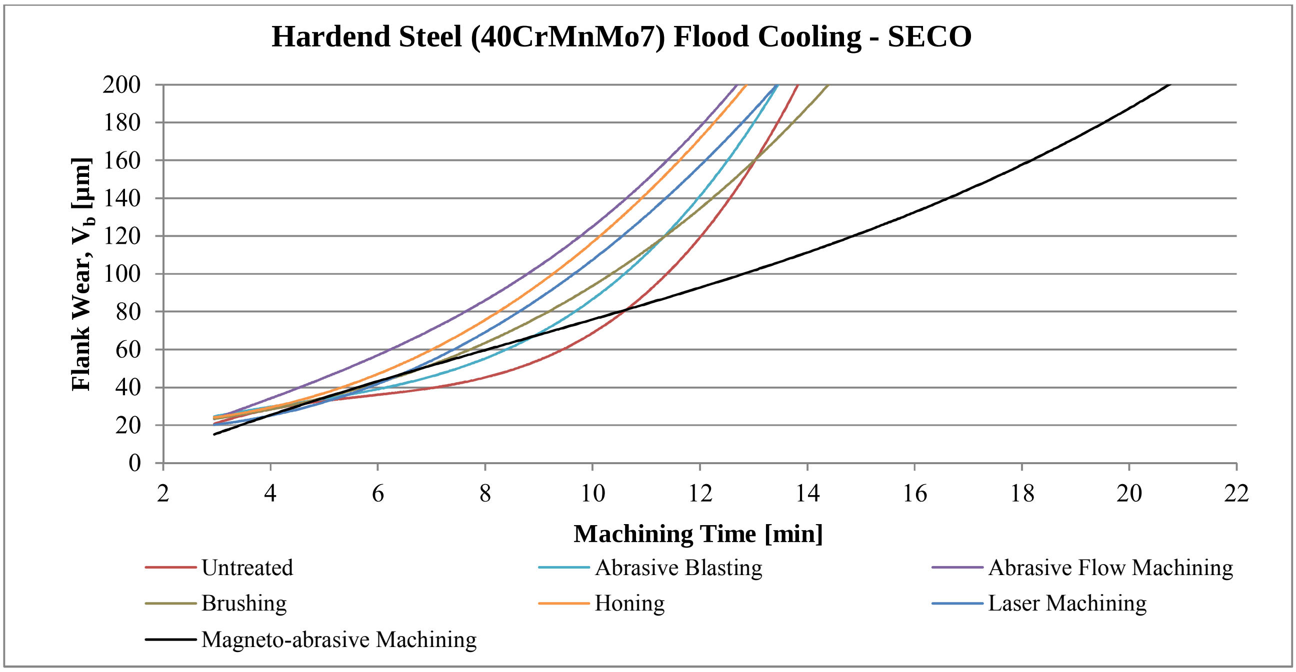


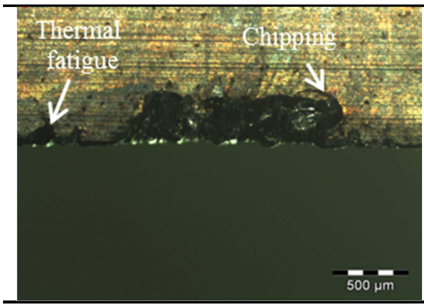
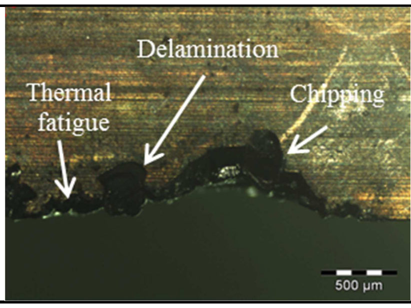
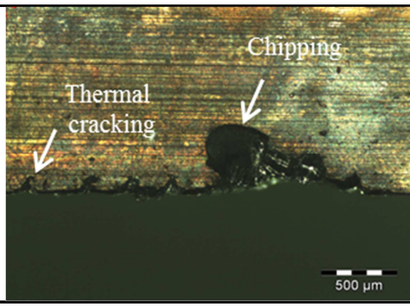
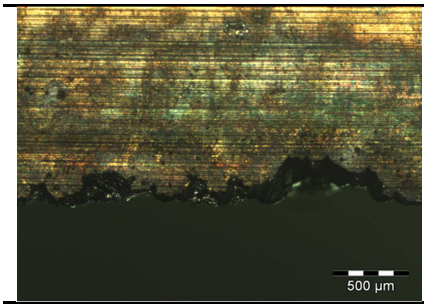
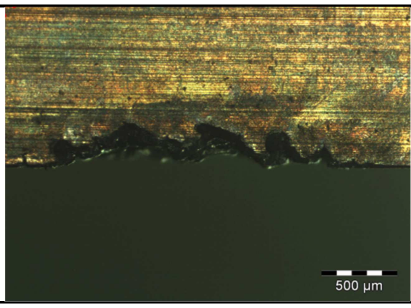
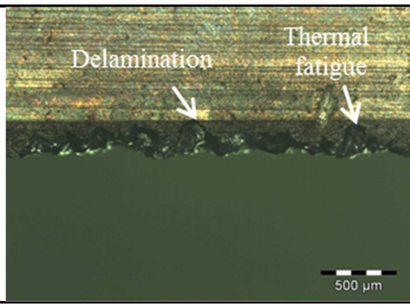
Figure 42: The tool life of flood cooling on various coating treatments, machining 40CrMnMo7 with SECO inserts

An overview of the performance of the cutting tool life and wear can be seen in Table 17. Under U, AB and AFM, chipping formed a large contribution to the tool failure. This, together with thermal cracking and thermal fatigue, accelerated the tool failure, particularly under U, AB and AFM coating treatments. Thermal cracking and fatigue was experienced in the early stages of machining under all the coating treatments, attributed to the cooling capacity of the cooling fluid.

AB and LM coating treatments not only experienced thermal fatigue and cracking but also delamination of the coating layers, as shown in Table 17. This removes the protective coating layer, exposing the substrate to the harsh cutting environment and reduces the tool life of the insert. Nevertheless, thermal fatigue was the major contributor to the failure throughout the coating treatments under flood cooling, although, under B, H and LM less chipping were encountered. This is evident by the thermal fatigue cracks forming alongside one another and the sections between the cracks being removed, often causing chipping of the cutting edge, as experienced under

U, AB and AFM. From Figure 42, MAM shows superior performance to the other coating treatments, reaching a tool life of 21.2 min machining time after 200µm wear.

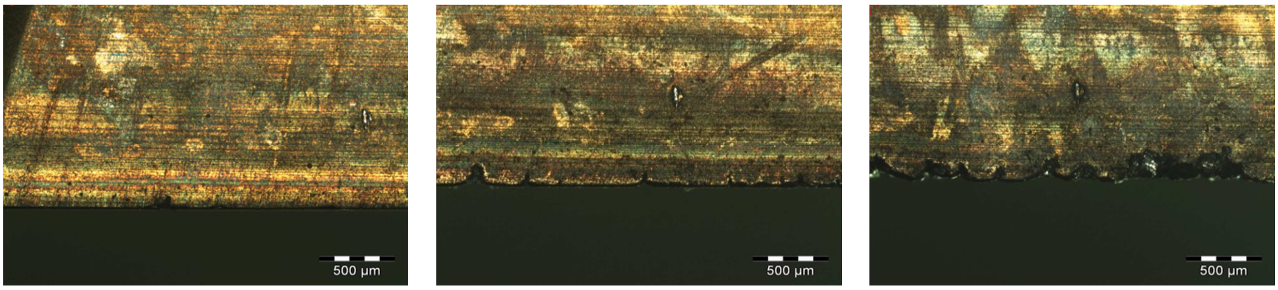
Table 17: Tool wear and tool life for coating treatments under flood cooling, machining 40CrMnMo7 with SECO inserts

U	AB	AFM
		
Wear after 13.7 min	**Wear after 13.3 min**	**Wear after 12.7 min**
B	**H**	**LM**
		
Wear after 14.3 min	**Wear after 12.9 min**	**Wear after 13.4 min**

Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM;

The wear progression for MAM coating treatment is given in Figure 43. Thermal cracking is present after a machining time of 5.9 min and progressively forms along the cutting edge until failure. Thermal cracking becomes pronounced after a machining time of 14.8 min, causing chipping and material removal from the cutting edge. The wear rate is almost linear throughout the machining under MAM coating treatment, as shown in Figure 43.

Again, thermal fatigue and chipping form the major wear mechanisms under flood cooling. It is clear that flood cooling has the capacity to reduce the temperature at the cutting zone. This, however, causes thermal loading on the cutting edge of the insert and results in a reduction in tool life. Therefore, the temperature fluctuations experienced during the milling process encourage the formation of thermal fatigue and enhances the deterioration of the cutting edge.



Wear after 5.9 min | Wear after 14.8 min | Wear after 21.2 min

Figure 43: Wear scar progression for magneto-abrasive machining coating treatment under flood cooling conditions, machining 40CrMnMo7 with SECO inserts

When considering dry cutting, the results show a wider spread of data for each coating treatment. Figure 44 displays the outcomes for the various coating treatments under dry cutting conditions, machining hardened steel 40CrMnMo7. Tool life under dry cutting, once again, is greater than under flood cooling. However, the wide spread data field indicates a necessity for the correct selection of the coating treatment and, to a large degree, coating. Nevertheless, the performance is favourable when considering the tool life during the machining of this difficult-to-cut material.

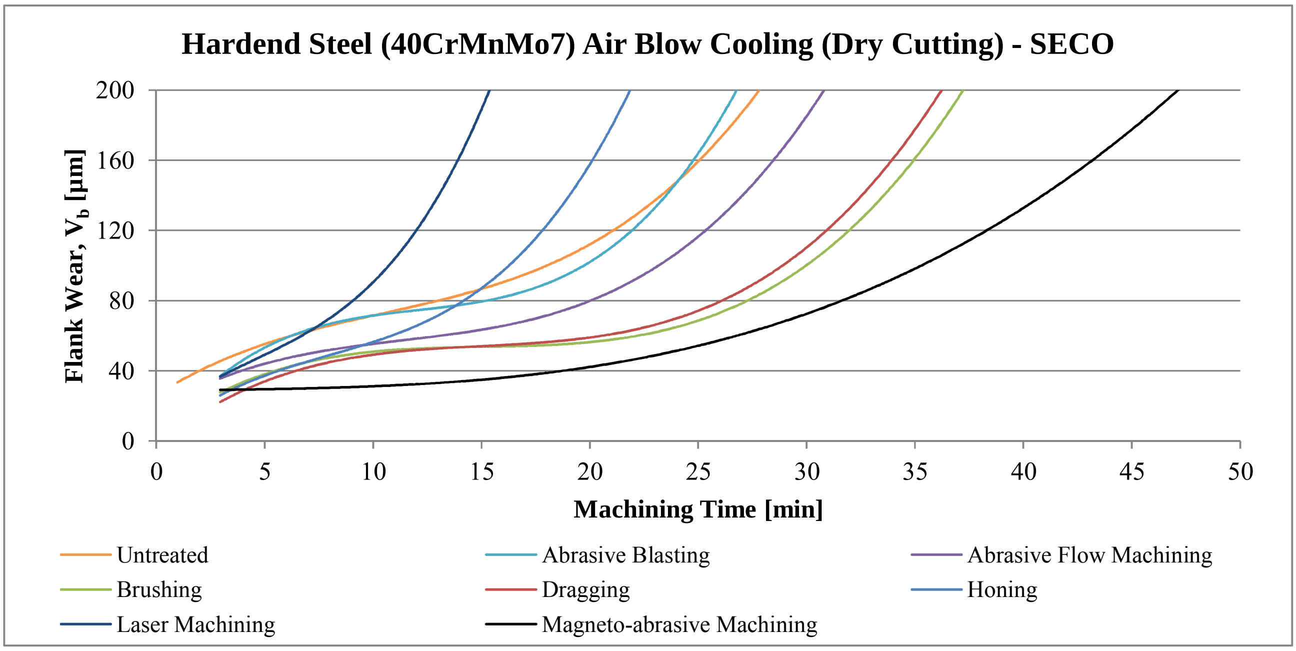
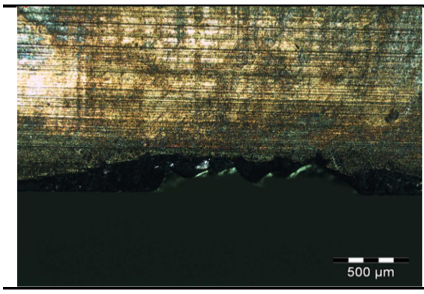
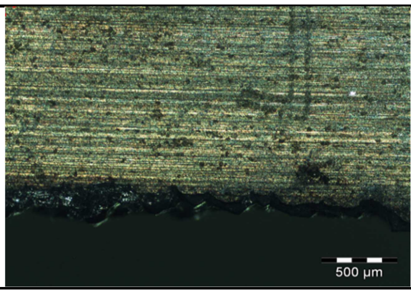
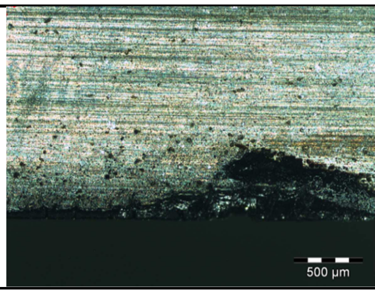
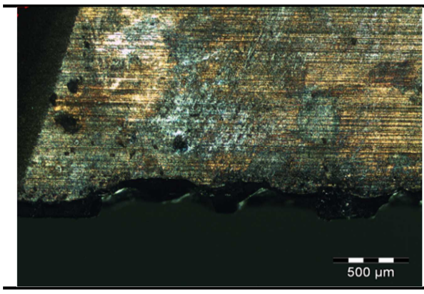
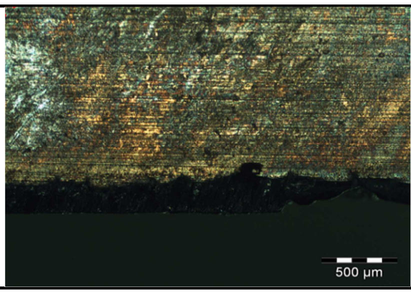
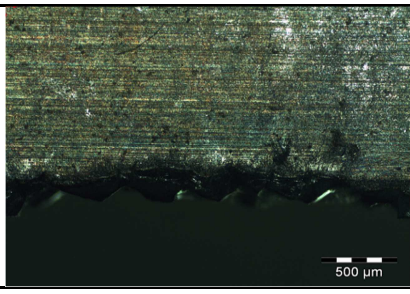


Figure 44: The tool life of air blow cooling (dry cutting) on various coating treatments, machining 40CrMnMo7 with SECO inserts

The trend of the wear for U, AB, AFM, H and LM coating treatment follows a similar pattern as depicted in Figure 44. The wear rate increases dramatically in the initial start-up stage of machining, evening out for a period of linear wear only to accelerate to the failure criterion of 200 µm in the later portion of machining time.

Under this wear arrangement AFM coating treatment achieved the preeminent tool life of 30.7 min, where LM had the least favourable tool life of 15 min. The tool life and wear formations of the various coating treatments are shown in Table 18. The wear mechanisms for the various coating treatments consist of notch wear and removal of the cutting edge due to chipping. The excessive chipping caused the removal of portions of the flank face, which is particularly evident in U, AB, B and LM coating treatments. This is evidence of the chip contact developing a hammering effect on the cutting edge. Under the AFM and H coating treatments, notch wear formed the majority of the flank wear, with H and AFM yielding a tool life of 21.6 min and 30.7 min respectively. The coating treatment B achieved favourable tool life of 37.5 min machining time, with chipping being the major wear mechanism. The wear tendency is linear in the primary phase of machining, increasing incrementally over the duration of the tool life. Thereafter, chipping developed suddenly at 200 µm.

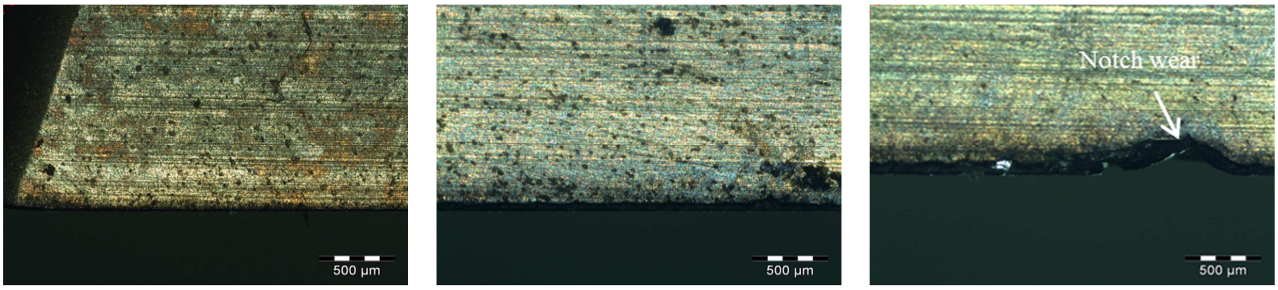
Table 18: Tool wear and tool life for coating treatments under air blow cooling (dry cutting), machining 40CrMnMo7 with SECO inserts

U	**AB**	**AFM**
		
Wear after 27.6 min	**Wear after 26.5 min**	**Wear after 30.7 min**
B	**H**	**LM**
		
Wear after 37.5 min	**Wear after 21.6 min**	**Wear after 15 min**

Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM;

The coating treatment that demonstrated the best tool life was MAM. Figure 45 shows the wear progression of the MAM coating treatment for the duration of 47.2 min machining time, up to failure criterion of 200 µm wear.

The initial wear after 5.9 min is distributed evenly along the cutting edge, increasing incrementally from this point up until 35.4 min machining time. At this point, there is evidence of notch wear forming at the maximum depth of cut, after which the development of the notch wear begins to increase substantially until finally failing after 47.2 min machining time, due to pronounced notch wear.



Wear after 5.9min | **Wearafter 35.4 min** | **Wear after 47.2 min**

Figure 45: Wear scar progression for magneto-abrasive machining coating treatment under air blow cooling (dry cutting) conditions, machining 40CrMnMo7 with SECO inserts

From the evidence presented it is noted that the chip load has a detrimental influence on the cutting edge, inducing large amount of chipping on both the flank and rake face when machining hardened steel. Further, a comparison of the outcomes for flood cooling and dry cutting is presented in Figure 46. It is therefore evident that MAM coating treatment is preferred when machining hardened steel for both flood cooling and dry cutting, but tends to yield more favourable tool life under dry cutting conditions.

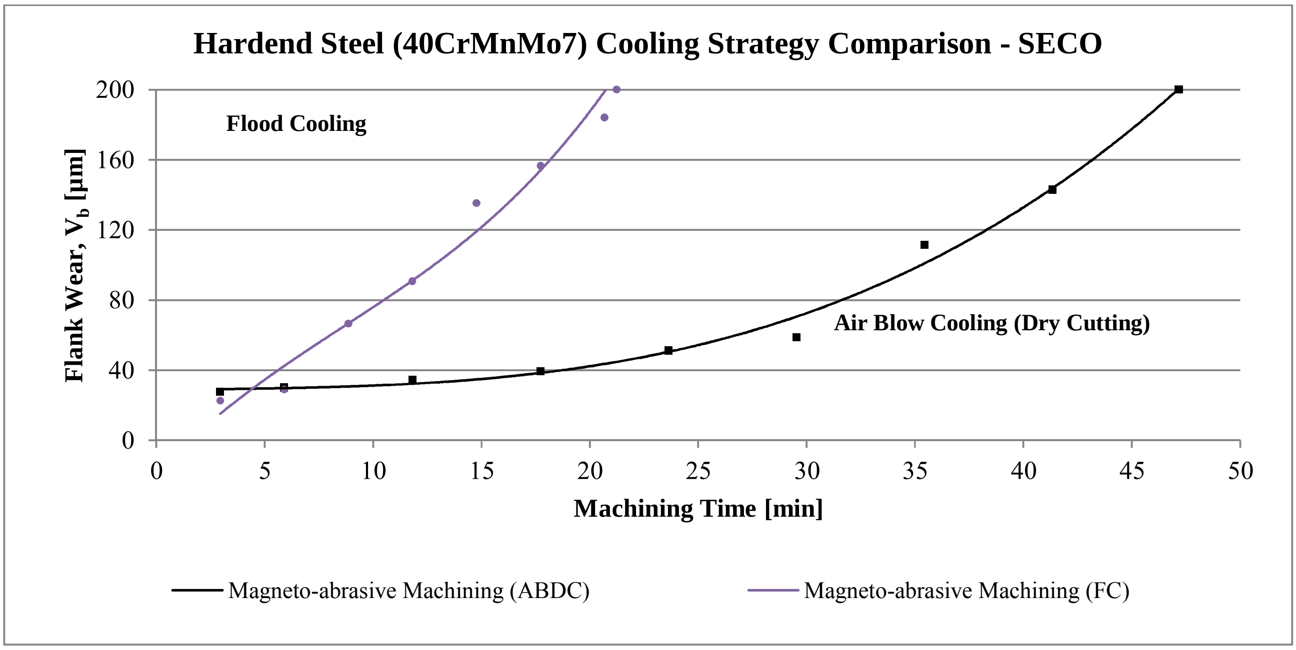


Figure 46: A comparison of the best performing coating treatments under flood cooling and air blow cooling (dry cutting), machining 40CrMnMo7 with SECO inserts

5.3.2 Performance of the Mitsubishi BAP3500 HPTSC strategies and techniques

On the commencement of the Mitsubishi tool holder experiments, catastrophic tool failure occurred when machining hardened steel under flood cooling conditions. Therefore, a re-evaluation of the cutting parameters is required. The recommended cutting parameters in the Mitsubishi technical guide were used as a starting point for the re-evaluation, in order to determine the cutting parameters that would best suit the cutter body as well as the material machined. These cutting parameters are indicated in Table 19 (A). It should be noted that the a_p and a_e are kept the same as that given inTable 10. However, the v_c and f_z are changed to the recommended cutting parameters for the Mitsubishi tool holder. Firstly, the recommended cutting parameters where investigated followed by an exploration of an increase in v_c.

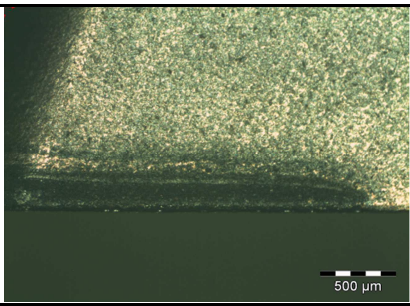
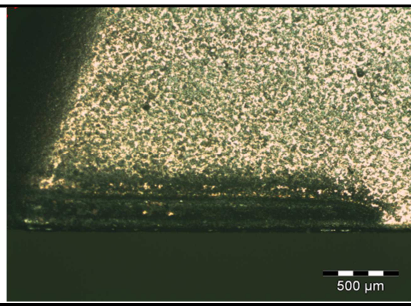
Table 19: Experimental parameter re-evaluation for machining 40CrMnMo7 with the Ø25 mm Mitsubishi tool holder under flood cooling benchmark

Hardened Steel (40CrMnMo7)				
Experiment	**Cutting Parameters**			
	Cutting speed v_c (m/min)	**Feed per tooth f_z (mm/z)**	**Axial depth of cut a_p (mm)**	**Radial depth of cut a_e (mm)**
(A)	100	0.15	3	4.7
(B)	150	0.15	3	4.7

Since the purpose of the HPTSC and focused HPTSC modification techniques is to determine the influence of the cooling on tool life and temperature removal capability, the revision of the preceding parameters increase the v_c to 150 m/min and maintains the f_z at 0.15 mm/z, as indicated in Table 19 (B). This is due to the v_c increasing the thermal demand in the cutting zone, whereas the f_z increases the mechanical loading.

There is evidence of plastic deformation on the cutting edge of the insert, as well as oxidation of the coating layer under both re-evaluation parameters. The results of the re-evaluation are given inTable 20. At the recommended cutting speeds (A and B) and lower feed rate, the insert experiences the fluctuating heat loading for shorter periods, reducing the effect of plastic deformation and maintaining the cutting edge. Due to the inherent lower thermal conductivity of the thermal barrier, under flood cooling, the removal of heat is limited to the vapour conductivity. Therefore, the application of the HPTSC and focused HPTSC modification techniques becomes a viable option to reduce the tendency of the formation of this thermal barrier. In order to prevent any further catastrophic tool failure, the cutting parameters (B) in Table 19 were selected for further experimentation.

Table 20: Tool wear and machining time evaluation for the experimental parameter re-evaluation under flood cooling, machining 40CrMnMo7 using Mitsubishi inserts

A	B
	
(V_c = 100 m/min)	(V_c = 150 m/min)
Machining time : 37.2 min	

In the following experiments, a different approach was taken due to the requirement of change in cutting conditions. The tool wear (µm) in the following experiments is used to give indication of the performance of the cooling strategies and techniques. The high material removal parameters, limited amount of material and recommended machining time of 30 min used in industry, along with the average machining time to complete a single pass in each experiment, where reason for the designated machining time of 37.2 min. All experiments ceased hereafter, with the tool wear determining the outcome of the experiments. The tool wear of the following experiments are displayed in Table 21 using the cutting parameter given in Table 19 (B).

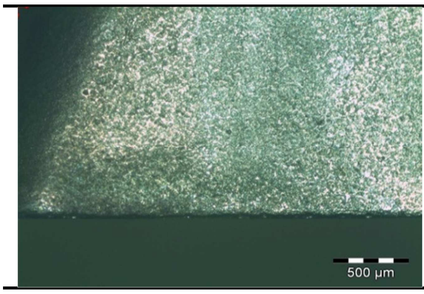
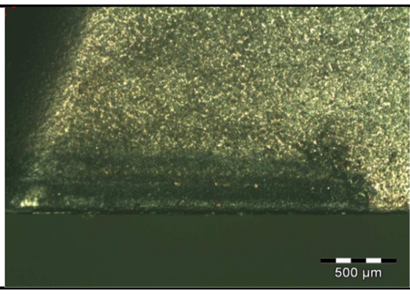
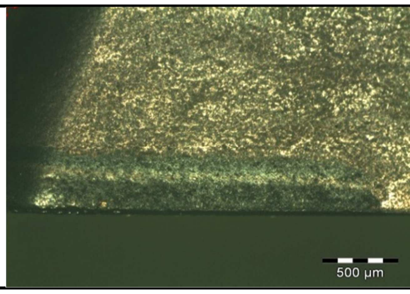
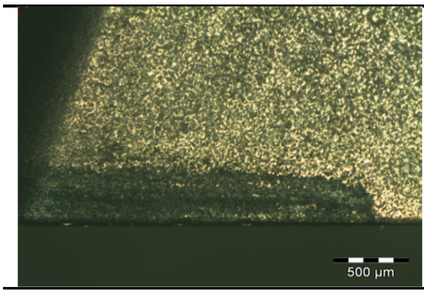
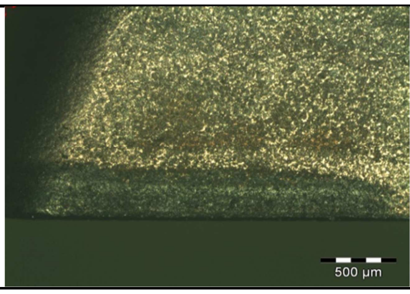
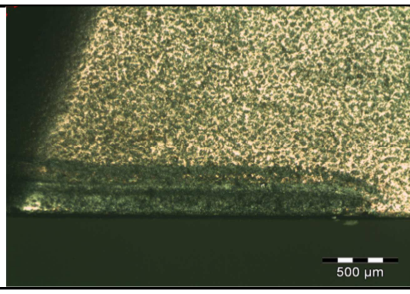
Table 21: Effect of various cooling strategies and techniques on tool wear during HPM 40CrMnMo7 using Mitsubishi inserts after 37.2 minutes machining time

Material	Cooling strategies and techniques					
	ABDC	FC	MI	MII	MIII	MIV
	Tool wear (µm)					
40CrMnMo7	63	84	73.92	64.68	73.92	66.34

Air blow cooling (dry cutting) : ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

From Table 21, it is evident that dry cutting has the lowest wear formation with flood cooling causing accelerated tool wear. It is notable that the HPTSC strategy reduces the tool wear in comparison to flood cooling and the focused HPTSC modifications equalling or further improving on the tool wear. The tool wear depiction for each cooling strategy and technique is given in Table 22 for the selected machining time. Plastic deformation and oxidation is present throughout the experiments where cutting fluid is applied, slightly increasing the tool wear and deteriorating the effect of the coating. These results show promise for dry cutting of hardened steel under the presented cutting conditions.

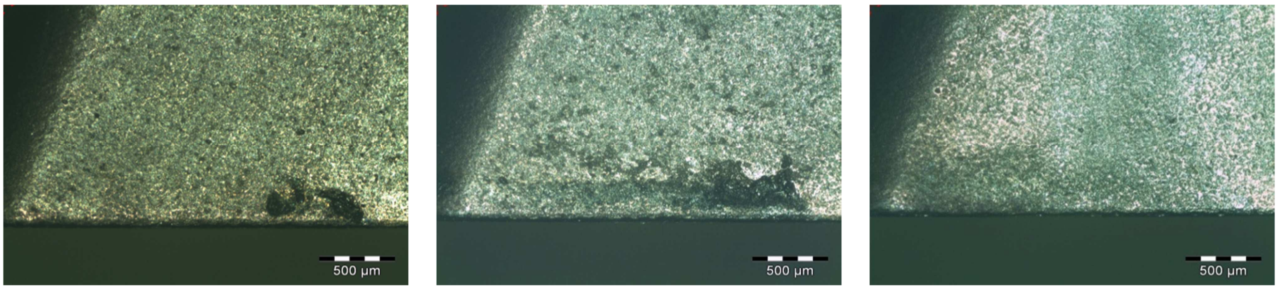
Table 22: Tool wear and tool life under the various cooling strategies and modification techniques, machining 40CrMnMo7 with Mitsubishi inserts

ABDC	**FC**	**MI**
		
	Machining time : 37.2 min	
MII	**MIII**	**MIV**
		
	Machining time : 37.2 min	

Air blow cooling (dry cutting) : ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

Dry cutting machining demonstrates favourable tool wear performance, which can be attributed to the reduction of the influence of fluctuating thermal demands maintaining a more stable temperature across the cutting edge of the insert. The temperature generated at the cutting surface may also softens the work material and reduces the cutting forces sustained, while the coating takes up the demand of the temperature, protecting the substrate from the harsh conditions generated.

The progression of the tool wear after 5 min indicates that there is an initial wear formation on the cutting edge, with slight formations of oxidation, as indicated in Figure 47. The formation of this oxidation seemingly increases up until a machining time of 22.3 min before becoming indistinct at 37.2 min machining time. An explanation for this could be due to the slight rounding of the cutting edge after the initial plastic deformation. This distortion reduces the cutting temperature experienced on the cutting edge and therefore decreases the oxidation reaction on the flank face. A graphical representation of the performance of the cooling strategies is shown in Figure 48.



Wear after 5.0 min **Wear after 22.3 min** **Wear after 37.2 min**

Figure 47: Wear scar progression under air blow cooling (dry cutting) conditions, machining 40CrMnMo7 with the Mitsubishi tool holder

What is notable from Figure 48 is that the MII cooling technique has a similar performance to dry cutting. Although the MIV technique wear bandwidth after 37.2 min machining time is similar to the MII technique, the wear trend fluctuates considerably and shows an increase in wear rate towards 37.2 min. It is therefore evident that a combination of the MII and MIII techniques is counter-intuitive and the application of the MII technique favoured under the given cutting parameters. A detailed representation of each cooling strategy and –technique on coated Mitsubishi inserts machining hardened steel are given in Appendix H1.

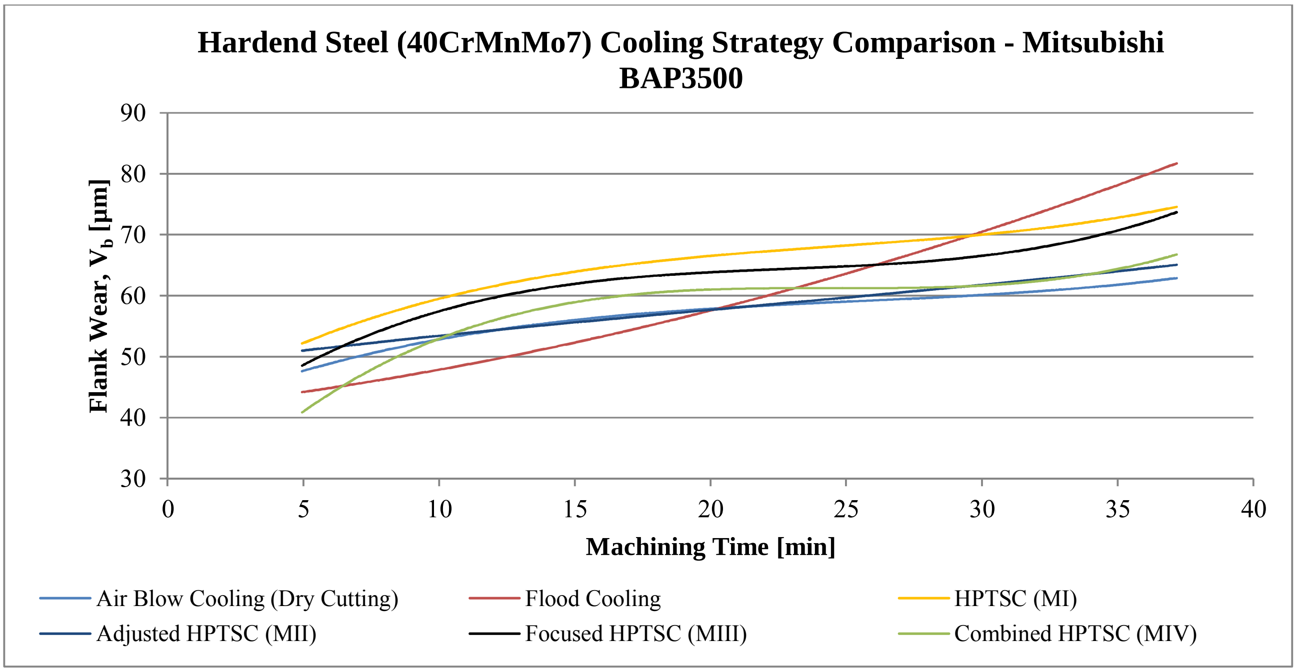


Figure 48: The tool life comparison of air blow cooling (dry cutting), flood cooling, HPTSC and focused HPTSC modifications, machining 40CrMnMo7 with Mitsubishi inserts

5.4 Conclusive remarks

Throughout the hardened steel and titanium experiments' using the SECO and Mitsubishi inserts, it was evident that air blow cooling (dry cutting) yields the best tool life when compared to the flood cooling benchmark. The temperature capability of the coating and coating treatments accommodated the thermal demands of the milling process. This reduced the formation of thermal fatigue, plastic deformation and oxidation, maintaining the cutting edge of the inserts. Therefore, allowing the insert to take up the mechanical load, uninfluenced by temperature, and increasing the tool life/machining time.

Whereas, in the application of cooling fluid, the cutting inserts were subjected to thermal shock loading due to the sudden cooling and heating at the entry and exit of cutting insert. The thermal load resulted in the formation of plastic deformation, oxidation and thermal cracking, causing sections of the cutting edge to break away exposing the substrate of the insert. Along with the interrupted cutting process; the formation of increased mechanical loading caused chipping of the cutting edge and delamination of the coating, thus resulting in reduced tool life/machining time.

6. Conclusion and Recommendations

6.1 Conclusion

The need to save space and reduce weight, along with the requirement for efficiency, have led aerospace and automotive industries to machine integral parts made of lightweight materials, in some cases replacing existing materials such as hardened steel, under high performance machining (HPM) conditions. Thus, the research questions in this work cover the HPM of titanium and hardened steel, with an emphasis on Ti6Al4V alloy and hardened steel 40CrMnMo7.

Cooling strategies and techniques potentially improve the machining process and tool life of the inserts by removing the heat generated in the cutting zone. The cooling strategies and techniques were evaluated according to their ability to transfer heat, heat removal, chip removal, lubrication as well aseconomic and environmental friendliness. Flood cooling, air blow cooling (dry cutting) and HPTSC have favourable attributes under these categories and were the selected cooling strategies and techniques.

The determination of a suitable cutting tool material, coating and coating treatment were investigated. Cemented tungsten carbide inserts have favourable resistance to mechanical loading, complimentary during interrupted machining, due to its high fracture toughness and transverse rupture strength in addition to its moderate stiffness. Coated carbides have an improved resistance to intermittent thermal loading, due to advancements in coating technology, where TiAlN is the favoured coating in industry. Therefore, due to the resistance to mechanical failure and thermal loading, along with its availability, TiAlN coated tungsten carbide inserts were used in the experiments.

Since HPTSC has the potential to impinge the cutting zone, reduce temperature and improve the chip removal, HPTSC modifications were designed on an existing tool holder to possibly increase the aforementioned characteristics by focused cooling. The focused HPTSC modification techniques used in the study were developed to investigate the potential of the focused cooling technique to remove heat from the cutting zone, minimising the effect of thermal and mechanical loading.

There are technologically advanced cutting fluids and lubricants on the market designed for isolated machining applications. They could give entirely different results. The coolant emulsion used in this study is Rocol ULTRACUT EVO 260 high performance cutting fluid, which is designed for a wide range of cutting conditions and includes the machining of titanium and hardened steel. The cooling strategies and techniques, as well as coating treatments, are evaluated using the tool life as the determining factor of performance. Therefore, experiments were set up in order to examine the effects of various coating treatments on TiAlN coated carbide inserts under flood cooling, air blow cooling (dry cutting), HPTSC and focused HPTSC modification conditions. The cutting parameters where set following a collaborative project and international standards, with the goal of obtaining results that are comparative to current published research. From the results presented in this study, the following was determined for each cooling strategy and technique:

Flood cooling

- When machining titanium and hardened steel, the cutting tools experienced adhesion and abrasive wear in the form of attrition. This promotes the formation of oxidation due to the creation of new surfaces during the wear process, reducing the tool life.
- Thermal fatigue was prominent over the entire cutting edge of the tool, causing sections to break away as well as aggravating delamination of the coating layers. This exposed the cemented carbide substrate to the mechanical and thermal loading, often resulting in chipping and catastrophic tool failure.

Air blow cooling (dry cutting)

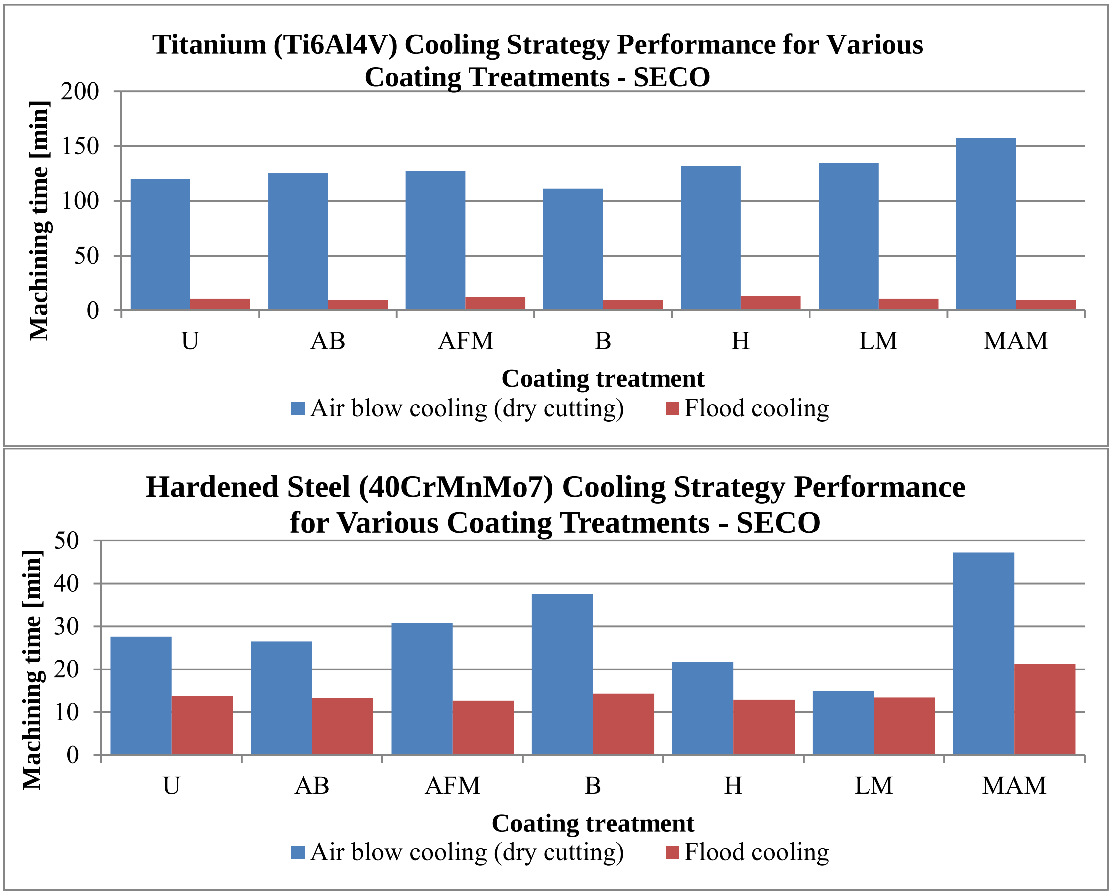
- The temperature experienced in the cutting zone makes the deformation and shearing of the chip easier and does not harm the tool. This is attributed to the coating resisting the effect of high temperature.
- There is evidence of thermal fatigue at later stages of machining time, which induced the chipping and hammering effect on the cutting edge of the insert. The reduced thermal fatigue is again attributed to the coating taking up the majority of the thermal loading.
- The wear is more predictable under the given cutting parameters for dry cutting conditions.

HPTSC and the focused HPTSC modification

- HPTSC produces an increased tool life trend when machining hardened steel under the re-evaluated cutting parameters, when compared to flood cooling. The adjusted HPTSC technique (MII) yielded the least tool wear after 37.2 min. The reduced tool wear is attributed to the techniques ability to remove heat and chips from the cutting zone. In all the HPTSC strategies and techniques, thermal loading was evident on the cutting edge.
- In the titanium experiments, the focused HPTSC modifications proved disadvantageous, shown by the reduced tool life in comparison to flood cooling. This is attributed to the increased heat removal of the focused HPTSC modification in all the experiments presented. The higher cooling capability of the technique contributed to the workpiece being work hardened and increasing the mechanical loading on the cutting tool, evident due to the formation of chipping on the flank face.

- The increased penetration of the cutting fluid in the cutting zone helped the removal of chips from the cutting zone, thereby reducing the chip contact. This proved unfavourable, since the low thermal conductivity of the titanium chips causes a focused heat load on the cutting tool tip. Thus, the reduced contact length means the temperatures are concentrated closer to the cutting edge, increasing the temperature and flank wear, which in turn causes a reduction of tool life.

When evaluating the machining of titanium and hardened steel with SECO inserts, using the various coating treatments under flood cooling and air blow (dry cutting), it was observed that the tool life under dry cutting outperforms that of flood cooling in both cases, represented in Figure 49. The coating treatment that performed best is magneto-abrasive machining (MAM), with a tool life of 157.3 min, when machining titanium (Ti6Al4V) and again MAM, with a tool life of 47.2 min, for hardened steel (40CrMnMo7).

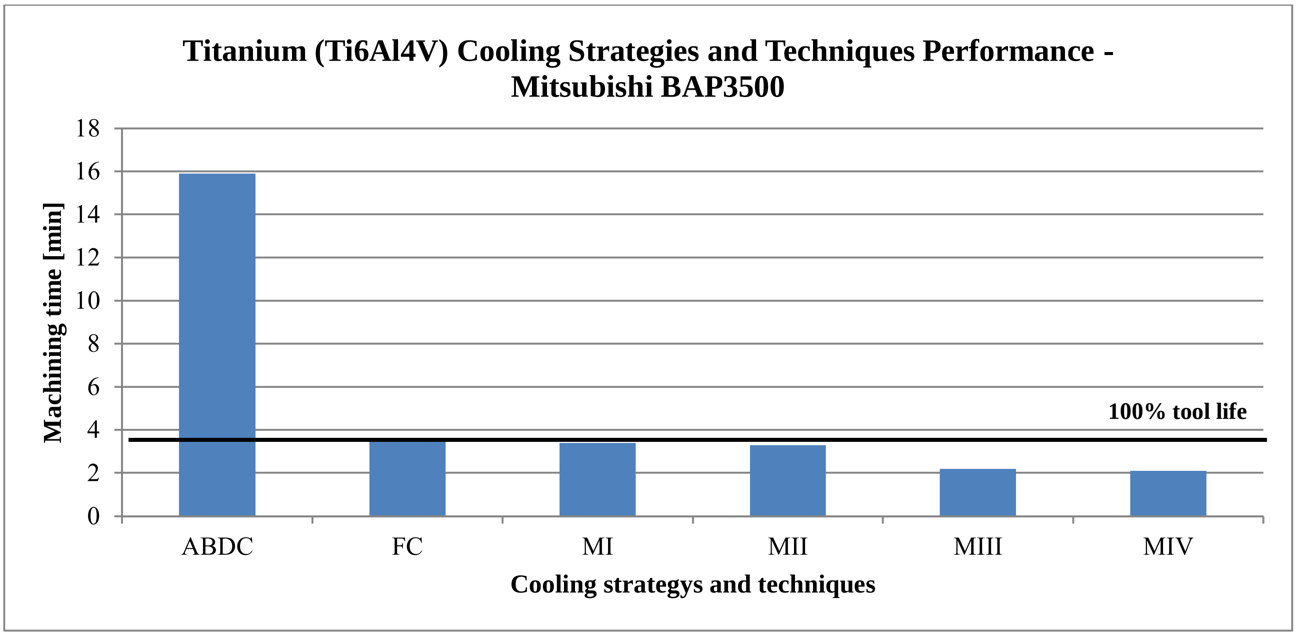


Untreated : U; Abrasive blasting : AB; Abrasive flow machining : AFM; Brushing : B; Honing : H; Laser machining : LM; Magneto-abrasive machining : MAM

Figure 49: Cooling strategy performance under various coating treatments, machining Ti6Al4V and 40CrMnMo7 with SECO inserts

Therefore, from the aforementioned results, when machining titanium and hardened steel with SECO inserts, the suggested coating is TiAlN with a coating treatment of MAM, applied under dry cutting conditions.

When evaluating the performance of the cooling strategies and techniques for machining titanium with Mitsubishi inserts, dry cutting improved tool life above 400 % compared to flood cooling, as indicated in Figure 50. The modified HPTSC techniques increased the cooling capability. However, this produced an adverse effect causing the tool life to be between 3 – 40 % less than that of flood cooling.

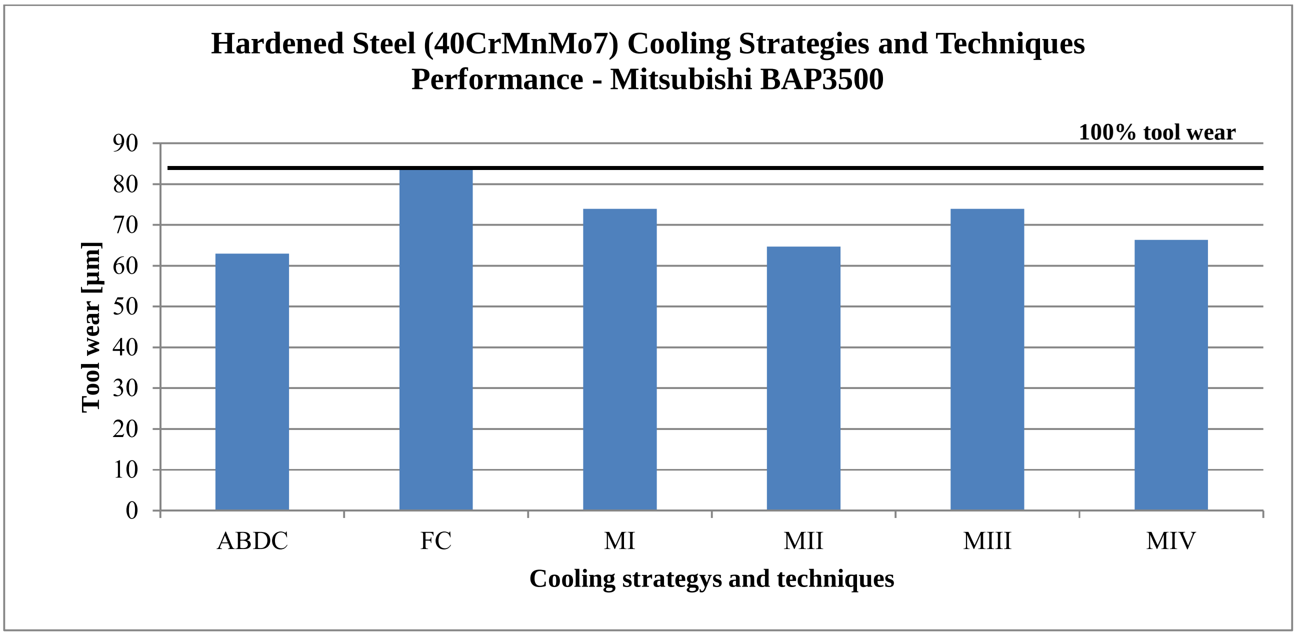


Air blow cooling (dry cutting) :ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

Figure 50: Performance of various cooling strategies and techniques, machining Ti6Al4V with Mitsubishi inserts

Thus, the suggested cooling strategy when machining titanium with coated Mitsubishi inserts is dry cutting, for the experimental parameters given in this study. The HPTSC techniques did not improve on the tool life as intended in this investigation. Yet, the increased thermal loading on the cutting edge shows supporting evidence that the HPTSC techniques impinge the cutting zone and increase the heat removal capability.

On the other hand, when comparing the performance of the modified HPTSC techniques to flood cooling and dry cutting for machining of hardened steel with Mitsubishi inserts, the HPTSC technique increased the potential to improve the tool life. It should be noted that the cutting parameters for these experiments where re-evaluated with reference to the recommended cutting parameters of the Mitsubishi catalogue, after the initial experiments caused the cutting tool to fail catastrophically. The cutting speed v_c was increased and the feed rate f_z was decreased but the depth of cut a_p and radial immersion a_e kept constant. The evaluation of the cooling strategies and techniques changed to the tool wear after a tool life of 37.2 min tool life. The tool wear improved under dry cutting as well as the HPTSC techniques. Dry cutting decreased the tool wear by 25 % where the HPTSC techniques decreased the tool wear between 18 – 23 % that of flood cooling, as indicated in Figure 51.



Air blow cooling (dry cutting) :ABDC; Flood cooling : FC; HPTSC (MI) : MI; Adjusted HPTSC (MII) : MII; Focused HPTSC (MIII) : MIII; Combined HPTSC (MIV) : MIV

Figure 51: Performance of various cooling strategies and techniques, machining 40CrMnMo7 with Mitsubishi inserts

From this, dry cutting offers the best potential to improve the tool life due to the reduced tool wear after 37.2 min machining time. The HPTSC techniques also offer an improvement in tool life potential. When comparing the focused HPTSC technique (MII) and the combined HPTSC technique (MIV), a combination of the adjusted HPTSC technique (MII) and focused HPTSC technique (MIII), the MIV technique experienced an increase in tool wear. This indicates that the MIII technique has an adverse effect on the performance of the MIV techniques potential to reduce tool wear, as illustrated in Figure 51. During the re-evaluation of the cutting parameters, the increased cutting speed had little effect on the tool wear. This indicates that the cutting tool coating took up a large portion of the heat in the cutting zone. This suggests that the initial failure occurred mainly due to mechanical loading and that the feed rate has a larger influence on tool wear, when machining hardened steel.

In conclusion, it is determined that under the given cutting parameters and experimental setup, the cooling technique of air blow cooling (dry cutting) has the potential to improve the tool life during the HPM of titanium and hardened steel. The trend to more environmentally friendly machining conditions encourages the reduced use of cooling fluids and harsh chemicals, lending to dry cutting creating a machining process that is environmentally friendly and cost efficient. It is important to select the correct cutting tool material, cutting tool coating, coating treatment and cutting parameters. For the cutting parameters presented in this study, the suggested coating is TiAlN with MAM coating treatment.

The HPTSC techniques did not improve upon the tool life but gives indication of their increased potential to remove the heat as well as the chips from the cutting zone and penetrate the thermal boundary layer. This increased potential, however, proved to be detrimental in the machining of titanium due to an increased thermal loading, which intensifies during the interrupted milling process. These techniques, however, show potential to increase the tool life when machining hardened steel 40CrMnMo7 under HPM.

The outcomes of the study provide useful machining guidelines for manufacturing industries. It aids them in the selection of optimal combinations of cutting parameters, cooling strategies or –techniques, coating and coating treatment, for the best tool life performance.

6.2 Recommendations

Based on the aforementioned results and discussions, further studies into the following research avenues are recommended:

- Investigate an optimised flow rate of the air blow cooling (dry cutting) and its impact on tool wear and surface quality. Closer attention should be paid to the mechanisms of tool failure and the impact on the coating and coating treatment as well as the effect the temperature increase has on the microstructure of the workpiece. From the results of this study, the suggested coating of the inserts should be TiAlN and a MAM coating treatment system applied for machining titanium and hardened steel.
- Investigate the impact of the focused HPTSC techniques under varying pressure and nozzle diameter during HPM of 40CrMnMo7.
- Focus the investigation on the potential of the HPTSC techniques to improve the tool life when machining 40CrMnMo7 under different cutting parameters, varying the feed rate and cutting speeds. A suggested starting point would be at a v_c of 150 m/min and a f_z of 0.2 mm/z.
- Investigate the impact of different cooling liquids on the machinability of Ti6Al4V

- Model the cost of implementing a HPTSC technique into an existing system.
- Further investigation on effect of different flow patterns onto the cutting interface.
- Investigate the effects of cooling the air-stream, with the possible introduction of liquid nitrogen.

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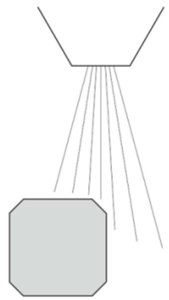
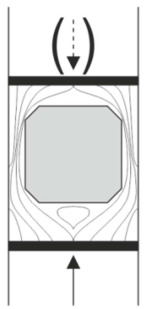
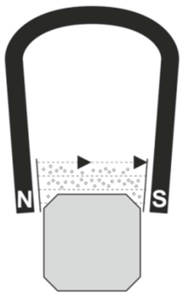
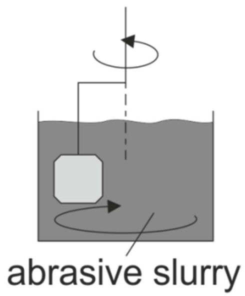
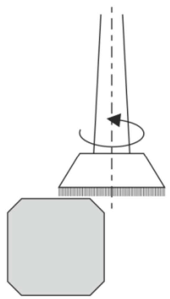
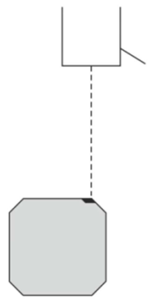
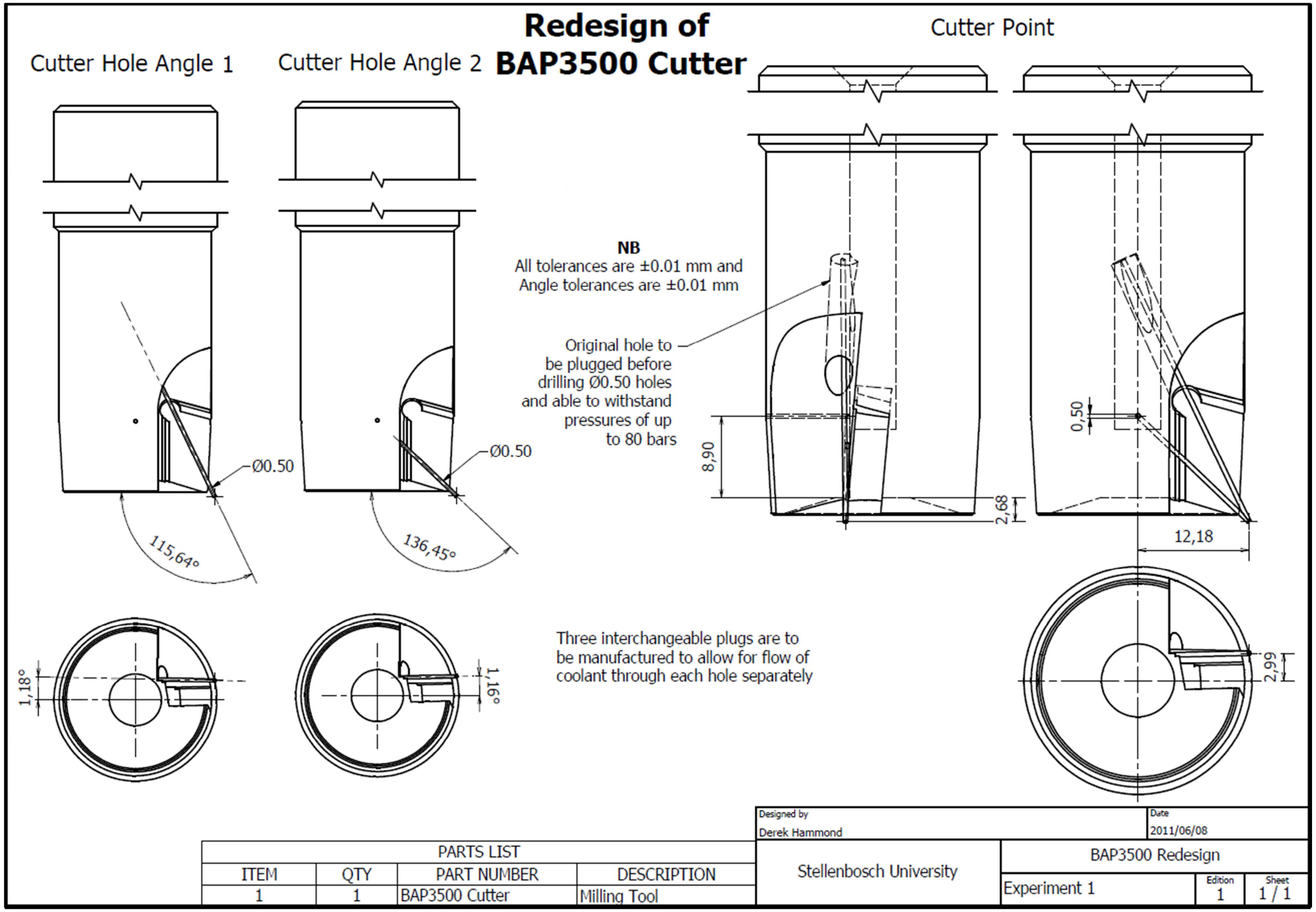
A. APPENDIX A: Characteristics of the employed cutting edge treatment methods [71]

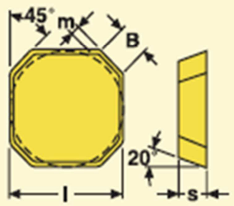
Moving particles			**Moving parts**	**Tool**	**Energy**
					
Abrasive blasting AB	Abrasive flow machining AFM	Magneto-abrasive machining MAM	Abrasive slurry AS	Brushing B	Laser machining LM

B. **APPENDIX B: Redesign of the Mitsubishi BAP3500 indexable milling cutter**



C. **APPENDIX C1: SECO SEAN 1203AFTN-M14 square insert specifications [72]**

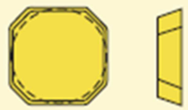
SEAN..



Tolerances (± mm)

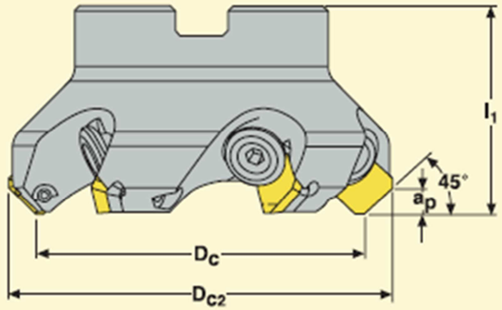
	l	s	m
SEAN	0,025	0,025	0,007

Size	Dimensions in mm: l	s
1203	12,7	3,18
1303	13,44	3,36
1604	16,8	4,79

Inserts	Part No.		B	Cutting rake	Prot. chamfer		Grades: Coated											Uncoated							Cermet
					Width mm	Angle	T150M	T200M	T25M	T250M	T350M	F15M	F17M	F20M	F25M	F30M	F40M	S10M	S25M	S60M	HX	H15	H25	C15M
	SEAN	1203AFN-E12	1,6	0°	–	–										■					■			
		1203AFTN-M14	1,6	0°	0,07	20°			■		■						■				■			■
	SEAN	1303AFN-E12	3,5	0°	–	–															■			
		1303AFTN-M14	3,5	0°	0,07	20°					■										■			
		1303AFTN-M15	3,5	0°	0,12	20°	■																	
		1303AFTN-MD15	3,5	0°	0,18	30°																		■
	SEAN	1604AFN-E15	4,1	0°	–	–															■			
		1604AFTN-M18	4,1	0°	0,09	20°					■													
		1604AFTN-M19	4,1	0°	0,12	20°	■																	

C. APPENDIX C2: SECO 220.13-12-0050-12 Ø50 mm milling tool holder [72]

220.13-12 SECO



Tool angles: $\gamma o = +12°$
$\gamma p = +20°$
$\gamma f = -3°$

Pitch	Part No.	Dimensions in mm D_c	D_{c2}	l_1	a_p*		KG		
Normal									
	R220.13 -0040-12	40	54	45	6	3	0,4	10700	SE..1203/1303
	-0050-12	50	64	48	6	4	0,6	9600	SE..1203/1303
	-0063-12	63	77	40	6	5	0,6	8500	SE..1203/1303
	-0080-12	80	94	50	6	6	1,0	7600	SE..1203/1303
	-0100-12	100	114	50	6	6	1,6	6800	SE..1203/1303
	-0125-12	125	139	63	6	7	2,8	6000	SE..1203/1303
	-8160-12	160	174	63	6	7	5,0	5300	SE..1203/1303

* With 13 mm long cutting edge, a_p = 5 mm.

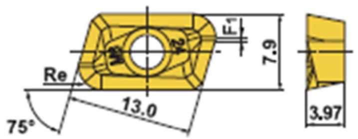
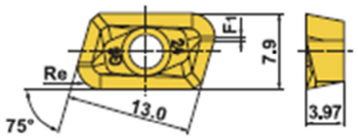
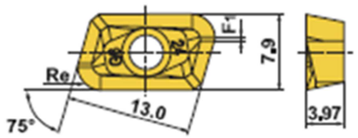
D. **APPENDIX D1: Mitsubishi XPMT13t3PDER-M2 insert specifications [51]**

INSERTS — MITSUBISHI / MITSUBISHI CARBIDE

Work Material		F7030	VP15TF	HTi10
P	Steel	◐	◐	
M	Stainless Steel	◐	◐	
K	Cast Iron		✱	
N	Non-ferrous Metal			◐
S	Heat-resistant Alloy, Titanium Alloy		◐	
H	Hardened Steel		◐	

Cutting Conditions (Guide) :
● : Stable Cutting ◐ : General Cutting ✱ : Unstable Cutting

Honing :
E : Round F : Sharp

Shape	Order Number	Class	Honing	Coated F7030	Coated VP15TF	Carbide HTi10	Dimensions (mm) F1	Dimensions (mm) Re	Geometry
	XPMT13T3PDER-M1	M	E	●	●		1.6	0.4	
	13T3PDER-M2	M	E	●	●		1.2	0.8	
	13T3PDER-M6	M	E	●	[illegible]		0.4	2.4	
	13T3PDER-M75	M	E	●	[illegible]		0.4	3.0	
	13T3PDER-M8	M	E	●	[illegible]		0.4	3.2	
	XPGT13T3PDER-G1	G	E		●		1.6	0.4	
	13T3PDER-G2	G	E		●		1.2	0.8	
	13T3PDER-G6	G	E		●		0.4	2.4	
	13T3PDER-G75	G	E		●		0.4	3.0	
	13T3PDER-G8	G	E		●		0.4	3.2	
	XPGT13T3PDFR-G1	G	F			●	1.6	0.4	
	13T3PDFR-G2	G	F			●	1.2	0.8	
	13T3PDFR-G6	G	F			●	0.4	2.4	
	13T3PDFR-G75	G	F			●	0.4	3.0	
	13T3PDFR-G8	G	F			●	0.4	3.2	

D. APPENDIX D2: Mitsubishi BAP3500 Ø25 mm indexable milling tool holder [51]

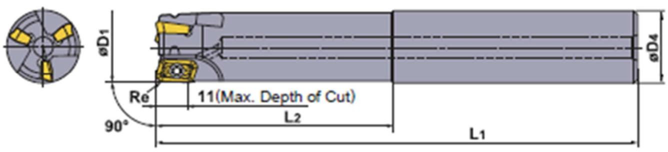
INDEXABLE MILLING — MITSUBISHI / MITSUBISHI CARBIDE

MULTI FUNCTIONAL MILLING 0° Roughing

BAP3500

Light Alloy	Cast Iron	Carbon Steel · Alloy Steel	Stainless Steel	Hardened Steel

- High rake angle.
- Contour machining is possible.
- Through coolant type.

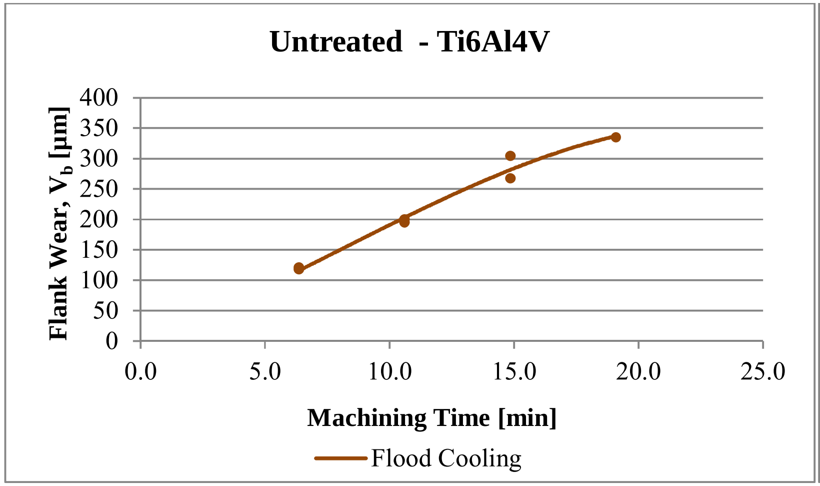


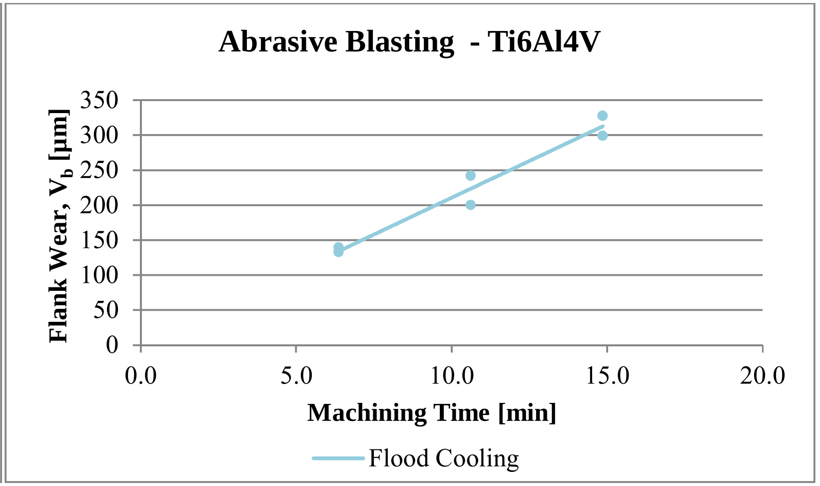
Right hand tool holder only.

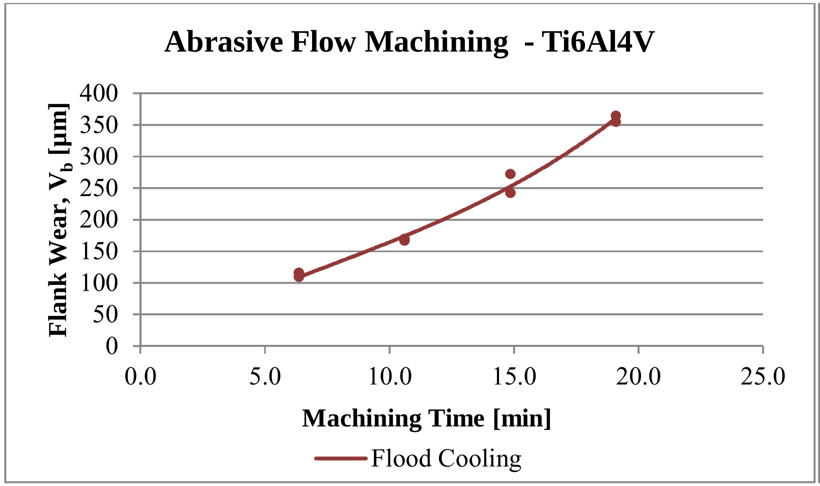
Type	Insert Corner Re	Order Number	Stock R	Coolant Hole	Number of Teeth	D1	L1	L2	D4	Clamp Screw*	Wrench	Insert
BAP3500R○○○○○○○○A	0.4 0.8	BAP3500R161SA16SA	●	○	1	16	100	30	16	TS3	TKY08F	XPMT13T3PDER-M1/M2 XPGT13T3PDER-G1/G2 XPGT13T3PDFR-G1/G2
		161SN16SA	●	–	1	16	100	30	16	TS3	TKY08F	
		202SA20SA	●	○	2	20	110	35	20	TS32	TKY08F	
		202SN20SA	●	–	2	20	110	35	20	TS32	TKY08F	
		253SA25SA	●	○	3	25	120	40	25	TS32	TKY08F	
		253SN25SA	●	–	3	25	120	40	25	TS32	TKY08F	
		324SA32SA	●	○	4	32	130	50	32	TS32	TKY08F	
		324SN32SA	●	–	4	32	130	50	32	TS32	TKY08F	
		405SA32SA	●	○	5	40	170	55	32	TS32	TKY08F	
		405SN32SA	●	–	5	40	170	55	32	TS32	TKY08F	
BAP3500R○○○○○○○○B	2.4 3.0 3.2	161SA16SB	●	○	1	16	100	30	16	TS3	TKY08F	XPMT13T3PDER-M6/M75/M8 XPGT13T3PDER-G6/G75/G8 XPGT13T3PDFR-G6/G75/G8
		161SN16SB	●	–	1	16	100	30	16	TS3	TKY08F	
		202SA20SB	●	○	2	20	110	35	20	TS32	TKY08F	
		202SN20SB	●	–	2	20	110	35	20	TS32	TKY08F	
		253SA25SB	●	○	3	25	120	40	25	TS32	TKY08F	
		253SN25SB	●	–	3	25	120	40	25	TS32	TKY08F	
		324SA32SB	●	○	4	32	130	50	32	TS32	TKY08F	
		324SN32SB	●	–	4	32	130	50	32	TS32	TKY08F	
		405SA32SB	●	○	5	40	170	55	32	TS32	TKY08F	
		405SN32SB	●	–	5	40	170	55	32	TS32	TKY08F	
Long Shank	0.4 0.8	202SA20LA	●	○	2	20	170	80	20	TS32	TKY08F	XPMT13T3PDER-M1/M2 XPGT13T3PDER-G1/G2 XPGT13T3PDFR-G1/G2
		202SN20LA	●	–	2	20	170	80	20	TS32	TKY08F	
		253SA25LA	●	○	3	25	170	80	25	TS32	TKY08F	
		253SN25LA	●	–	3	25	170	80	25	TS32	TKY08F	
		323SA32LA	●	○	3	32	200	90	32	TS32	TKY08F	
		323SN32LA	●	–	3	32	200	90	32	TS32	TKY08F	
		403SA32LA	●	○	3	40	200	90	32	TS32	TKY08F	
		403SN32LA	●	–	3	40	200	90	32	TS32	TKY08F	

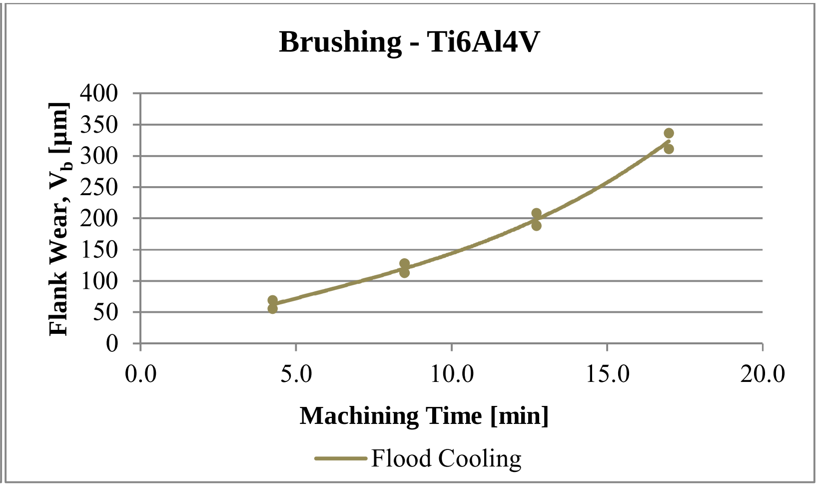
Dimensions (mm)

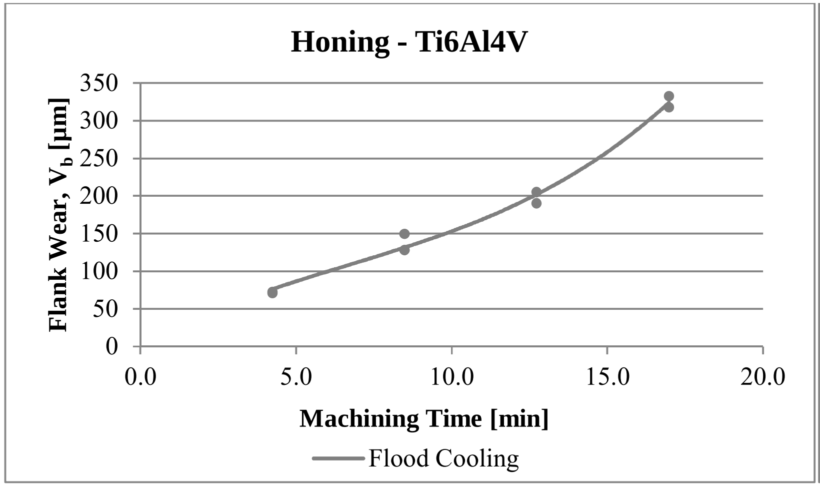
E. **APPENDIX E1: HPMTi6Al4V using various coating treatments on SECO inserts under flood cooling conditions**

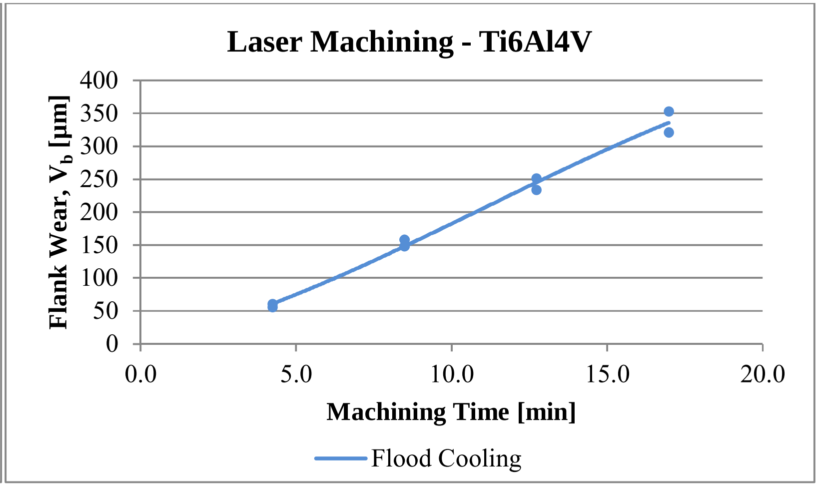


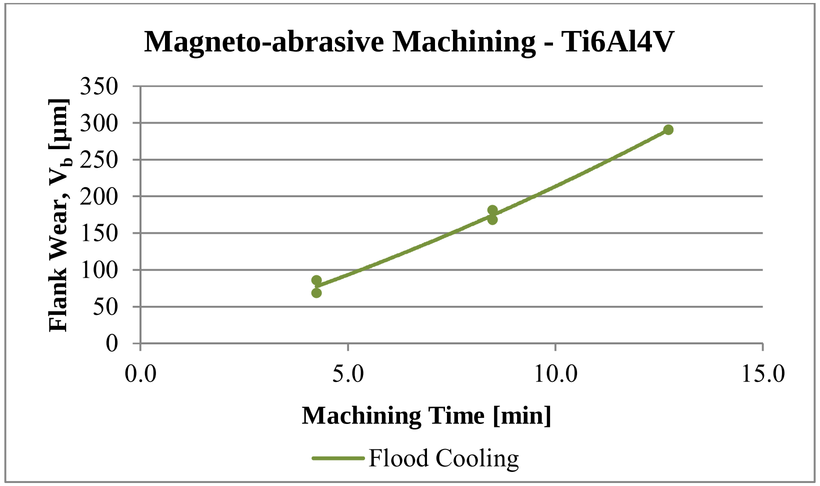




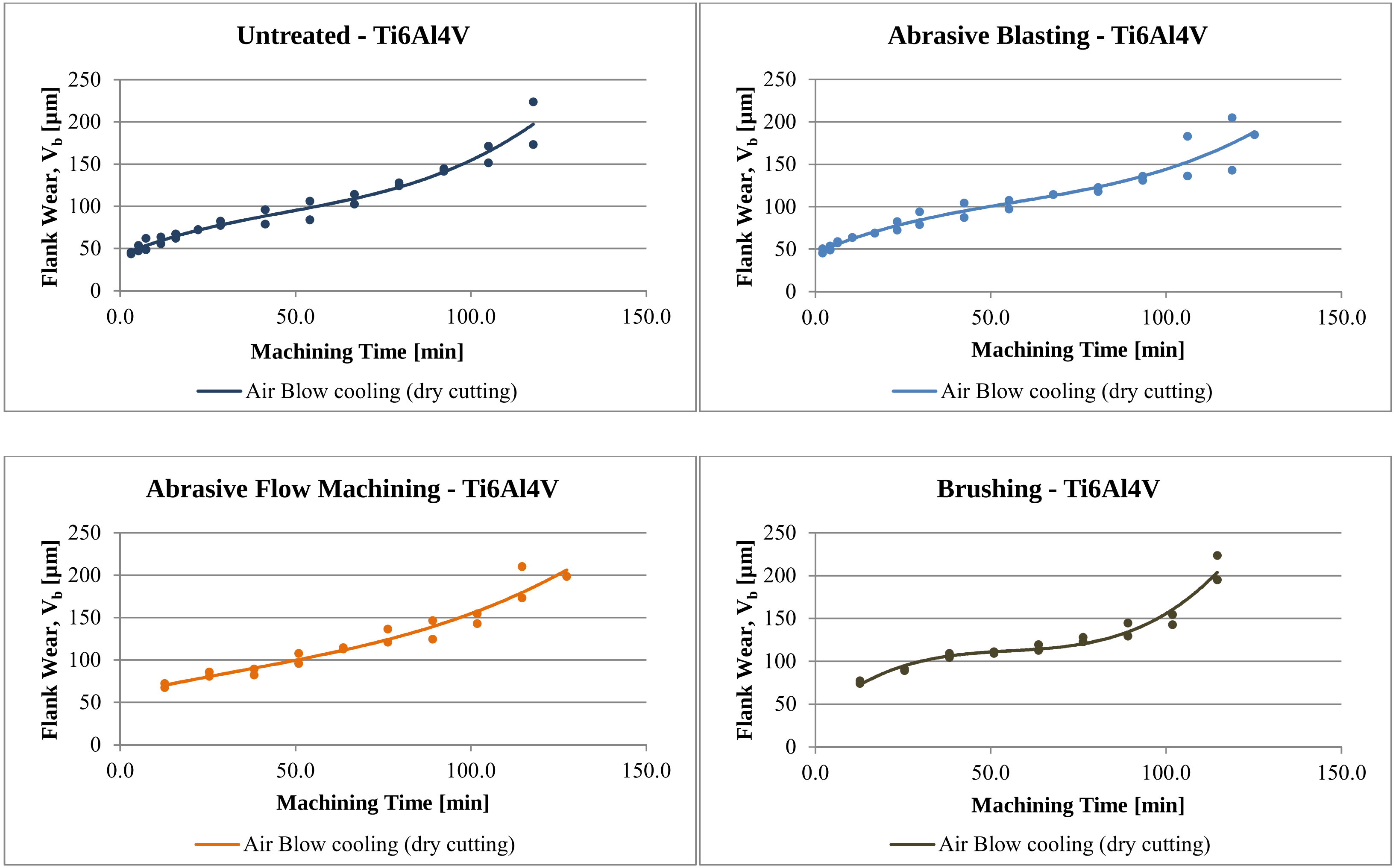


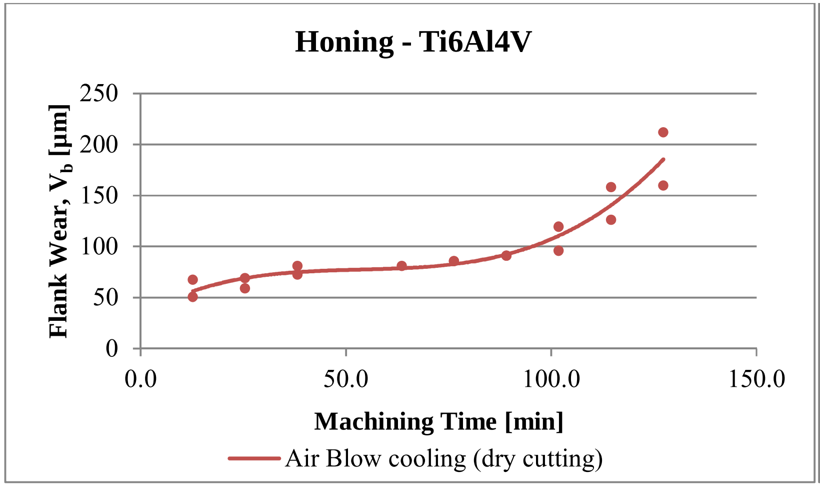

Honing - Ti6Al4V
Flank Wear, V_b [µm]
350
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
Machining Time [min]
Flood Cooling

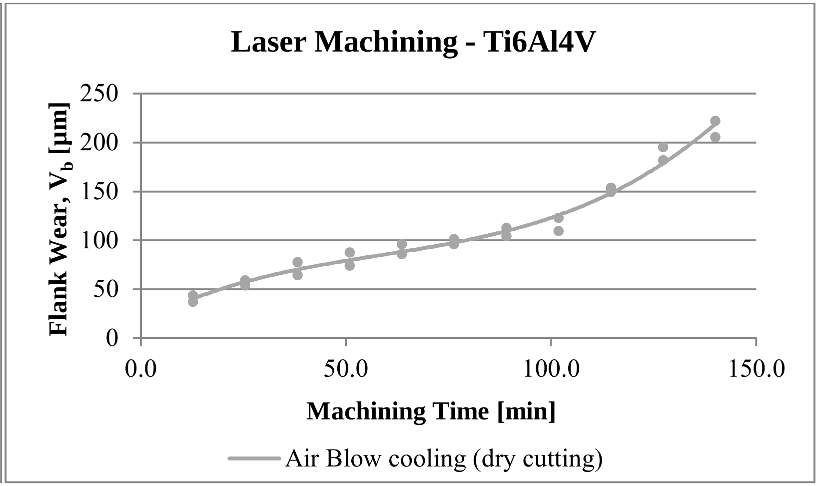

Laser Machining - Ti6Al4V
Flank Wear, V_b [µm]
400
350
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
Machining Time [min]
Flood Cooling

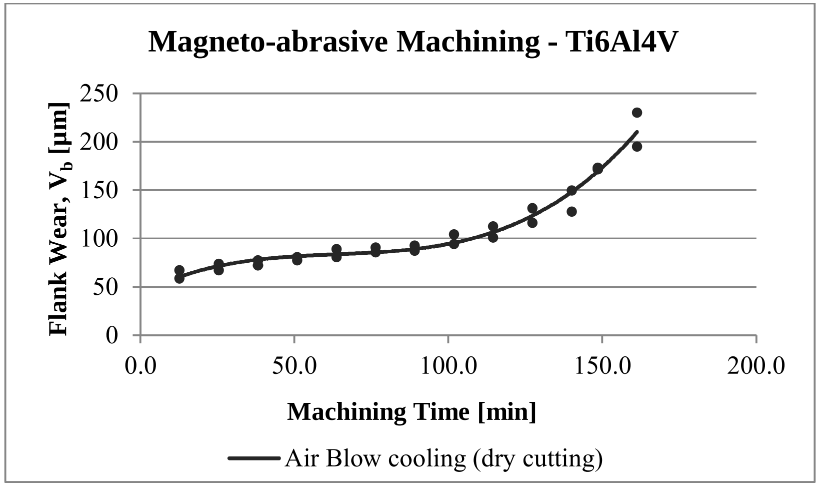

Magneto-abrasive Machining - Ti6Al4V
Flank Wear, V_b [µm]
350
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
Machining Time [min]
Flood Cooling

E. APPENDIX E2: HPM Ti6Al4V using various coating treatments on SECO inserts under air blow cooling (dry cutting)

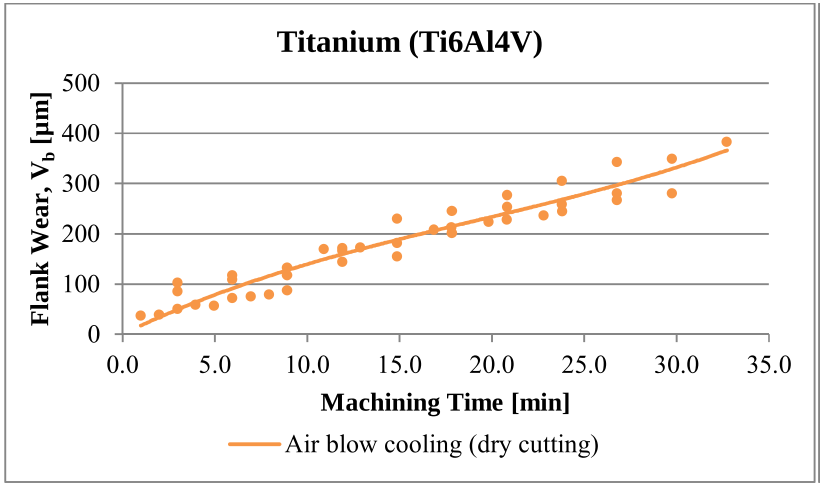


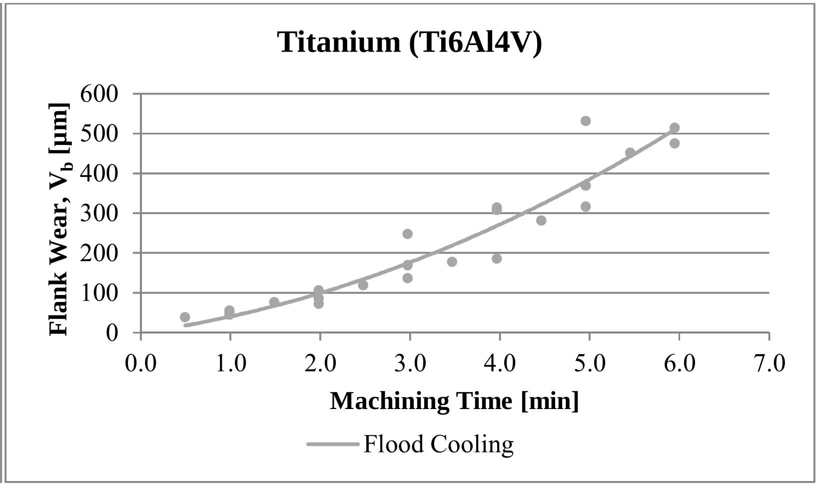

Honing - Ti6Al4V
Flank Wear, V_b [µm]
250
200
150
100
50
0
0.0
50.0
100.0
150.0
Machining Time [min]
Air Blow cooling (dry cutting)

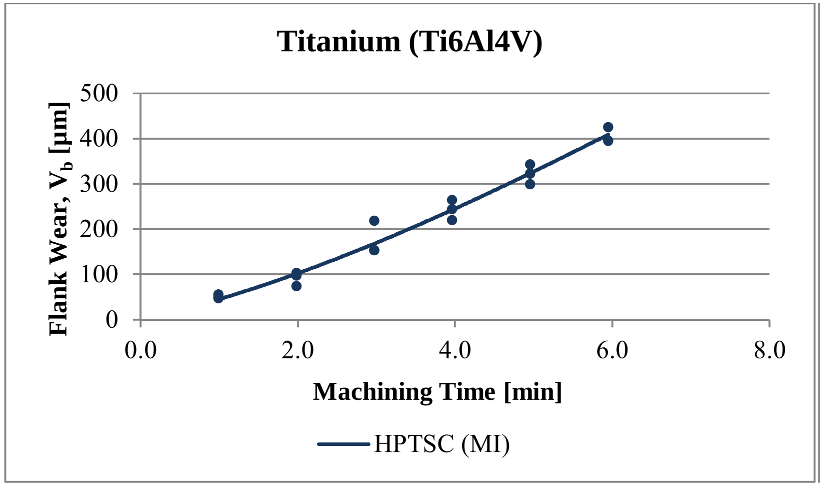

Laser Machining - Ti6Al4V
Flank Wear, V_b [µm]
250
200
150
100
50
0
0.0
50.0
100.0
150.0
Machining Time [min]
Air Blow cooling (dry cutting)

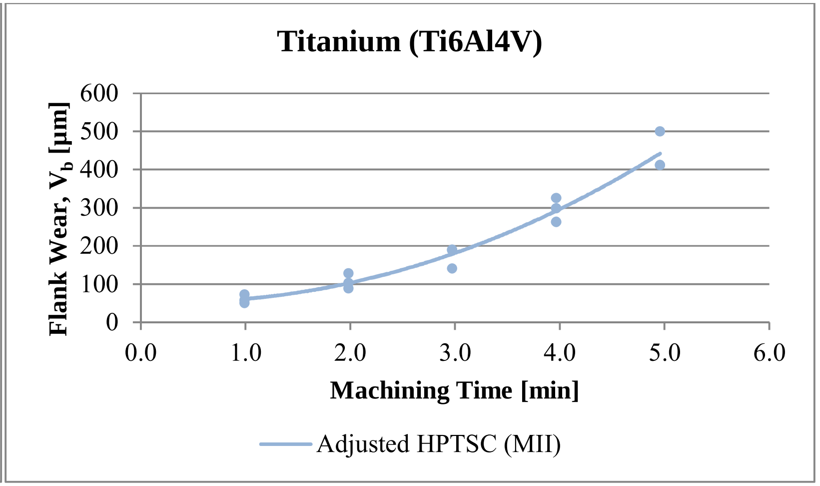

Magneto-abrasive Machining - Ti6Al4V
Flank Wear, V_b [µm]
250
200
150
100
50
0
0.0
50.0
100.0
150.0
200.0
Machining Time [min]
Air Blow cooling (dry cutting)

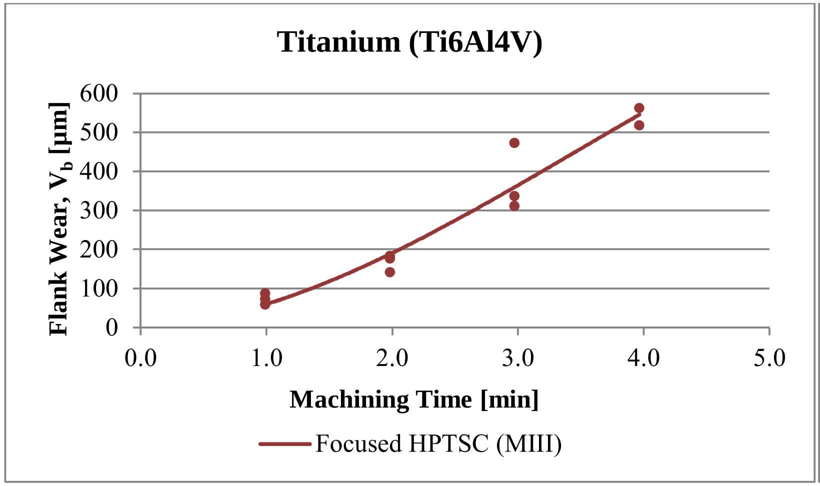
F. **APPENDIX F1: HPM Ti6Al4V using Mitsubishi inserts under the selected cooling strategies and modification techniques**

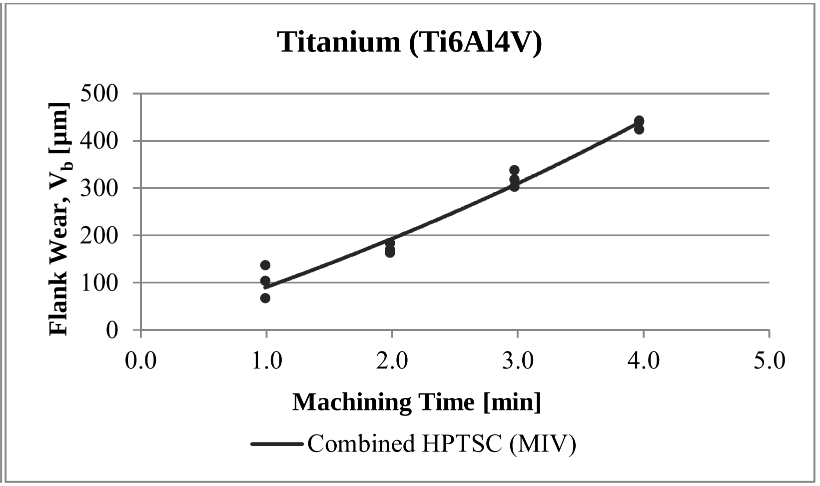




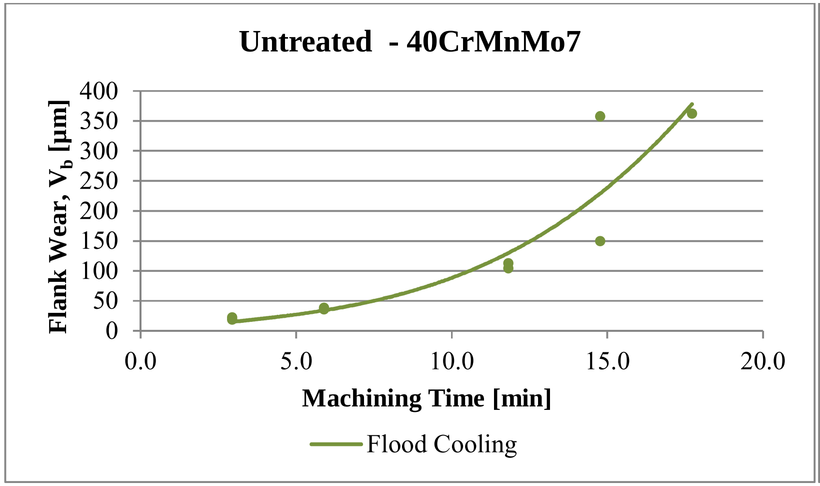


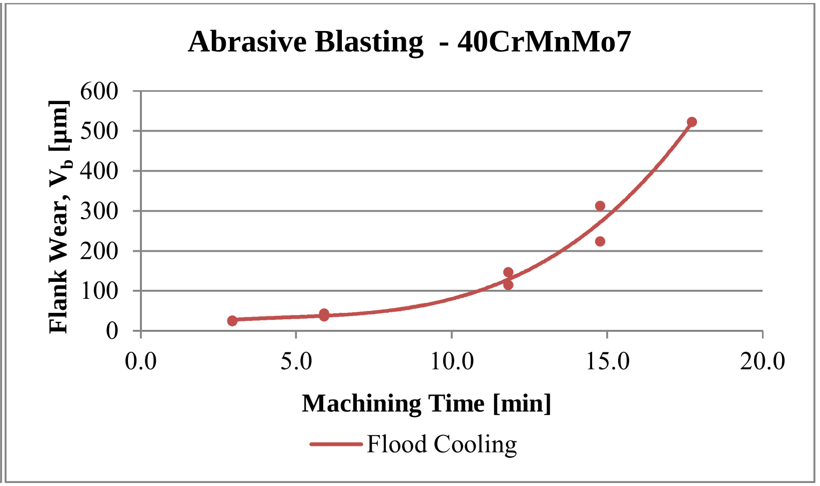


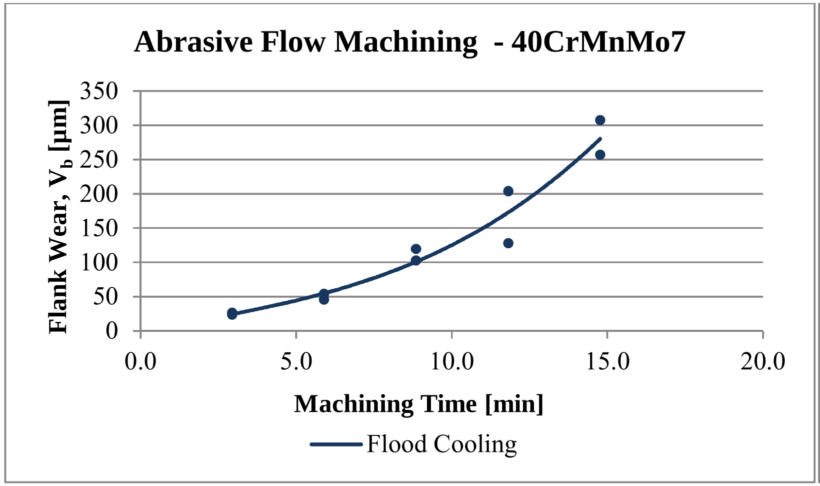

Titanium (Ti6Al4V)
Flank Wear, V_b [µm]
600
500
400
300
200
100
0
0.0
1.0
2.0
3.0
4.0
5.0
Machining Time [min]
Focused HPTSC (MIII)

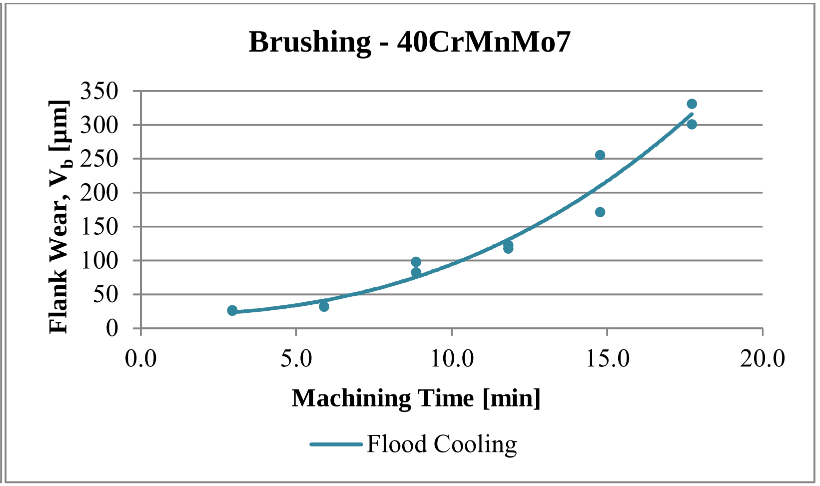

Titanium (Ti6Al4V)
Flank Wear, V_b [µm]
500
400
300
200
100
0
0.0
1.0
2.0
3.0
4.0
5.0
Machining Time [min]
Combined HPTSC (MIV)

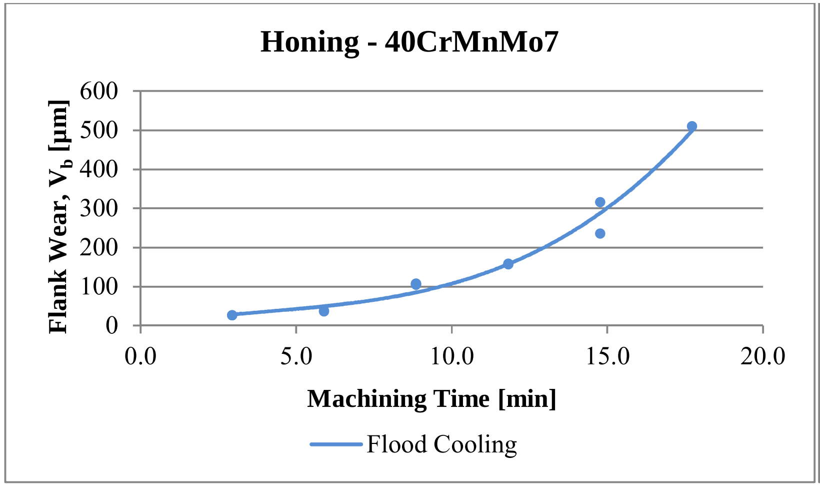
G. APPENDIX G1: HPM 40CrMnMo7 using various coating treatments on SECO inserts under flood cooling conditions

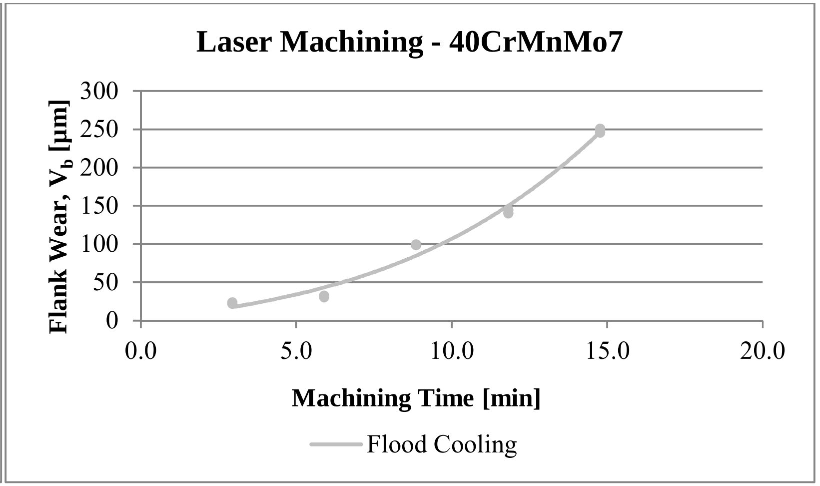


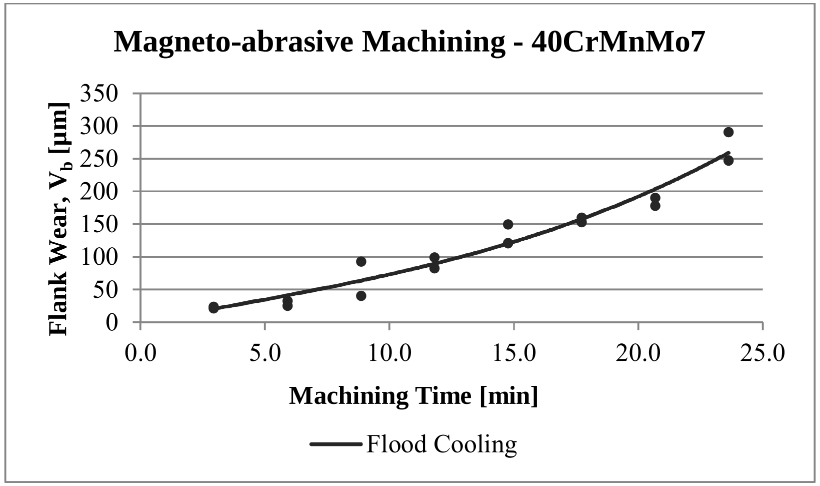




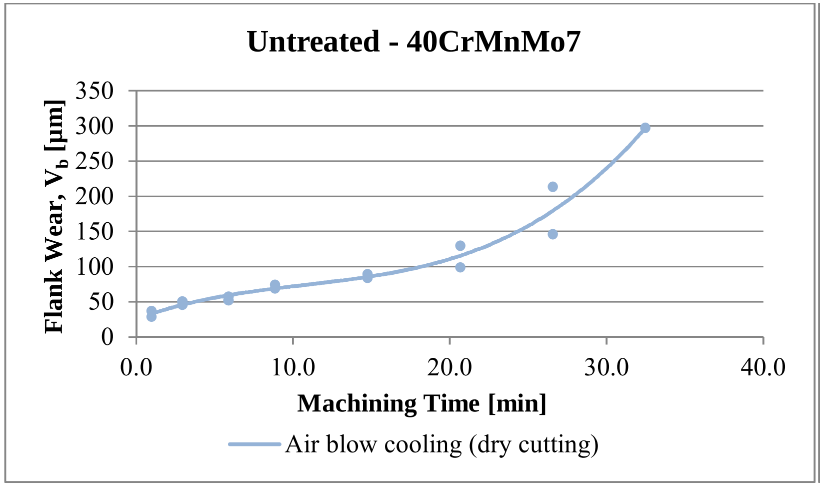


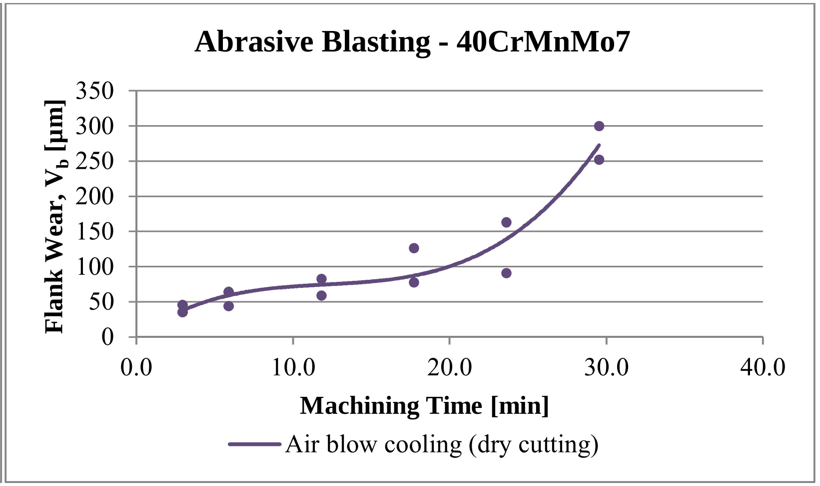

Honing - 40CrMnMo7
Flank Wear, V_b [µm]
600
500
400
300
200
100
0
0.0
5.0
10.0
15.0
20.0
Machining Time [min]
Flood Cooling

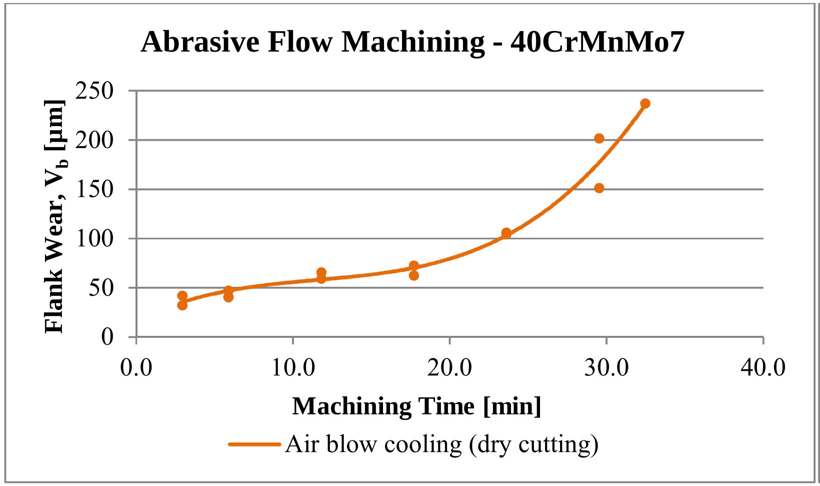

Laser Machining - 40CrMnMo7
Flank Wear, V_b [µm]
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
Machining Time [min]
Flood Cooling

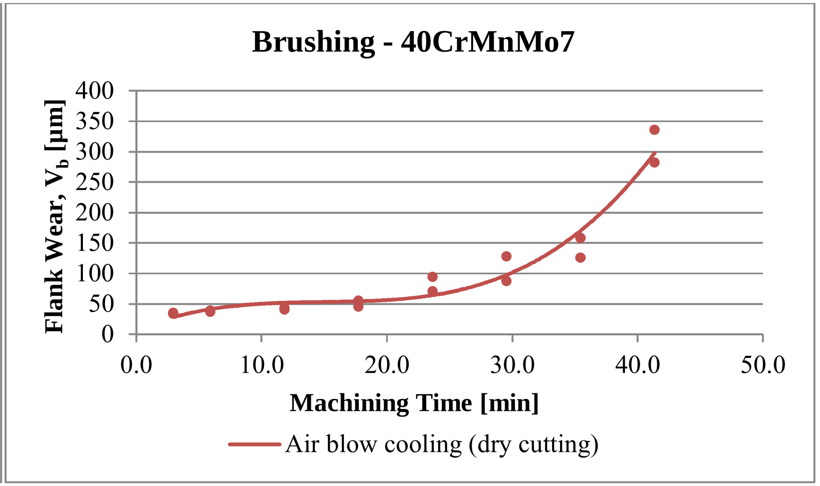

Magneto-abrasive Machining - 40CrMnMo7
Flank Wear, V_b [µm]
350
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
25.0
Machining Time [min]
Flood Cooling

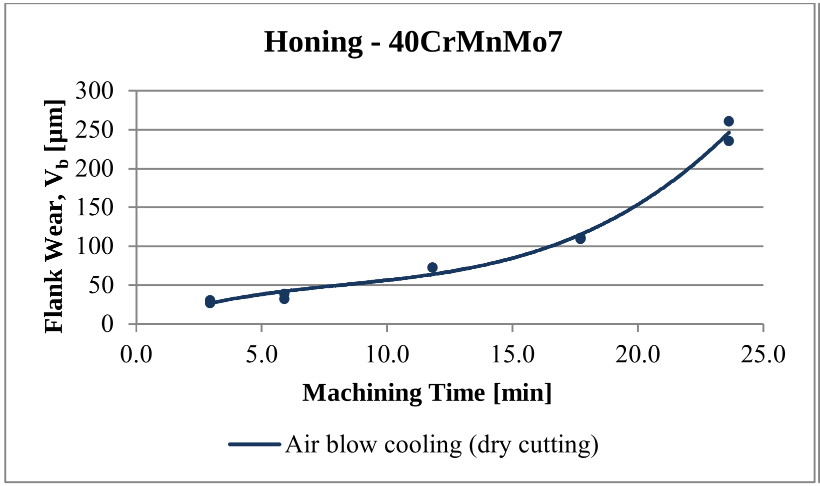
G. **APPENDIX G2: HPM 40CrMnMo7 using various coating treatments on SECO inserts under air blow cooling (dry cutting)**

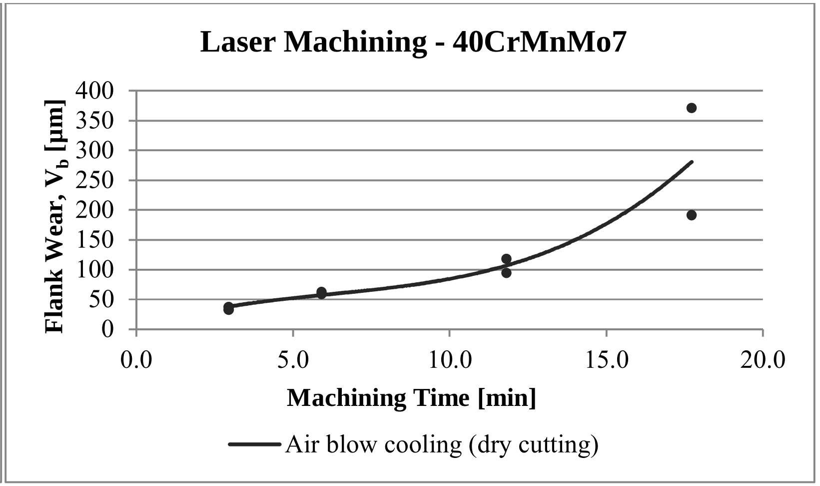


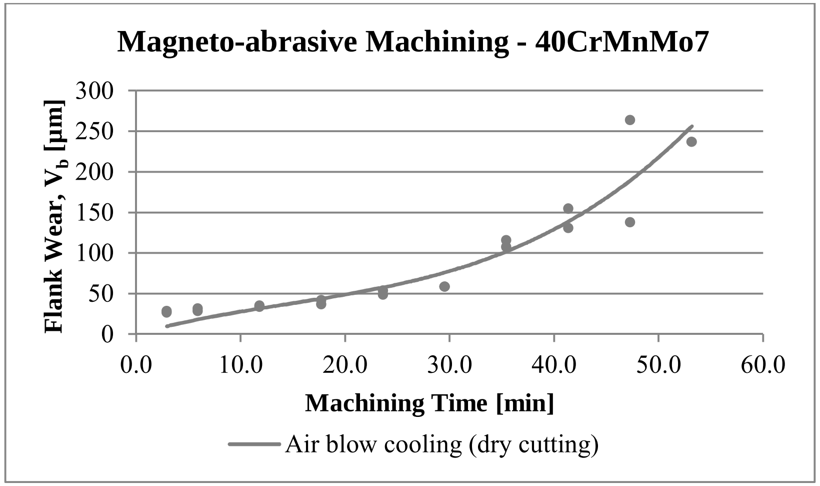




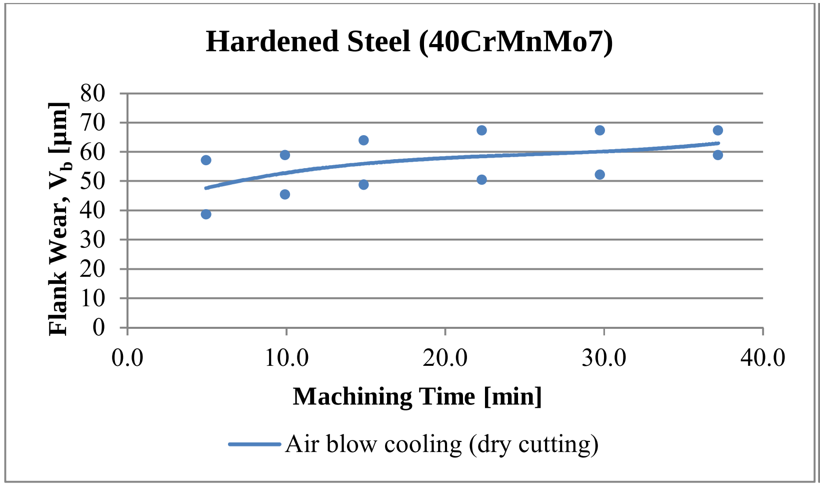


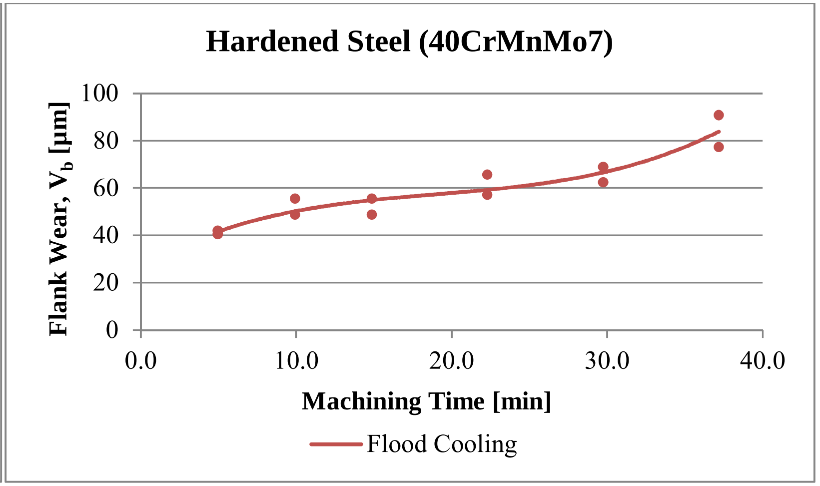

Honing - 40CrMnMo7
Flank Wear, V_b [µm]
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
25.0
Machining Time [min]
Air blow cooling (dry cutting)

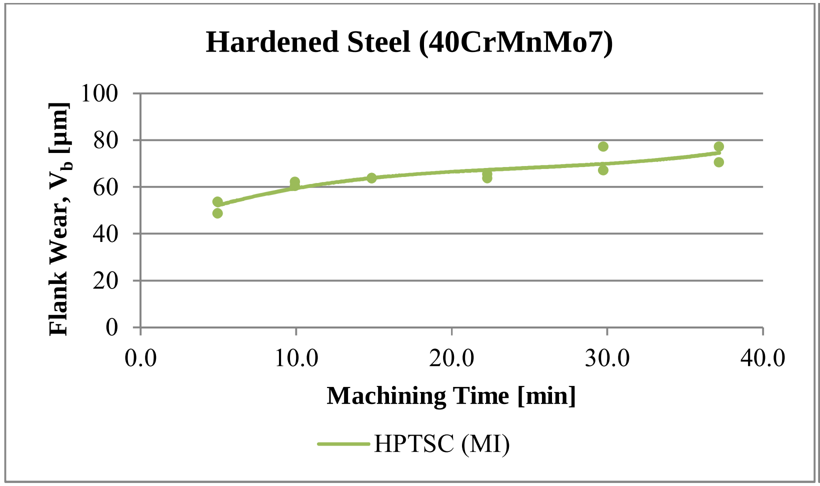

Laser Machining - 40CrMnMo7
Flank Wear, V_b [µm]
400
350
300
250
200
150
100
50
0
0.0
5.0
10.0
15.0
20.0
Machining Time [min]
Air blow cooling (dry cutting)

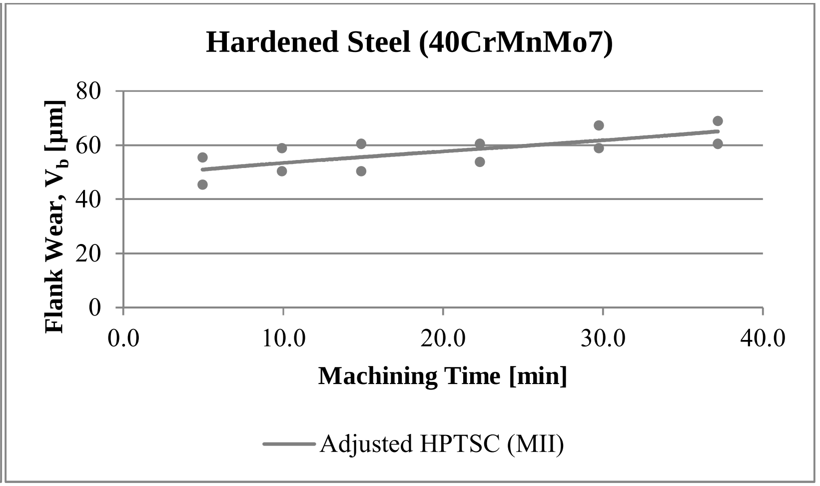

Magneto-abrasive Machining - 40CrMnMo7
Flank Wear, V_b [µm]
300
250
200
150
100
50
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Machining Time [min]
Air blow cooling (dry cutting)

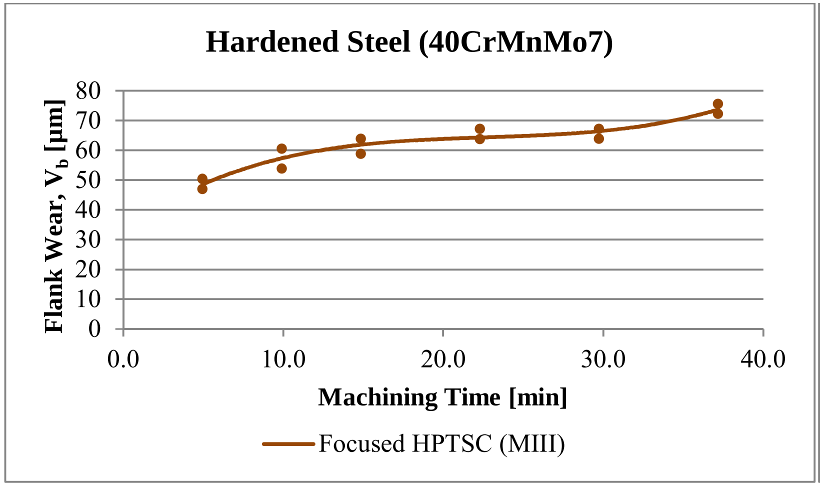
H. **APPENDIX H1: HPM 40CrMnMo7 using Mitsubishi inserts under the selected cooling strategies and modification techniques**



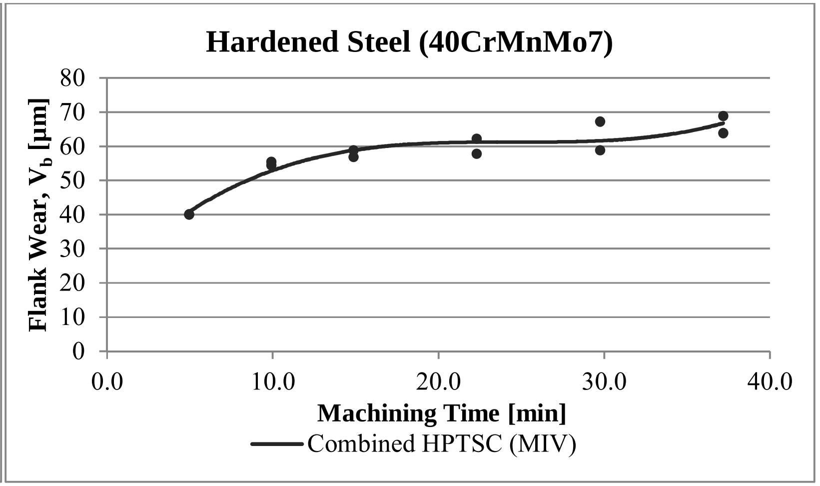








Hardened Steel (40CrMnMo7)
80
70
60
50
40
30
20
10
0
Flank Wear, V_b [µm]
0.0
10.0
20.0
30.0
40.0
Machining Time [min]
Focused HPTSC (MIII)



Hardened Steel (40CrMnMo7)
80
70
60
50
40
30
20
10
0
Flank Wear, V_b [µm]
0.0
10.0
20.0
30.0
40.0
Machining Time [min]
Combined HPTSC (MIV)