



THE INVESTIGATION AND DESIGN OF A FOCUSED HIGH PRESSURE COOLING TECHNIQUE FOR THE MILLING OF Ti6Al4V

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ABSTRACT

Titanium is used in aircrafts structures and engines. The materials' low thermal conductivity and chip segmentation during machining cause a fluctuating heat load on the cutting edge. The extreme reactivity of titanium at elevated temperatures and its adhesive phenomena gives it the characteristic of being difficult-to-machine. The reduction of the chip contact length on the cutting tool edge will help to reduce the friction and thereby slow down tool wear. Various lubrication and cooling strategies were explored and evaluated in order to develop a new cooling technique that will be able to reduce the chip contact length. This will help to improve tool life and the surface integrity of the machined components. The tool wear was measured with an optical microscope in order to realize the performance of the different strategies. It was found that the high pressure cooling strategy showed to perform superior to the other strategies. Improved chip removal and reduced chip contact length with the cutting edge were found. Thereby, a new focused high pressure cooling cutting tool could be designed. The steps to design a cutting tool are shown and commented on. It is concluded that the high pressure cooling techniques show promising results and that future work is necessary to explore these benefits.

1. INTRODUCTION

Titanium has a remarkably strength-to-weight ratio that allows aerospace industries to substitute steel with Ti6Al4V in numerous applications. Structural lightweight construction in aerospace applications means large thin-walled parts with a high mechanical strength. Titanium can function at elevated temperatures without much change in mechanical properties [1]. The main reason for the increasing demand of titanium components, is its superior strength-to-weight ration, high operating temperatures, corrosion resistance and good compatability with composite materials [2]. The use of integral parts is a great improvement in comparison with a number of separate sheet metal parts joined by fasteners. Because of the relatively low number of similar parts in the aerospace industry at present it is not efficient to produce such parts by forming. Welding is not popular either because of cost sensitivity to complexity, residual stresses and the risk of material imperfections. Therefore, the usual way to produce integral parts is by machining of rolled or forged plates. As a consequence a very high amount of material up to 80-95% has to be removed [3]. In the case of the Boeing 787 the so called "buy-to-fly ratio" amounts approximately 8:1 even though the use of partially pre-formed blanks [4]. Typical integral parts in aerospace industry are engine and landing gear suspension parts, flap tracks, wing boxes and supporting cell structure elements.

The machining challenges can be subdivided into thermal- and mechanical tool demands. Titanium is reactive at high temperatures [5,6] during machining. The tool face temperature is a function of the cutting speed (v_c) and exposure time to this thermal load. The combination of titanium's low thermal conductivity and the fact that approximately 80% of the heat generated [7] is retained in the tool, results in a concentration of heat in the cutting zone. The fast moving segmented chips have a short contact length with the tool tip generating temperatures up to the region of 1100°C [8,6] for finishing operations. These issues cause complex tool wear mechanisms such as adhesion, diffusion and oxidation [9]. The recommended cutting speeds (v_c) for titanium alloys of around 30 m/min with high-speed steel (HSS) tools, and around 60 m/min with cemented tungsten carbide (WC) tools, result in rather low productivity [10]. The mechanical demands are a combination of the work piece chip load on the cutting edge and the machining vibrations. Catastrophic tool failure, due to mechanical overload, is caused by self-excited chatter and forced vibrations owing to the formation of shear localization during chip generation and the fluctuating frictional phenomenon between the tool and chip flow [11,12]. Hereby, the combination with a low Young's modulus (114GPa) encourages chatter and work piece movement away from the tool [13]. Some of the properties of titanium are indicated in the Table 1 below. High cutting temperatures, tool vibration and decreased tool life are a result of these properties. This makes the machining of titanium a time consuming operation as well as costly and consumable intensive [14].

Density	4.43 g/cm ³
Melting Point	1650 °C
Modulus of Elasticity - Tension	114 GPa
Modulus of Elasticity - Torsion	42 GPa
Thermal Conductivity	6.6 W/m°C
Specific Heat	565 J/Kg°C

Table 1: The properties of the Ti6Al4V work piece material [15]

New cooling- and lubrication strategies show promising results to improve the production rate and quality of the components [11,12]. In this study various cooling- and lubrication strategies were explored in order to design and develop an innovative cooling technique.

The experimental approach, evaluation and design are discussed and shown. Future experiments are also discussed.

2. RESEARCH APPROACH

Current research institutes are exploring flood, minimum quantity lubrication, high pressure cooling and nitrogen strategies for the machining of Ti6Al4V. The research approach of this study is illustrated in Figure 1. The figure shows the different critical phases before designing and developing a new lubrication strategy.

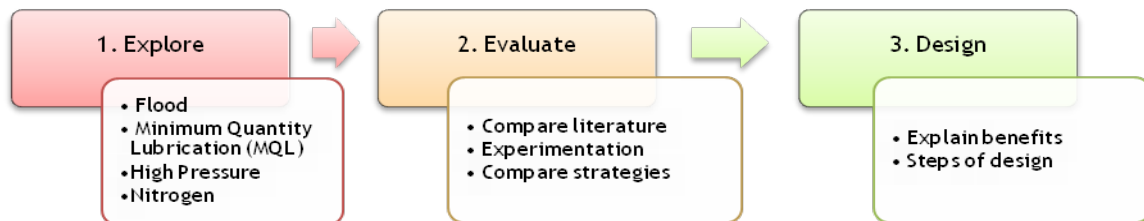


Figure 1: Research approach to design an innovative lubrication strategy for the milling of Ti6Al4V

Various strategies were evaluated to determine the best possible technique for the milling of titanium. The evaluation consisted of experimental data from various studies and a comparison of the different strategies. The design phase explains the benefits of the new design and illustrates the steps taken to design the innovative cooling technique.

3. EXPLORATION OF VARIOUS COOLING- AND LUBRICATION TECHNIQUES

In the exploration phase the different cooling- and lubrication strategies were studied to understand the benefits and drawbacks before starting with the design. The different tasks of the coolants are illustrated in Figure 2. Flood coolant helps with the flow and removal of the heat.

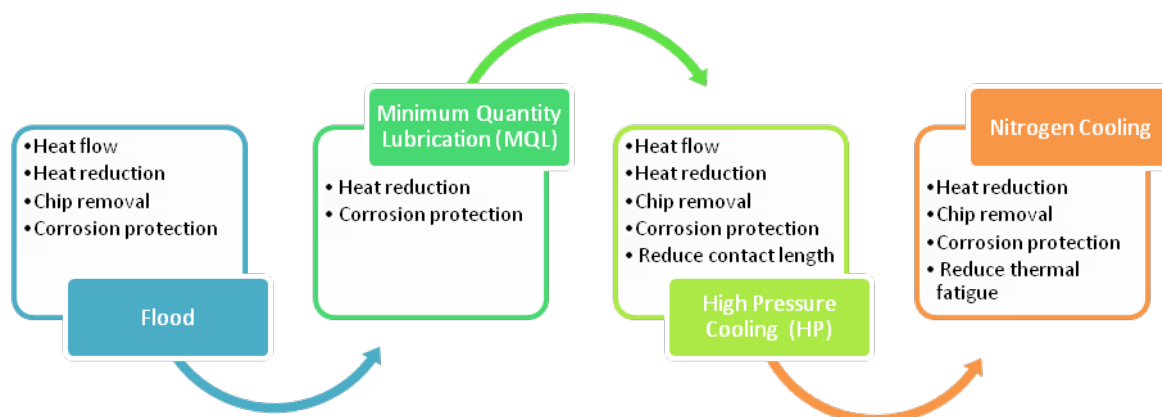


Figure 2: Tasks of coolants in milling process [16]

Minimum quantity lubrication also reduces the heat, but its main benefit is to help with tool corrosion. High pressure cooling enhances both the chip removal and heat flow away from the cutting edge, but is superior in reducing the contact length of the Ti6Al4V chip on the tool edge. Nitrogen cooling can reduce the thermal fatigue of cutting tools.

3.1 Flood cooling

Flood cooling, is best described as an uninterrupted flow of an abundant quantity of coolant directed onto both the tool and work piece. Chips are removed by a flushing action. With flood cooling thermal shock on milling tools are minimized and the ignition of chips eliminated particularly when grinding actions are used [8]. This method is the benchmark for all experiments as it is the most widely used in standard machining.

3.2 Minimum quantity lubrication (MQL)

Minimum quantity lubrication (MQL) is an economic technique of applying coolant. This method applies small quantities of oil in the form of mist onto the cutting edge to improve cutting performance [17]. The study of MQL has been found to be unsuited for the machining of titanium. The temperature experienced during the machining of titanium at high speeds becomes too great for MQL cooling applications [18].

3.3 High pressure cooling (HP)

The concept of coolant under high pressure (HP) is to reduce the temperature generated at tool-work piece and tool-chip interfaces. HP coolant causes discontinues chips that are small and easy to dispose off [8]. When cooling, a thermal barrier (thin water vapour blanket) is created by the cooling fluid on the surface of the material. The ability of the HP to impinge on the thermal barrier during the machining of titanium is an important aspect to consider. Chip contact length and impingement of the thermal barrier layer can be improved by HP coolant in turn increasing heat transfer from the work piece to the coolant. This leaves an opportunity to experiment with different application strategies of HP coolant to reduce wear and chip contact. According to researchers [18], HP coolant is effective in the removal of chips by reducing its contact length on the tool, depicted in Figure 3(B1 and C1). Figure 3(A) displays the effects during conventional wetting (CW), otherwise known as flood cooling. Figure 3(B) shows the effects using HP neat oil (HPNO) and Figure 3(C) indicates the benefits of using high pressure water soluble oil (HPWS). Figure 3(C), indicate a drastic reduction in crater wear of the rake face, (C2), and an improved flank face wear, (C3). The HPWS therefore demonstrates a definite improvement in wear and is a tribute to the greater thermal coefficient of the water constituent of the coolant.

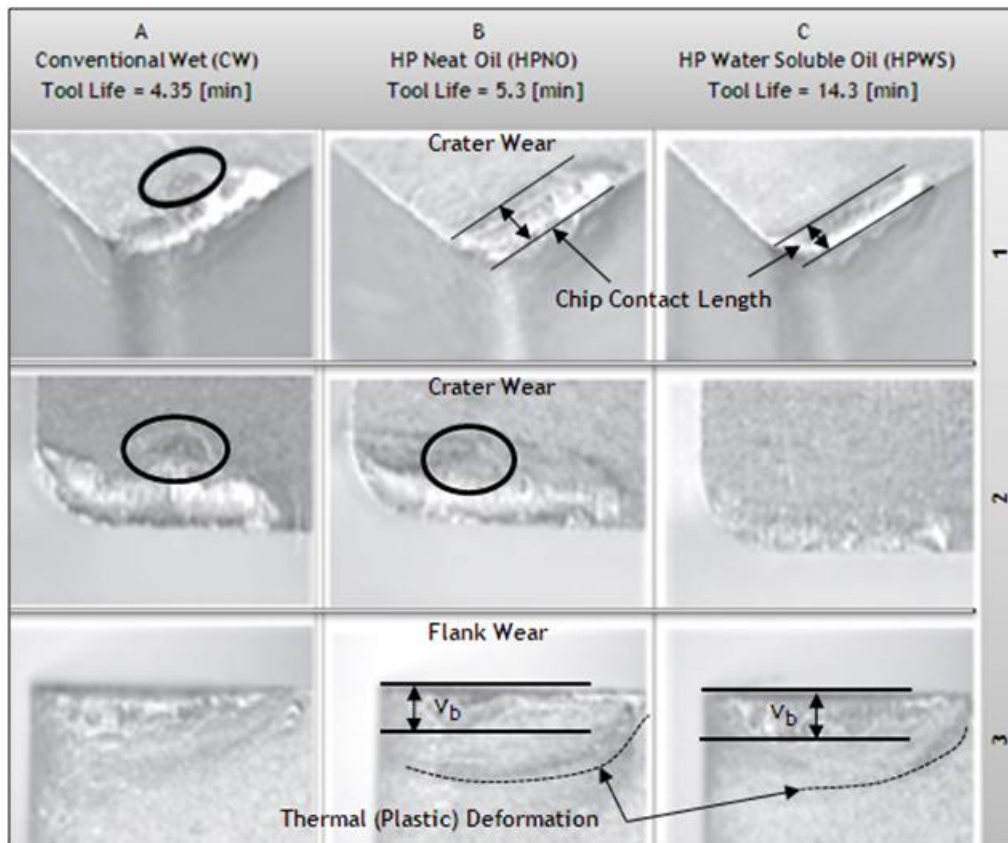


Figure 3: Wear phenomena on the cutting tool edge after machining Ti6Al4V ($v_c=100\text{m/min}$, $S_o=0.20\text{mm/rev}$, $P = 100\text{ bar}$ and $d_n = 0.8\text{mm}$) [18]

The improvements of high pressure cooling on the flank wear are graphically depicted in Figure 4. The graph compares the flank face wear (V_b) relative to the machining time. The intervals of inspection (in minutes) are initially measured over short intervals, but at a later stage increased. It is clear that the high pressure water soluble (HPWS) has superior advantages in the ability to reduce the wear on the flank face during machining. HP coolant leads to drastic improvement in the tool life and reduces flank face wear. From this it can be concluded that the thermal loading on the tool has been reduced with high pressure coolant, predominantly when using water soluble oils.

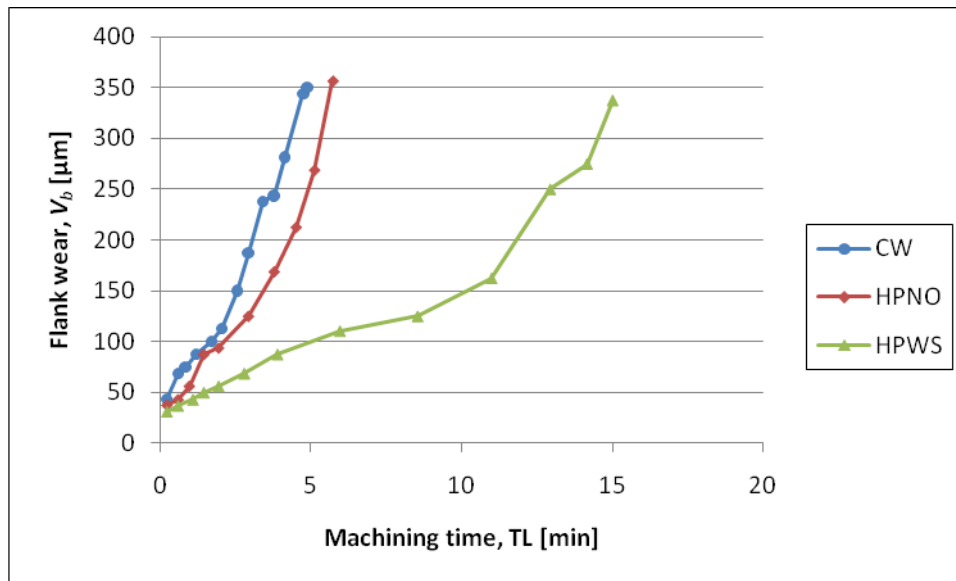


Figure 4: Growth of tool wear turning Ti6Al4V alloy ($v_c = 100\text{m/min}$, $S_o = 0.20\text{mm/rev}$, $p=100\text{ bar}$ and $d_n=0.8\text{mm}$) under conventional wet, high-pressure neat oil (HPNO) and high-pressure water-soluble oil (HPWS) [18]

3.4 Nitrogen Cooling

Liquid Nitrogen (LN_2) cooling typically has two approaches, spray- and local application. With spray application the nitrogen is applied using a nozzle directed at the cutting interface. There are various ways how these nozzles are created and positioned [19,20]. With local application the nitrogen is applied with the goal to focus the cooling power primarily onto the cutting tool [21,22]. Nitrogen is classified as an environmentally friendly coolant because it evaporates into the atmosphere without polluting, and eliminates disposal issues as experienced with other cutting fluids.

3.4.1 Spray cooling

Researchers [19] designed a high pressure jet system, shown in Figure 5, that sprays LN_2 onto the rake and flank face of the cutting tool. A continuous flow of LN_2 was supplied at a flow rate that will not to overcool the work piece.

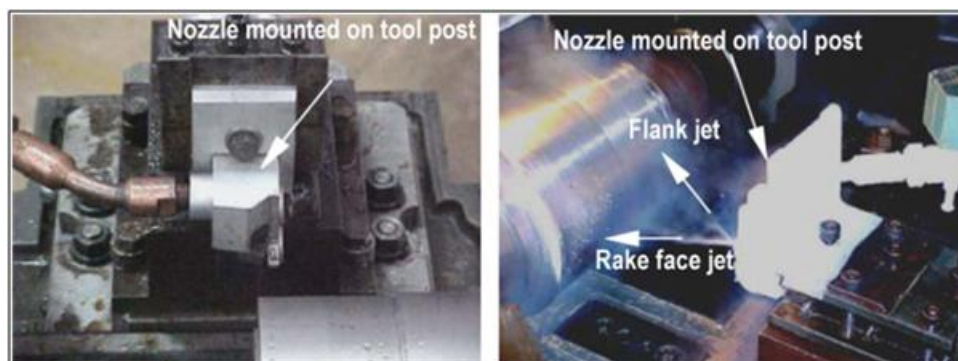


Figure 5: Liquid nitrogen delivery set-up [19]

The LN_2 jet cooling yielded a tool life improvement of 71% compared to flood cooling at a relative high cutting speed ($v_c=70\text{ m/min}$). The tool life improvements at higher cutting

speeds were however deteriorated. This is attributed to the difficulty experienced by the LN_2 to penetrate the tool-chip interface at high cutting speeds [23].

3.4.2 LN_2 conduction cooling using a modified tool holder

This cooling technique cools the mounting surface of the cutting insert by flooding a chamber below the insert with LN_2 . Ahmed et al [21] also tested two different configurations of gas discharge. The results are depicted in Figure 6. The first design discharged the gas towards the cutting zone and in the second design the LN_2 gas was discharged away from the work piece. The LN_2 is fed from the reservoir to a cavity below the insert. In these experiments, carbide inserts were used on an ANSI 4340 work material. In the case of the evaporated gas being discharged towards the cutting zone (design 1), the tool life of the insert is reported to be 30 times the tool life for dry cutting.

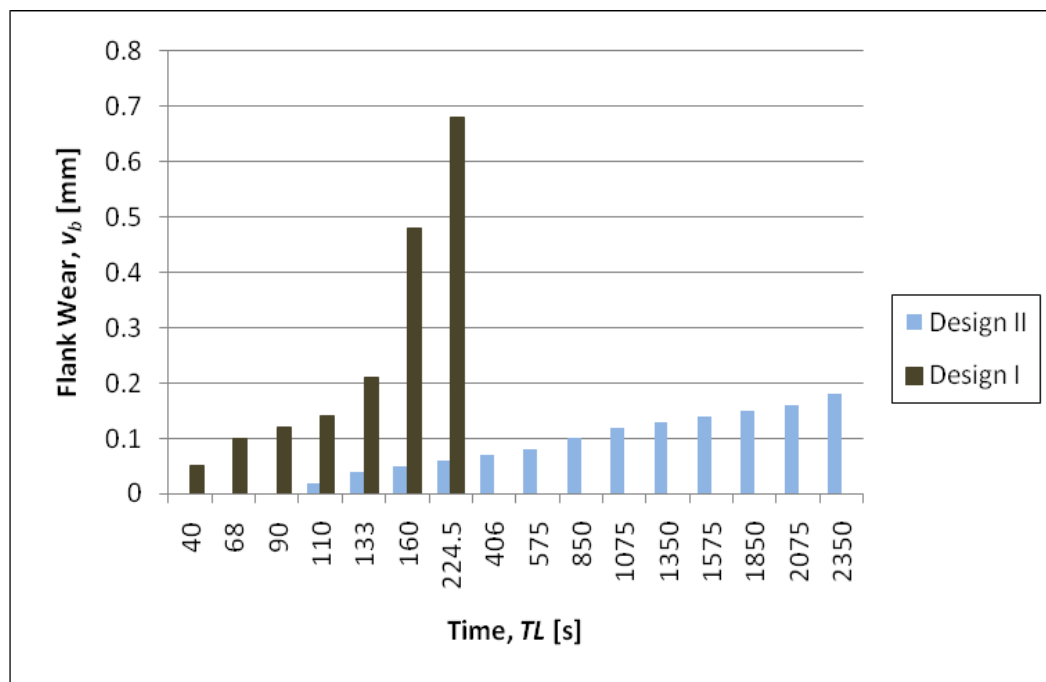


Figure 6: Flank wear vs. time ($v_c = 450$ m/min) [21]

The surface finish attained is however inferior to that of dry cutting. It indicates that the discharge causes hardening by overcooling of the work piece. In the second configuration (design 2) tool wear is significantly lower. When measuring the tool wear after only 3 minutes of machining, as shown in Figure 6, the insert used in design 1 was worn 13 times more than the insert used in design 2. The surface finish achieved with design 2 was significantly better.

3.4.3 Closed loop LN_2 jacket cooling

In this configuration LN_2 is circulated on the rake face of the cutting tool. Thus only exposing the cutting edge to the LN_2 [22]. There is an inlet and outlet to facilitate the circulation of the LN_2 and exhaust of the gaseous nitrogen.

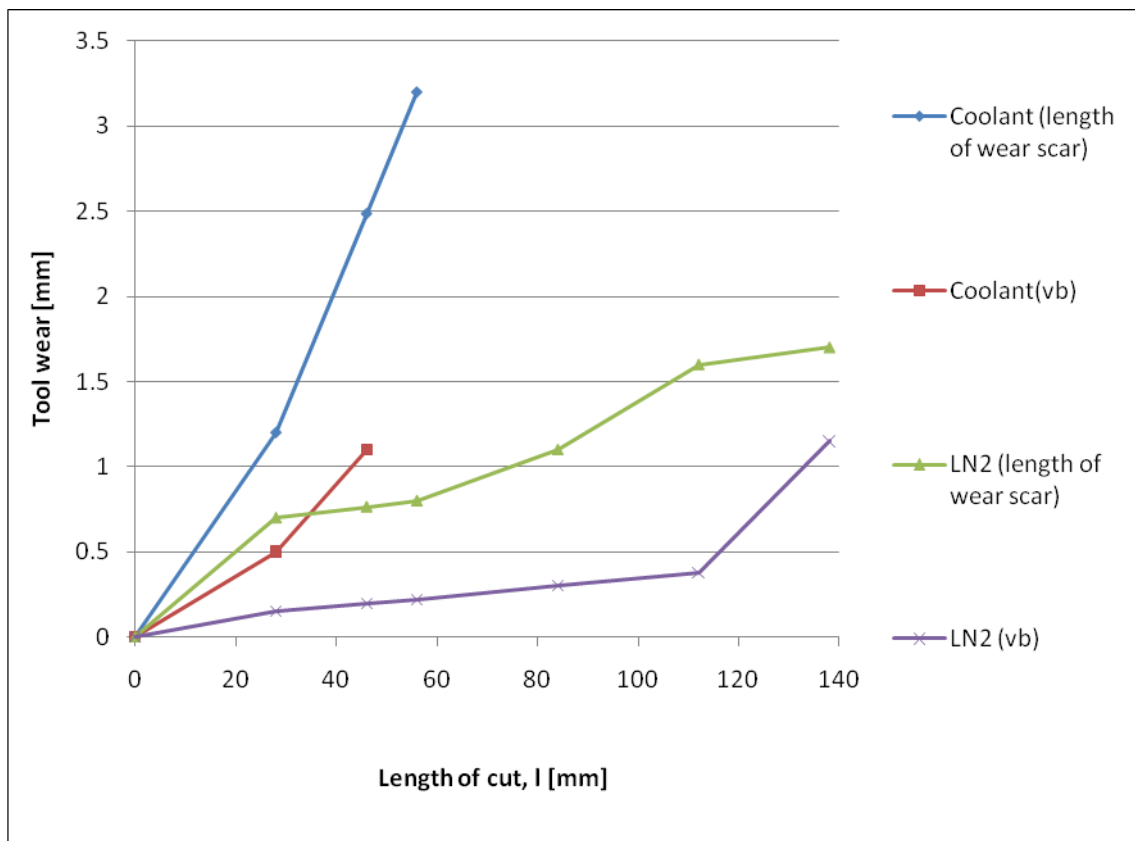


Figure 7: Comparing the effect of using LN₂ to that of flood coolant while machining Ti6Al4V [22]

A cutting speed of 132 m/min (depth of cut=1 mm and feed rate=0.2 mm/rev) with conventional flood cooling was used as benchmark. The flank wear amounted to 1.1 mm (after 46 mm) of machining with flood cooling, while with LN₂ it amounted to only 0.22 mm. Further experimentation showed that LN₂ cooling machined 112mm before reaching failure criteria, compared to 20mm for flood cooling. This represents a 460% improvement in tool life. Cutting forces remained constant indicating retention of tool hardness. The LN₂ treatment resulted in surface finish improvement as well. The conclusion is therefore derived that closed loop LN₂ cooling improves tool life and surface finish by means of controlled insert surface temperatures.

3.4.4 Cooling by means of modified chip breaker

Two directional jets were formed by etching out channels on the cutting tool surface of a chip breaker, forming jets when it is mounted on the carbide cutting insert [20]. The channels direct the LN₂ at the cutting edge, as shown in Figure 8. The titanium is lifted from the insert by the chip breaker which improves the LN₂ penetration of the chip-tool interface. A secondary jet was added to deliver LN₂ to the flank face.

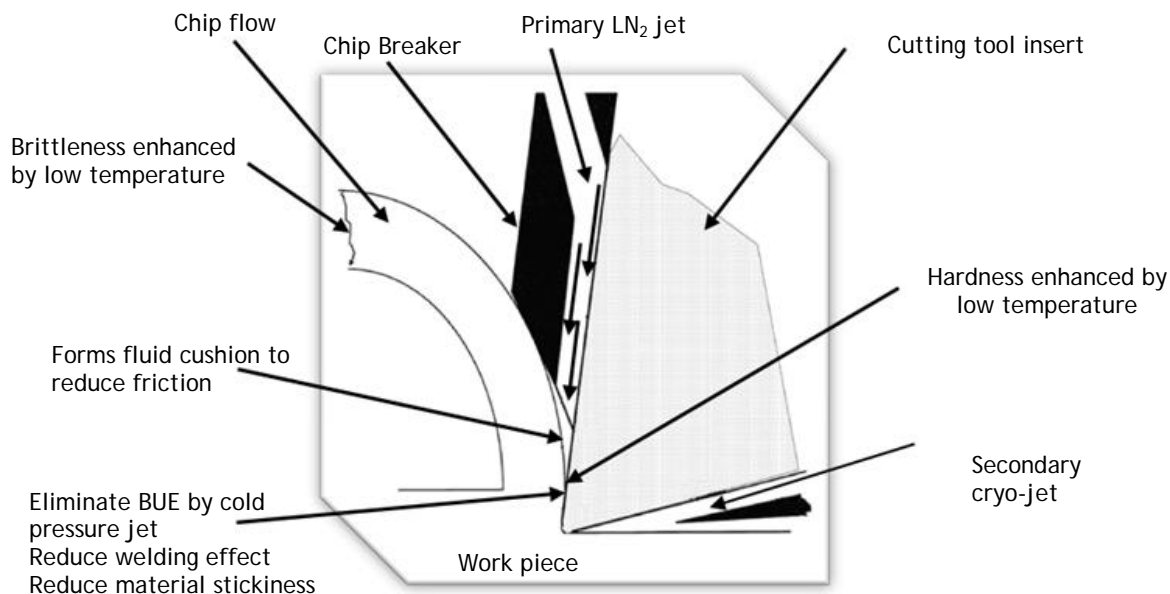


Figure 8: Modified chip breaker design [20]

Flood cooling experiments were performed to establish a benchmark. The findings shown in Table 2 are believed to be state-of-the-art by machining specialists. The best position for the chip breaker was experimentally determined using the distance (l) from and angle (λ) relative to the cutting edge as variables. The optimal values for the values was found to be $\lambda=15^\circ$ and $l=1.25\text{mm}$ [20].

Cooling method	Cutting speed, v_c [m/min]			
	60	90	120	150
Conventional Emulsion	1050 s	290 s	158 s	56 s
Primary nozzle only	N/A	547 s	N/A	N/A
Prim. and sec. nozzle	1653 s	948 s	437 s	296 s
Percentage improvement over flood cooling				
Primary nozzle only	N/A	89%	N/A	N/A
Prim. and sec. nozzle	57%	227%	177%	429%

Table 2: Tool life and improvements for different cutting conditions [20]

The table shows the experimental results. Experiments were conducted activating only the primary nozzle or the primary and secondary nozzles at different cutting speeds. An improvement of 57% in tool life was achieved at 60 m/min. As cutting speed increased a drastic tool life enhancement of 429% at 150 m/min was recognized. This proves the cooling power of much higher temperatures are generated at 150m/min.

4. EVALUATION OF VARIOUS COOLING- AND LUBRICATION TECHNIQUES

4.1 Comparing experimental results from literature

In Figure 9 the performance of different cooling methods are reported by expressing the material removed relative to cutting speed. The figure shows that LN₂ cooling results in

improved tool life compared to conventional flood coolant. The commonly known trend that tool life is highly dependent on cutting speed remains applicable.

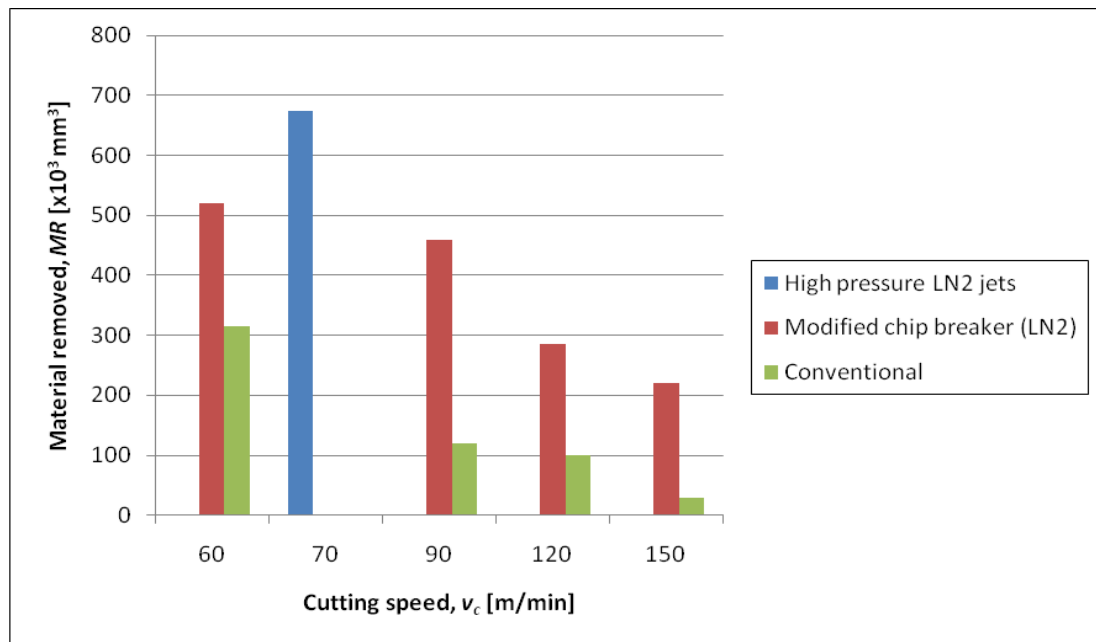


Figure 9: Tool life in terms of material removed for LN₂ compared to conventional cooling

High pressure coolant demonstrates improvements in tool life when machining Ti6Al4V with cemented carbide (coated and uncoated) tools. These improvements are clearly visible in Figure 10 illustrating significant tool life under high pressure in comparison to conventional cooling methods. Surface finish is not compromised with high pressure cooling. Circularity and hardness of the machined surface are also not affected [24].

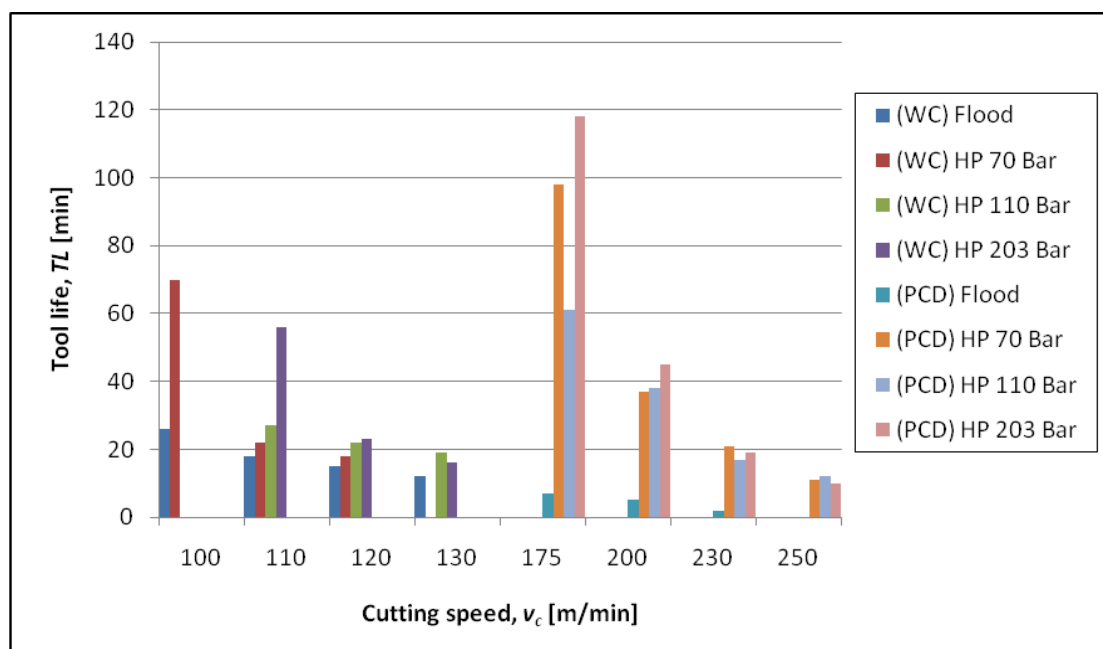


Figure 10: Tool life when machining titanium alloy with uncoated WC and PCD under different coolant strategies [24]

Tool life usually increases with higher coolant pressures as cutting temperatures tend to be lower. Increased tool life is obtained while machining titanium with polycrystalline diamond (PCD) at higher cuttings speeds which is indicated in Figure 10. This is due to the tool material's higher hot hardness. Cutting speeds up to 250 m/min are obtained which were previously not obtainable using conventional cutting tool materials [24].

4.2 Gaseous cooling experimental design and results

When machining titanium temperatures as high as 900°C have been measured at a cutting speed of 75 m/min [25]. At such high tool temperatures, the coolant vaporises on tool contact and creates a vapour layer on the surface of the tool. This creates an insulation boundary layer that significantly reduces the heat dissipation of the tool. In order to quantify this, the heat transfer coefficient for water is reduced approximately ten times between 380°C to 830°C. This phenomenon occurs when a two phase coolant such as water is used, also being referred to as coolant jet impingement. With titanium machining cooling is extremely important and this often results in premature tool failure [26]. In order to simulate milling, a face turning operation [27] was executed on a 56.5 mm Ti6Al4V round bar with an 8 mm slot milled through the centre. The cutting speed kept constant by utilizing the G96 function of the lathe. The cutting parameters for the experiment are given in Table 3.

Depth of cut	DOC	1 mm
Feed rate	f_n	0.1 mm/rev
Cutting speed	v_c	50, 60, 70, 80, 90, 100
Cutting distance	l	96 m

Table 3: Cutting parameters for the experiments

An Olympus GX51 inverted optical microscope was used for the analysis of the wear scar. In order to reduce thermal shock and at the same time improve the cooling of high temperature cutting tool surfaces, gaseous cooling was studied. Several pilot test runs were made where the tool failed as a result of mechanical shock before thermal cracks could be identified. Judicious adjustments of cutting parameters were necessary to identify the cracks in the first two stages of development according to Wang et al [28]. Flood cooling at 50 m/min as exposed in Figure 11(a) shows comb type crack initiation while gaseous cooling (Figure 11(b)) displays a rake face without cracks.

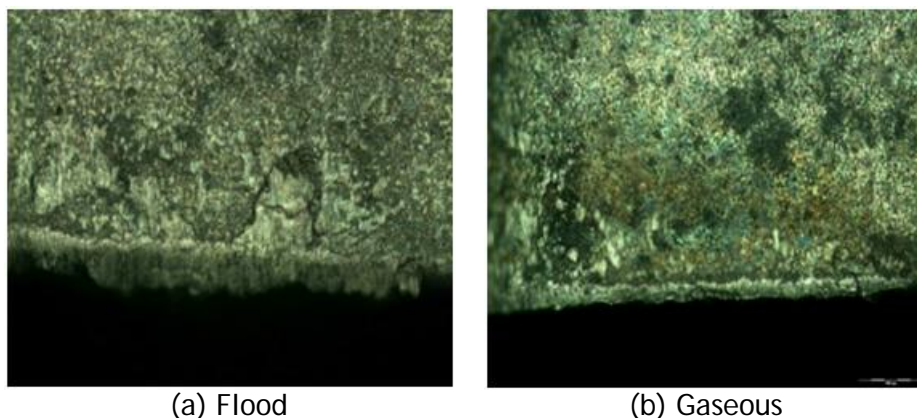


Figure 11: Cutting speed of 50 m/min (200x)

Additionally the cutting edge of the flood cooling already suffers from chipping while the gaseous cooling's cutting edge is intact. As illustrated in Figure 12, at 60 m/min the flood

cooled test specimen has moved through all four stages of thermal cracking with the cutting edge being broken away through transverse cracking.

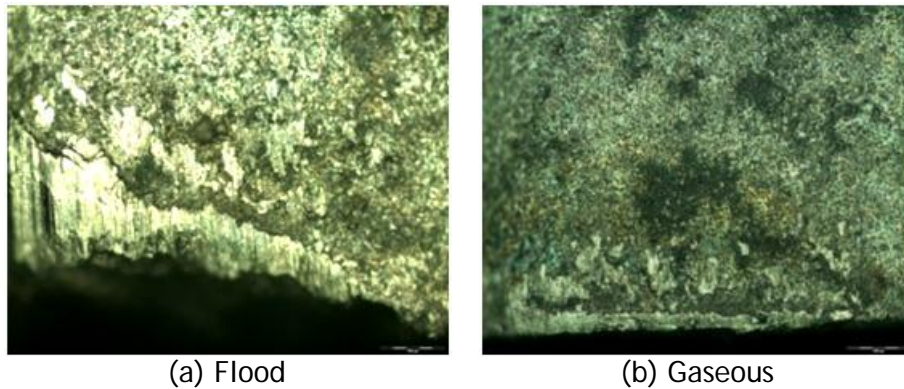


Figure 12: Cutting speed of 60 m/min (200x)

Again the gaseous cooled test specimen does not show any thermal cracking. Figure 13 clearly shows that the flood cooled specimen has suffered severe tool edge failure; whereas the gaseous cooled specimen's cutting edge is relatively intact.

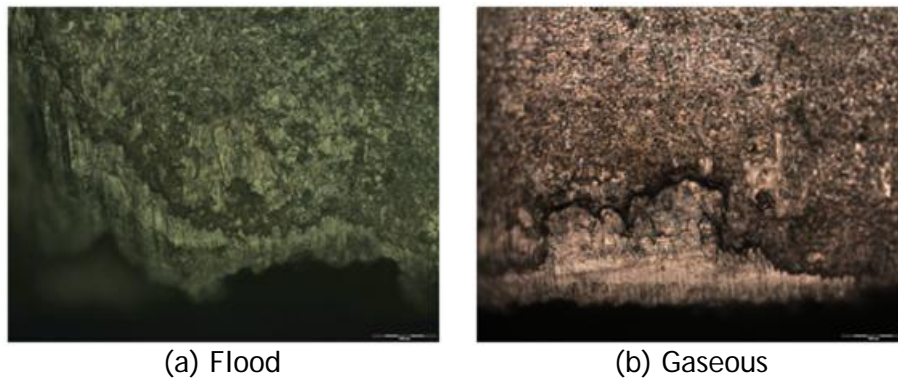


Figure 13: Cutting speed of 80 m/min (200x)

As shown in Figure 14, the flood cooled specimen shows a severely compromised cutting edge at $v_c=100$ m/min while the gaseous cooled specimen's cutting edge is intact with early signs of thermal cracking.

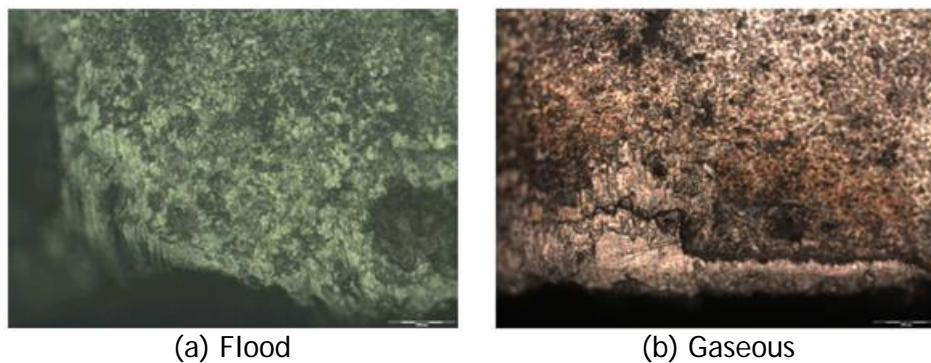


Figure 14: Cutting speed of 100m/min (200x)

It can therefore be concluded that gaseous cooling delivers significant improvements in tool life by preventing thermal cracking [29].

5. DESIGN OF FOCUSED HIGH PRESSURE NOZZLE

The intension of the new design is to improve the chip removal rate and reduce cutting temperatures to enable higher cutting speeds. This can be achieved by focusing the high pressure through spindle cooling onto the cutting heat zone. The original cutter tool is shown in Figure 16.

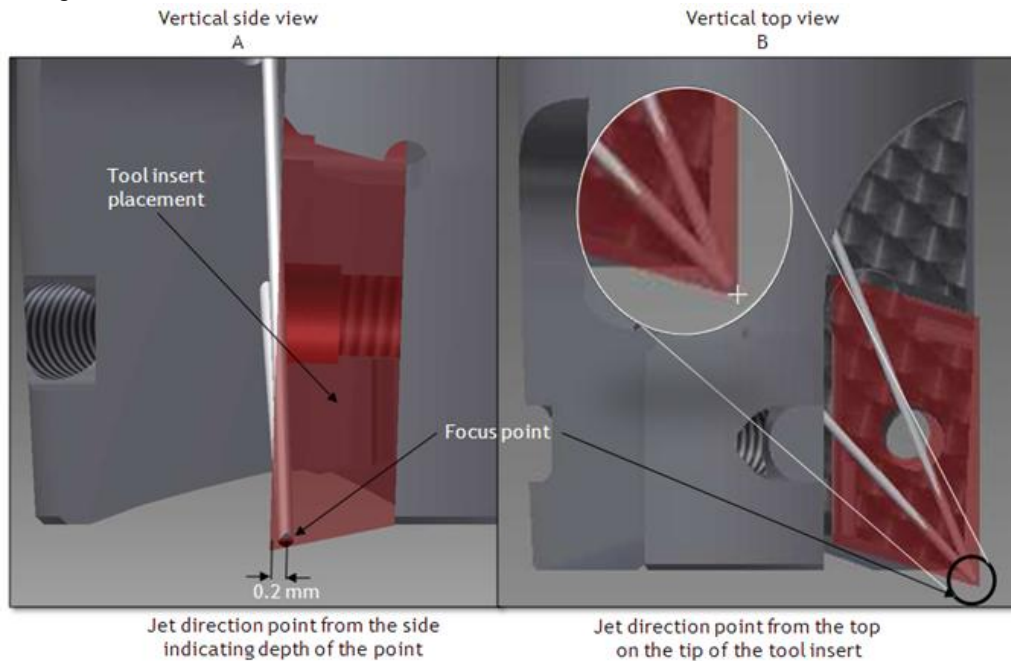


Figure 15: Vertical side and top of the complete jet design and placement

The isometric view and the original cutter are demonstrated in Figure 16 with the new improved holes depicted in white.

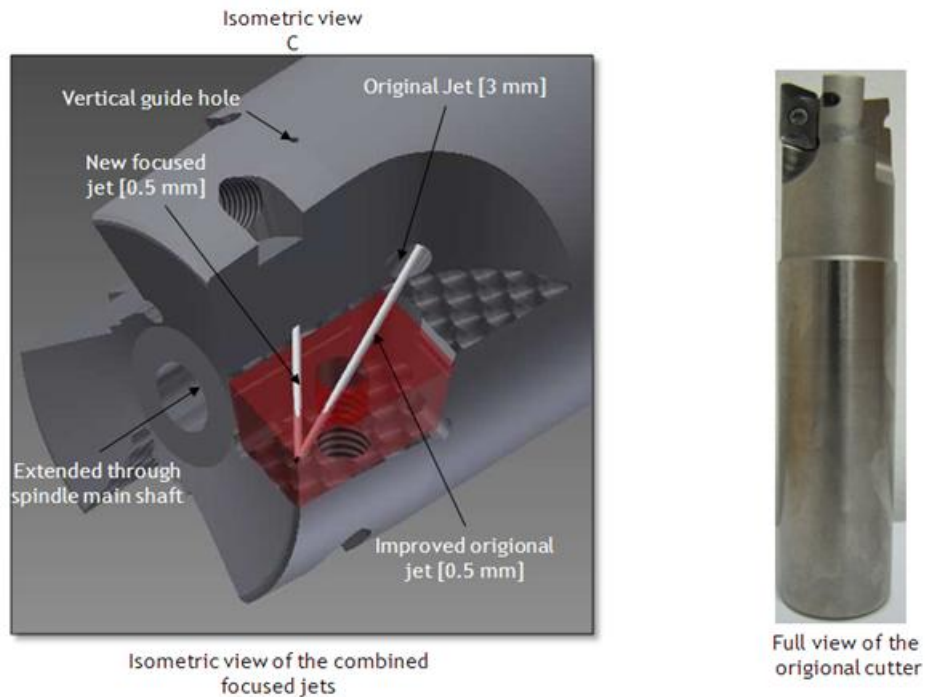


Figure 16: Isometric view of the complete jet design and placement and the original cutter

The contact with the cutting tool and the direction of the jets are illustrated in Figure 17. The proposed focused high pressure nozzle, shown in Figure 16, reduces the original hole diameter from 3mm to 0.5mm as illustrated Figure 8 (C). It directs the jet at a point 0.2 mm, shown in Figure 8 (A), below the cutting tip of the insert, Figure 8 (B). This will cause the coolant to come into contact with the cutting tool before the tip of and curl upwards under the forming chip as depicted in Figure 17. Ultimately reducing contact and possibly break the chip sooner. The breaking action causes discontinuous chips that constrain the contact between the insert and chip.

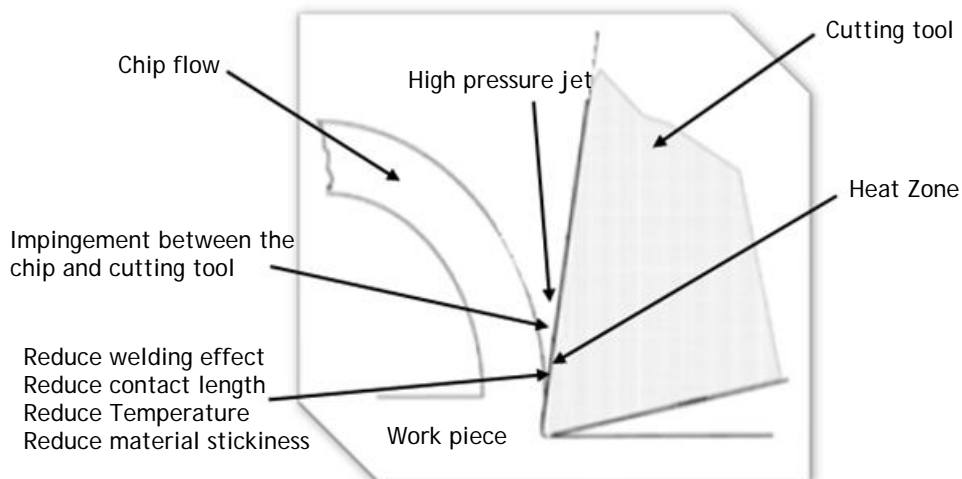


Figure 17: Jet contact with insert and formed chip

The improved original jet design as shown in Figure 18 will be focused at the focus point. The original hole will be plugged and the improved original hole re-drilled through the

plug. The aim is to focus the original flushing hole on the heat zone and to penetrate under the chip as depicted in the figure.

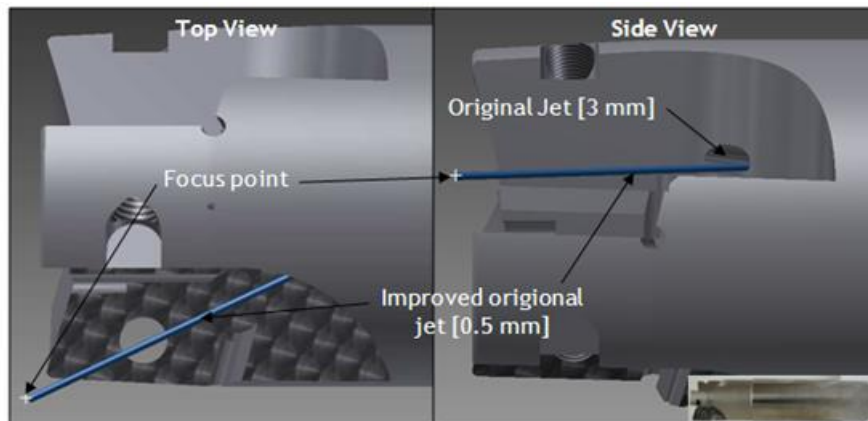


Figure 18: Improved original jet

A new focused 0.5 mm hole will be aimed at the focus point as indicated in Figure 19. A vertical guide hole will be drilled into the extended through spindle main hole, both shown in Figure 16. The new focused jet hole will then be drilled in a direction from the focus point through a point 0.2 mm above the flat of the tool, indicated in the figure's side view, till it reaches the vertical guide hole. Once this has been completed the vertical guide hole and extended through spindle main hole will be plugged as deep as possible. This will reduce the distance travelled by the coolant jet with the intent of increasing the cooling capacity and flushing ability of the jet. The shorter distance will reduce the expansion of the jet diameter and increase the jets focus on the cutting edge.

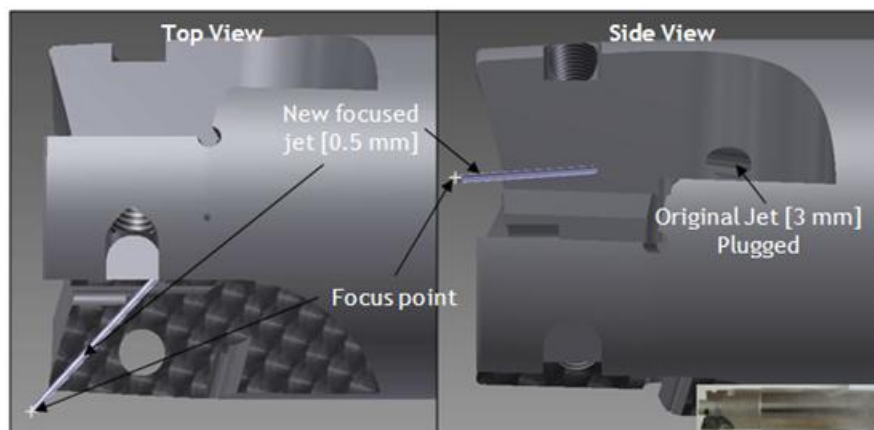


Figure 19: New focused jet

The improved jets' diameter of contact will be greater than that of the new focused jet, Figure 19, which will allow for greater flushing ability of produced chips. In contrast to the improved original jet the new focused jet has a focuses cooling capacity on the cutting edge of the insert. Both these attributes of flushing and focused cooling are favorable and a proposed combination of the two techniques is eligible. A graphical representation of the combined techniques is given in Figure 16 (C).

6. FUTURE WORK: FURTHER EXPERIMENTATION WITH NEW DEVELOPED TOOL

Firstly, different cooling methods were evaluated and through spindle cooling took the focus of the attention. A new focused high pressure strategy designed and different methods of application proposed. The strategies will be tested in experiments which are discussed in detail through this section. A general layout of phase one procedure can be seen in Figure 20.



Figure 20: Approach for future experiments

The experiments will be divided into two phases. The first phase will be the benchmarking phase to determine the improvements of different cooling strategies. The strategies will be re-evaluated and the best performing strategy will undertake further experiments in the second phase. The second phase tests will be to determine the advantages of the best cooling strategy from phase one under different cutting parameters. All experiments will be performed on a CNC 5-Axis Hermle milling machine as shown in Figure 21.

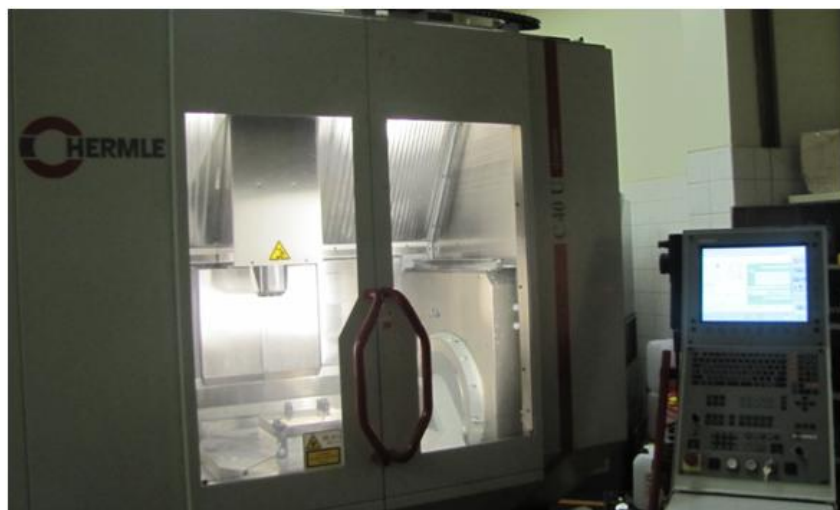


Figure 21: Hermle 5-Axis milling machine

Phase one will consist of four experiments, each composing of four cuts constituting one experiment. Each experiment will have the same material removal parameters indicated in Table 4.

Axial depth of cut (DOC)	a_p	10 mm
Radial DOC	a_e	2 mm
Machining time	t	30 min
Cutting speed	v_c	60 m/min
Feed rate	f_z	0.2 mm/tooth

Table 4: Experimental cutting conditions

The layout of the first phase experiments are indicated in Figure 22 & 23. Experiment 1 will use the original tool cooling technique as the benchmark for the following experiments. The original hole will be modified and a focused stream directed at the cutting edge in experiment 2. A new focused jet closer to the cutting edge will be introduced into experiment 3, where experiment 4 will consist of both the focused and new focused jet.

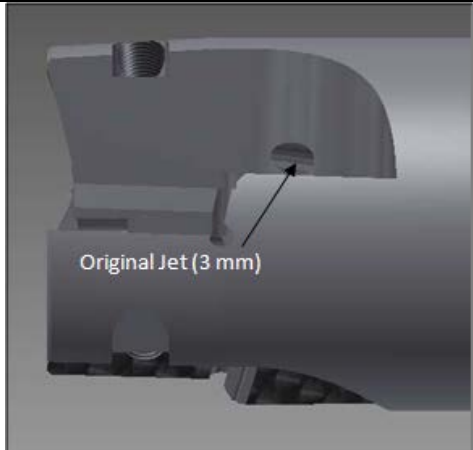
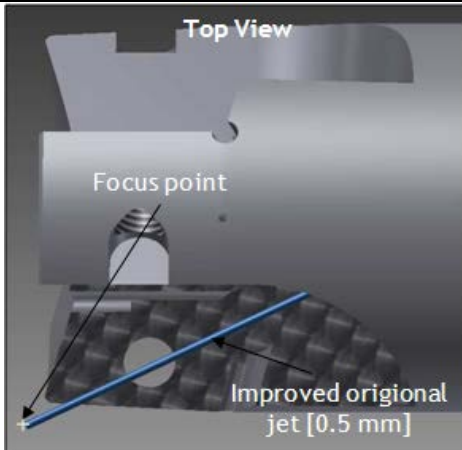
Phase 1	
Experiment 1	Experiment 2
 <p>Original Jet (3 mm)</p>	 <p>Top View</p> <p>Focus point</p> <p>Improved original jet [0.5 mm]</p>
<ul style="list-style-type: none"> • 3 mm jet • Original tool (Flushing) 	<ul style="list-style-type: none"> • 0.5 mm jet • Improved original tool

Figure 22: Phase 1 of the experiment 1 and experiment 2 with the new designed lubrication strategy

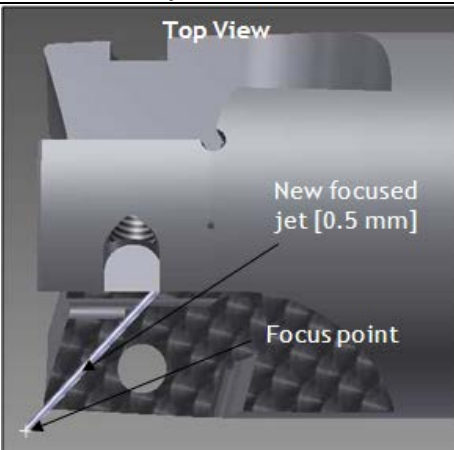
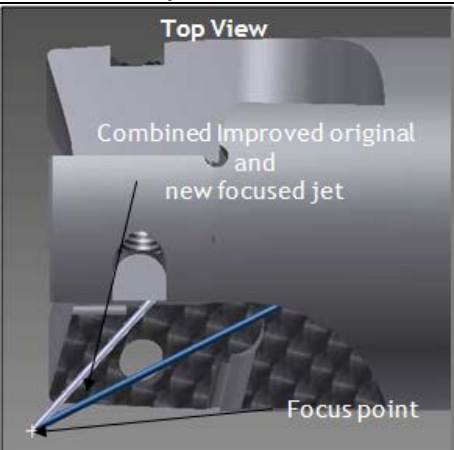
Experiment 3	Experiment 4
 <p>Top View</p> <p>New focused jet [0.5 mm]</p> <p>Focus point</p>	 <p>Top View</p> <p>Combined Improved original and new focused jet</p> <p>Focus point</p>
<ul style="list-style-type: none"> • 0.5 mm jet • Plugged original hole • New focused jet 	<ul style="list-style-type: none"> • 0.5 mm jet • Combined Improved original and new focused jet

Figure 23: Phase 1 of the experiment 3 and experiment 4 with the new designed lubrication strategy

The second phase will experiment with different cutting speeds and feed rates using the focused/improved cooling strategy that yield the best results from phase one. From literature it was found that cutting speed and feed rate are great contributors to the wear of tools and will be the two main parameters that are changed during phase two. All

experiments will be done under the same material removal parameters as indicated in Table 4. Each run will have four cuts with interval readings of the wear band width with cutting parameters indicated in Table 5. The results will be documented and give a better indication of the improvements of the new focused/improved strategy taking into account both phase one and phase two outcomes.

Experiment 1	Cutting speed	v_c	60 - 120 m/min
	Feed rate	f_z	0.2 mm/tooth
	Axial DOC	a_p	10 mm
	Radial DOC	a_e	2 mm
Experiment 2	Cutting speed	v_c	60 m/min
	Feed rate	f_z	0.1 - 0.2 mm/tooth
	Axial DOC	a_p	10 mm
	Radial DOC	a_e	2 mm

Table 5: Cutting parameters for phase 2 of the experiments with the new designed lubrication strategy

In each experiment, phase one and two, the wear scar will be measured on the flank face of the insert. The wear band width will give an indication of the effect of the chip contact and cooling of the cutting edge. The measurement of the wear will be done in interval of 5 min for a period of 30 minutes. This will then be plotted on a wear [μm] vs. machined time graph [min].

7. CONCLUSION

Tool wear was measured with an optical microscope. It was found that the high pressure cooling strategy showed to perform superior to the other strategies. Improved chip removal and reduced chip contact length with the cutting edge were found to be the main reason for this. A high pressure cooling strategy was designed and the steps to design a cutting tool are shown and commented on. As the high pressure cooling technique show promising results, future work is necessary to explore these benefits. The aim will be to improve the milling process as there is little being done to improve the cooling strategy in this operation.

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