Textured insert for improved heat extraction in combination with high-pressure cooling in turning of superalloys

Nageswaran Tamil Alagan
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Nageswaran Tamil Alagan
To build a better world
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Nageswaran Tamil Alagan

12th October 2017
POPULÄRVETENSKAPLIG SAMMANFATTNING

Nyckelord: Legering 718; Högtrycksobjning; Värmeavledning, Texturerat skärverktyg; Volframkarbid, Verktygslivlängd, Verktygsslitage


Detta arbete är ett försök att förbättra värmeöverföringen från skärzonen vilket kan leda till en ökad verktygslivlängd. För att nå detta mål har ett förbättrat gränssnitt skapats mellan skärverktyg och kylvätska i högtemperaturzonerna i skärverktyget.


Experiment genomfördes genom svarvning i legering 718 med obelagda skärverktyg av hårdmetall. Alla experiment utfördes med högtrycksobjning av skärverktygen, med ett tryck på 16 MPa på skärverktygets spånsida och 8 MPa på skärverktygets släppningsida.

ABSTRACT

Title: Textured insert for improved heat extraction in combination with high-pressure cooling in turning of superalloys

Keywords: Alloy 718; High-pressure coolant; Heat dissipation, Textured insert; Tungsten carbide, Tool life, Tool wear.

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Heat generated in a machining process is a common and critical obstacle faced in today’s machining industries. The heat generated in the cutting zone has a direct negative influence on the tool life which, in turn contributes to increase the manufacturing costs. Especially, in machining of Heat Resistant Super Alloys, HRSA this is a very limiting factor. HRSA are capable of retaining their mechanical strength and hardness at elevated temperatures. This property is advantageous in the application in e.g. aero-engines but also a disadvantage, since it also lowers the machinability significantly.

This work is an attempt to improve the heat transfer from the cutting zone, which would lead to an increase in the tool life. To achieve this goal, the cutting tool has been modified to create an improved interface between the coolant and tool in the high-temperature areas.

Two generations of inserts have been designed and investigated. Firstly, an insert with surface texture features has been created with the purpose of increasing the available surface area for heat dissipation: First generation, Gen I. Secondly, a Gen II was designed as a further improvement of Gen I. Here, several channel features on the rake face were added, reaching out from the contact zone to the near proximity of the cutting edge. This with the purpose of improving access of the coolant closer to the cutting edge.

The experiments were conducted in facing operations of Alloy 718 with uncoated round carbide inserts. All experiments were carried out with high-pressure coolant assistance, with a pressure of 16 MPa on the rake face and 8 MPa on the flank face, respectively.

The two generations of inserts, Gen I and Gen II, were experimentally evaluated by tool wear analysis in comparison with a regular insert. The results shows that the tool life increased significantly for the Gen I insert, compared to a catastrophic failure of the regular insert at the same conditions. Regarding the Gen II insert, an increase in tool life by approximately 30 to 40 percent compared to Gen I insert was observed.
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APPENDED PAPERS

Paper A. Next Generation Insert for Forced Coolant Application in Machining of Inconel 718

Presented at the 12th International conference on High Speed Machining in Nanjing, China, October 2015 – Authors: Nageswaran Tamil Alagan, Tomas Beno, Anders Wretland

Author's contribution: Principal and corresponding author. Contributed to further develop the design of a textured insert; (first generation insert) by applying the initial idea in practical test cases. Planned and conducted experiments and measurements to validate the design concept. Wrote the main manuscript and delivered the oral presentation at the conference.

Paper B. Investigation of modified cutting insert with forced coolant application in machining of Alloy 718

Presented at the 18th CIRP conference on Electro Physical and Chemical Machining in Tokyo, Japan, April 2016 – Authors: Nageswaran Tamil Alagan, Tomas Beno, Anders Wretland

Author's contribution: Principal and corresponding author. Contributed to design of a textured (second generation insert). Planned and conducted experiments and measurements. Wrote the manuscript and presented paper orally at the conference.

Paper C. EDS analysis of flank wear and surface integrity in machining of alloy 718 with forced coolant application

Presented at the 3rd CIRP conference on Surface Integrity, North Carolina, USA, June 2016 – Authors: Henrik Jäger, Nageswaran Tamil Alagan, Jonas Holmberg, Tomas Beno, Anders Wretland

Author's contribution: Co-author of the paper. Performed experiments and contributed with experimental data. Contributed to data analysis. Participated in the conference poster discussion.
Paper D. Characterization of tool wear when machining Alloy 718 with high pressure cooling using conventional and surface-modified WC-Co tools.

Published in Springer Journal of Superhard Materials – Authors: Philipp Hoier, Uta Klement, Nageswaran Tamil Alagan, Tomas Beno, Anders Wretland

Author’s contribution: Co-author of the paper. Performed machining experiments and contributed with experimental data and data analysis.
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$A_D$</td>
<td>Theoretical chip area</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$a_p$</td>
<td>Depth of cut</td>
<td>[mm]</td>
</tr>
<tr>
<td>$a$</td>
<td>Clearance angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Rake angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\kappa_r$</td>
<td>Entering angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\psi_r$</td>
<td>Lead angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>Inclination angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Shear plane angle</td>
<td>[°]</td>
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<tr>
<td>$D_1$</td>
<td>Diameter of the workpiece before machining operation</td>
<td>[mm]</td>
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<tr>
<td>$D_2$</td>
<td>Diameter of the workpiece after machining</td>
<td>[mm]</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Main cutting force</td>
<td>[N]</td>
</tr>
<tr>
<td>$F_f$</td>
<td>Feed force</td>
<td>[N]</td>
</tr>
<tr>
<td>$f_n$</td>
<td>Feed/revolution</td>
<td>[mm/rev]</td>
</tr>
<tr>
<td>$h$</td>
<td>Convection heat transfer coefficient</td>
<td>[W/m$^2$K]</td>
</tr>
<tr>
<td>$h_1$</td>
<td>Theoretical chip thickness</td>
<td>[mm]</td>
</tr>
<tr>
<td>$h_2$</td>
<td>Actual chip thickness</td>
<td>[mm]</td>
</tr>
<tr>
<td>$h_{min}$</td>
<td>Minimum chip thickness</td>
<td>[mm]</td>
</tr>
<tr>
<td>$h_{ex}$</td>
<td>Maximum chip thickness</td>
<td>[mm]</td>
</tr>
<tr>
<td>$i_C$</td>
<td>Inscribed circle</td>
<td>[mm]</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
<td>[W/m K]</td>
</tr>
<tr>
<td>$l_m$</td>
<td>Machined length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$n$</td>
<td>Spindle speed</td>
<td>[rev/min]</td>
</tr>
<tr>
<td>$\lambda_h$</td>
<td>Chip compression ratio</td>
<td></td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
<td></td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>Fluid boundary layer thickness</td>
<td></td>
</tr>
<tr>
<td>$\delta_T$</td>
<td>Thermal boundary layer thickness</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>$Q_{\text{cond}}$</td>
<td>Rate of conduction heat transfer</td>
<td>[W]</td>
</tr>
<tr>
<td>$Q_{\text{conv}}$</td>
<td>Rate of convection heat transfer</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>$r$</td>
<td>Nose radius of the cutting tool</td>
<td>[mm]</td>
</tr>
<tr>
<td>$U_\infty$</td>
<td>Upstream velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$R_a$</td>
<td>Average surface roughness on new surface</td>
<td>[µm]</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>Inlet temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$T_S$</td>
<td>Surface temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of material removed</td>
<td>[cm³]</td>
</tr>
<tr>
<td>$V_B$</td>
<td>Flank wear</td>
<td>[µm or mm]</td>
</tr>
<tr>
<td>$v_{\text{ch}}$</td>
<td>Chip velocity</td>
<td>[m/min]</td>
</tr>
<tr>
<td>$v_c$</td>
<td>Cutting speed</td>
<td>[m/min]</td>
</tr>
<tr>
<td>$Q$</td>
<td>Metal removal rate</td>
<td>[cm³/min]</td>
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**ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BSA</td>
<td>Base surface area</td>
</tr>
<tr>
<td>BUE</td>
<td>Built-up-edge</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>Co</td>
<td>Cobalt</td>
</tr>
<tr>
<td>EDS</td>
<td>Electron-dispersive X-ray spectroscopy</td>
</tr>
<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>Gen I</td>
<td>First generation insert</td>
</tr>
<tr>
<td>Gen II</td>
<td>Second generation insert</td>
</tr>
<tr>
<td>HRSA</td>
<td>Heat Resistant SuperAlloys</td>
</tr>
<tr>
<td>LOM</td>
<td>Light optical microscope</td>
</tr>
<tr>
<td>MRR</td>
<td>Material removal rate [cm$^3$/min]</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>SCL</td>
<td>Spiral cutting length [m]</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>TSA</td>
<td>Total surface area</td>
</tr>
<tr>
<td>WC</td>
<td>Tungsten carbide</td>
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</table>
CHAPTER 1. INTRODUCTION

For nearly three centuries, the traditional manufacturing industry has helped to grow the economy exponentially and improve the standard of living. Today, it still plays a vital role in advancing countries’ economies in global competition. A worldwide survey conducted by the McKinsey Global Institute, shows that the manufacturing sector contributes to about sixteen percent of the world’s gross domestic product, GDP [1]. Advancing manufacturing technology is key to unlocking future global competitiveness. This has encouraged nations to focus on strengthening their manufacturing technology. This is done by facilitating research and innovation and to build a high-end competence infrastructure in this area. The intention is to generate increased growth and benefit the nation’s economy by providing larger tax revenues. At present, several countries has initiated strategic programs solely focused on advancing the manufacturing sector [2]–[4]. One among them, Produktion 2030 initiated in Sweden, has envisioned to reinforce the manufacturing industry and develop strategies for environmentally friendly manufacturing.

One of the most important sectors to strengthen in manufacturing technology is aerospace. In particular, civil aviation has seen exponential growth over the last decades.

The aviation industry is driven by the individual needs of moving between places in less time, at low cost and in a more convenient way. The International Air Transport Association, IATA, states that within the overall operating cost, one-third is represented by fuel [5]. The fuel operating cost creates a requirement for the aircraft manufactures to design aircrafts with good aerodynamic properties and equipped with high performance engines.

The introduction of new jet engines, which exhibit lower fuel consumption and emission levels, is closely related to the development of new superalloys. The physics behind the air-breathing jet engine is based on the Brayton open cycle [6]. To improve the jet engine efficiency, one of the key requirements is to have the maximum engine temperature ratio, $T_{\text{in}}$ to $T_{\text{out}}$. High operating temperatures in jet engines require high-performance materials that can exhibit and retain their mechanical properties at elevated temperatures.

This requirement has led to the development and use of a group of alloys called Heat Resistant SuperAlloys, HRSA. HRSA possess distinct characteristics like excellent mechanical strength, high strength-to-weight ratio, low thermal conductivity, and resistance to creep, corrosion and oxidation at elevated temperatures.
Continuous improvement of HRSAs in the aero engine industry has increased the engine operating temperature at a rate of 10°C per annum in average since the 1950s, resulting in a lowering of emissions and fuel consumption [7].

One of the vital techniques in the manufacturing of HRSA parts is machining. Development of new materials with improved design performance regarding the mechanical properties of the parts at high temperature reduce at the same time their machinability.

Machinability is a dimensionless quantity used to characterize the “easiness to cut” of a material under a specified set of cutting conditions [8]. Trent and Wright expressed the complexity in defining machinability through the following quote [9]:

“The machinability of an alloy is similar to the palatability of wine - easily appreciated but not readily measured in quantitative terms”.

![Fig. 1. Trends for comparison of operating temperature, machinability and productivity for four different HRSA over time.](image)

The machinability of HRSA has decreased over time, as new materials have been introduced into the market, on other hand it has led to increase the operating temperature, see Fig. 1. The intention for the future is to move the productivity trend above the current machinability line, see Fig. 1. The ongoing research in the field of materials science will continue to develop new HRSAs and most likely increase their hardness at elevated temperature even further. This will challenge manufacturing technology to increase productivity of difficult-to-cut materials, or at least to maintain the level.

Regardless of the introduction of new materials, the fifty-year-old “work horse” material Alloy 718 remains, even by today’s standard a very difficult-to-cut material. Superalloys cause intense tool wear and require lower cutting parameters. As the tool wear increases, it affects the quality of the machined surface and it
may even damage the component causing it to end up as scrap. The entire process chain of machining HRSA components requires high precision which turns out to be both time consuming and expensive.

These conditions create a necessity for further research in order to capture the physics involved in the machining technology of HRSA materials.

1.1 Machining of HRSA

Machining is fundamentally a complicated process, which is governed by many different factors, as shown in Fig. 2. One of the prioritized areas is to improve the service life of the cutting tool, to counteract the falling trend in machinability. Improvements in the tool life also lead to a decrease of the non-productive time, such as tool change.

![Fig. 2. Important factors in machining.](image)

The service life of the cutting tool constitutes a part of the productivity chain in the machining process. Material Removal Rate, MRR, is a function of cutting speed, feed rate and depth of cut, see Fig. 3. This is quantified in cubic centimetre per minute. An increase in one or in combination with the cutting condition leads to an increase in MRR. However, increasing the productivity through MRR could counteract on the tool life. As a consequence, the effect of the existing mechanical, thermal and chemical load mechanisms are also prone to increase.
This leads to rapid deterioration of the cutting tool, which decreases the service life of the tool. This mechanism becomes intense with HRSA materials due to their properties, which in turn aggravates the tool.

![Diagram of productivity, cutting conditions, and tool life.](image)

Fig. 3. Relation between productivity, cutting conditions and tool life.

Introducing the concept by looking upon the machining process from a MRR perspective, the MRR can be increased by either increasing cutting speed or feed rate. Here, we will consider the depth of cut to be constant, for simplicity. ISO-MRR are curves where one maintains a constant material removal rate for a given set of values of both cutting speed and feed rate, the depth of cut assumed constant. In Fig. 4, each consecutive ISO MRR curve represents a twofold increase of MRR.

The increase in MRR in the direction of increased feed rate is mainly limited by the ultimate strength of the tool, which constitutes a mechanical barrier [10], see Fig. 4. The ultimate strength of the tool decreases in conjunction with rising temperature from heat generated in the cutting zone.

Boosting MRR by increasing the cutting speed leads to a raise in heat generation in the shear zones in combination with hot chips sliding over the cutting tool, which constitutes a thermal barrier. When the cutting speed is selected closer to the region of the thermal barrier, as shown in Fig. 4, the tool softens at the elevated temperature, leading to tool deformation and failure. As the cutting tool operates in the higher region of MRR with high values of both feed rate and cutting speed, the combined effect of the mechanical and thermal load causes rapid tool wear. A significant character of HRSA materials is their low thermal conductivity, which gives rise to a more focused heat on the very cutting edge and causes rapid deterioration of the cutting tool.
Heat generation and heat transfer were recognized, as early as 1798 by Count Rumford [11], as major governing factors when conducting boring operations on canons in Bavaria. The power consumed is largely converted into heat around the cutting zone. In the cutting zone, heat is generated in the primary, secondary and tertiary shear zones, see Fig. 5. When machining non-HRSA materials, most of the heat is carried away by the chips and the remaining heat is dispersed both into the cutting tool and the workpiece material.

Machining HRSA, however, is a totally different matter, with high temperature located at the cutting edge. This is due to the low thermal conductivity of the workpiece material, thus acting as a thermal insulator. Consequently, the heat dissipation into the cutting tool is increased significantly [8], see Fig. 6.
For the reasons given above, there is a higher steady state temperature in the cutting zone which influences tool life and properties of the machined workpiece, especially for continuous processes.

![Comparison of heat dissipation between non-HRSA (left) and HRSA (right), the figure shows higher concentration of heat accumulated in the proximity of the cutting edge when machining HRSA due to the low thermal conductivity of the alloy.](image)

Fig. 6. Comparison of heat dissipation between non-HRSA (left) and HRSA (right), the figure shows higher concentration of heat accumulated in the proximity of the cutting edge when machining HRSA due to the low thermal conductivity of the alloy.

Previous research has revealed that an effective way of lowering the overall cutting temperature is by flood cooling. Results show improved tool life and surface finish compared to dry machining [12]–[14]. In 1952, Pigott and Colwell [12], first applied the new concept of a pressurized coolant jet focused closer to the cutting edge to improve cooling and extend the tool life. They conducted experiments in a lathe equipped with oil as a coolant and supplied jet pressure ranging from 2.75 to 4.13 MPa. Their results show that the tool life increased by seven to eight times. They also obtained better chip breakability [12].

In 1991, E.O. Ezugwu et al. for the first time used high-pressure jet assisted machining of Inconel 901 at 14 MPa. The experiment showed contradicting results regarding tool life. The work revealed that the use of high jet coolant has the capability to extract heat, breaking chips more efficiently and lowering tool-chip contact length [15]. This was a breakthrough which has broadened the research area of high pressure jet assisted machining of HRSA. It also initiated further research in the areas of tool holders with external and internal jet nozzles, more precise nozzle technology for high-pressure jet assisted machining.

1.2 Research Description

Previously, research in machining has been conducted on cutting tools and cooling technologies independently of each other. This is surprising, since both areas are frequently used in industrial applications and have been studied in academia. But both areas have so far been developed in parallel.
INTRODUCTION

This research is dedicated to the study of the interface between the coolant and the cutting insert. Also, to investigate the possible benefits of surface modifications to high temperature areas of the insert to promote a more efficient heat transfer from the insert to the coolant.

There are several ways to improve the heat transfer from the cutting insert. Firstly, heat conduction through the boundary layer between the high-pressure coolant jet and the insert rake and flank faces. There is a relationship between the available useful area for heat transfer surface and the amount of heat transfer that could be dissipated. Here, the intention is to increase the surface area on the insert in regions which exhibits high thermal gradients. This to improve the heat transfer in these areas. Secondly, convection. The purpose is to promote high surface velocity in order to reduce the thickness of the thermal boundary layer where pure conduction appears. In this work, no investigation has been carried out on the radiation part of the heat transfer.

![Thermal factors in machining](image)

Fig. 7. Thermal effects in machining.

Another phenomenon that can occur in the proximity of the cutting zone is the boiling of coolant. This takes place when the fluid interacts with the hottest faces of the cutting tool. Boiling is a very good way of transferring heat, in particular if pool boiling occurs. However, if the temperature of the hot surface is too high and the heat flux too great compared to what the liquid is capable of transferring, a Leidenfrost film could be created. This Leidenfrost film is a vapor layer that insulates the hot surface from coolant and thereby restricts the access of additional coolant to reach the hot surface, thus lowering the heat transfer rate [16]. Formation of a Leidenfrost film is highly disadvantageous in machining operations, restricting the heat transfer. Thus, there is an incentive to further investigate how such a formation can be counteracted, or totally eliminated, during the machining operations. If a steady state temperature with respect to
heat flux could be established, that is below the Leidenfrost point, it would be very beneficial.

1.3 Research Objective

The overarching research objective of this work is to counteract the influence of the reduced machinability by the introduction of new HRSA materials, besides improving the productivity of HRSA materials used in production today. Moreover, obtained results can also benefit the machining of other hard-to-cut materials, thereby, enhancing productivity in a wider range of the metal working industry.

This will be obtained by looking into thermal aspects of machining. The intention is to create a favourable interface between cutting tool and coolant. Thus, a more effective use of the coolant to improve the heat transfer rate from the cutting zone.

1.4 Research Questions

The objective to create an improved interface between cutting tool and coolant for effective heat transfer in the cutting zone is approached through a set of research questions:

1. Can an increase of available surface area by adding cooling surface features for heat transfer in regions where high-thermal gradients are present reduce tool wear?

2. On which surface (rake or flank, or both) will the creation of adding cooling surface features have the most influence on the tool wear?

3. Can tool wear be influenced by the introduction of multiple surface features in the contact zone on the rake face to bring more access of coolant in the proximity of the cutting edge?

1.5 Research Methodology

This research work was initiated with an extensive literature study of high-pressure coolant-assisted machining and, in particular, focused on the application involving HRSA materials. The intention was to comprehend the essential knowledge of previous research in this field. The result of the literature survey is reported in Chapter 2.
INTRODUCTION

The research articles collected were at first selected based on the journal’s impact factor. In the primary survey, the papers were searched in journals with impact factor above one. However, the field of research turned out to be very narrow and with a relatively short history. Therefore, the number of papers are very scant. Hence, a secondary literature survey was conducted which included conference papers and low impact factor journals. This extended the survey and offered a more complete picture of the scientific work conducted in this area.

With the result from the literature survey serving as a baseline of knowledge, one was able to verify and avoid replicates of already existing work. Thereby, proposed hypothesis and research questions selected, were valid see section 1.4. Identified areas of scarcity of knowledge were in the interaction between the coolant and cutting tool. In particular, no focus had been on the physics behind heat transfer or how an interface could be designed, relating to high pressure coolant assisted machining.

Firstly, a square pyramid geometry was developed as a texture and these were then superimposed on a regular carbide insert in the areas, rake and flank, where high thermal gradients are present. This new insert was called Gen I. To increase the surface area on the cutting tool, a volume was removed through a square pyramid geometry in form of indents. These indents can create a larger surface area while at the same time not limiting the structural strength of the cutting tool. These textures were used to investigate the effect of increasing the available surface area for heat transfer.

Experiments were conducted using cast Alloy 718 with the high-pressure coolant present. Three spiral cutting lengths, SCL, were chosen in evaluation of the inserts. In aspect of contact time between insert and workpiece at lower cutting conditions it was important to have longer SCL as 565 m, at the same time for higher cutting speed and feed rate to avoid insert breakage, 188m of SCL was preferred. The thermal conditions were varied by changing cutting speed and feed rate while the depth of cut was kept constant. This was done to understand how the heat dissipation affect the tool wear between Gen I and regular insert.

Secondly, it was important to understand which of the faces of the cutting tool, rake or flank has the most influence on heat dissipation. This was done by creating inserts with increased surface area only on the rake (named rake insert) and only on the flank (named flank insert). There were also inserts with texture on both rake and flank. The experiments were repeated for these inserts using the same cutting conditions as for regular inserts and Gen I.

Thirdly, the introduction of multiple surface features in the contact zone on the rake face acting as channels to bring more access of coolant in the proximity of the cutting edge. Here, the intention was to improve the cooling of the cutting edge itself where machining of HRSA materials which exhibits highest
temperature. The channel features on the rake face were added to the Gen I insert geometry, to be called Gen II. In addition to the above, this is supposed to improve the chip bending, thus lowering the chip contact area on the rake face in the secondary shear zone and lower the heat generated due to friction caused by mechanical interaction. Experiments for Gen II were repeated for the same cutting conditions that were used for Gen I and the regular insert.

All the cutting tools were examined after the experiments using Energy-dispersive X-ray spectroscopy, EDS, analysis, to understand the thermal conditions that the cutting tools were exposed to the process. The round shape of the insert created the necessity to build a standard for a consistent evaluation and analysis of the tool wear.

### 1.6 Limitations

This thesis work has limitations in its scope that are listed below:

- The research has been focused on machining on only one type of workpiece, cast Alloy 718 and one cutting tool material, uncoated cemented carbide.
- Only one type of insert size, shape and grading was used, *i.e.*, RCMX 12 04 08 H13A.
- Due to the workpiece dimensions, only facing operation was performed.
- For cooling fluid, one type of emulsion with a concentration of 5 pct. was used.
- The pressure used was 16 MPa on the rake face and 8 MPa on the flank face, respectively.
- Considering texture design, one geometry only, *i.e.*, square pyramid, was tested.
- No investigation has been carried out on the radiation part of the heat transfer.

### 1.7 Thesis Outline

This thesis is organized as follows:

The introductory chapters are *Chapter 1-2* and discuss the current state of the art in high pressure jet assisted machining and *Chapter 3* provides an introduction to the machining process.

The following chapters describe the aspects that are related to the experimental work. *Chapter 4* discusses the thermal and cooling aspect of the machining process; *Chapter 5* elaborates on different tool wear mechanism and tool wear.
INTRODUCTION

Chapter 6 holds information about different generation inserts and experimental data.

Subsequently, Chapter 7 consists of tool wear investigation results and analysis of experiments conducted for a regular and two new generations of experimental inserts.

Finally, Chapter 8 and 9 hold the conclusion and future work, followed by references and appended papers.

Fig. 8. Overview of the different generations of inserts studied and related tool wear investigation papers (*indicates paper in progress, not included in the thesis).
CHAPTER 2. CURRENT STATE OF THE ART

This chapter will discuss the comprehensive framework of the current state of art in high pressure jet assisted machining, focused on turning operation. In the upcoming sections will explore the main findings and a comparative study of the improvements over the years achieved using high-pressure coolant in the machining process. Thus, how it has helped to formulate this research work by identifying the knowledge gap.

In Fig. 9, illustrates the worldwide researchers’ experiments on different pressure during machining operations of varying materials from standard steel to HRSA. In 1950’s about 5 MPa (50 bar) was considered as a high-pressure, over the decades in the 20th century, the coolant pressure went as high as 360 MPa (3600 bar) an increase in pressure by approx. 70 times. In the beginning of 20th century, researchers move towards work on an optimized pressure range between 11 to 50 MPa, since increase in pressure lowered the tool life.

High-pressure coolant technology was of a primary interest to lower the cutting temperature to improve the tool life and cutting conditions. Since the flood cooling was insufficient to reach the hottest zones. Pigott and Colwell were the first to apply the pressurized jet to improve the cooling in the cutting zone. R.J.S. Pigott was awarded the Egleston medal for his findings in the year 1952. The impelling cause of their investigation was the existence of inadequate cooling strategies and the arrival of new materials that required better cutting conditions. Their results showed high-pressure coolant can increase the tool life by 7-8 times, compared to flood cooling. They increased cutting speed the improvement was even higher about 20-30 times or speed can be doubled for the same tool life [12].
Fig. 9. Overview of investigated pressure used in machining research over years.
In Table 1, summarized the findings of different researchers based on years, compared the process conditions, workpiece and cutting tool material, criteria of high-pressure coolant conditions, followed by evaluation and findings.

Table 1. An insight of the research contributions of various researchers from 1952 to 1990.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Workpiece</th>
<th>Cutting tool</th>
<th>Process conditions</th>
<th>Coolant conditions</th>
<th>Evaluation/Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>Pigott. R. J. S and Colwell. A. T [12]</td>
<td>SAE 3150, AISI 3140</td>
<td>High speed steel, Tungsten carbide</td>
<td>v&lt;sub&gt;c&lt;/sub&gt;: 80 to 120 SFPM</td>
<td>Flank face pressure: 0.18 to 4.13 MPa, Nozzle diameter: 0.35 to 1.2 mm</td>
<td>Tool life improved 7-8 times. Temperature in the edge of the tool dropped by 24°C.</td>
</tr>
<tr>
<td>1965</td>
<td>Rama Iyengar. H.S., Salmon. R., Rice. W.B [17]</td>
<td>AISI C-1025 steel</td>
<td>18-4-1 high-speed steel</td>
<td>a&lt;sub&gt;p&lt;/sub&gt; = 2.54 mm, v&lt;sub&gt;c&lt;/sub&gt; = 21 and 40 m/min</td>
<td>Coolant: through the tool, Cutting fluids: water, sulphurated mineral oil, kerosene, soluble oil-water emulsion</td>
<td>Evaluated temperature through chip color and they discussed chip curl diameter and cutting force. Cutting forces, chip curl diameter and temperature were reduced.</td>
</tr>
<tr>
<td>1966</td>
<td>Rice. W. B., Salmon. R. and Advani. A. G [13]</td>
<td>SAE 1040 steel</td>
<td>High-speed steel</td>
<td>v&lt;sub&gt;c&lt;/sub&gt; = 23 m/min, a&lt;sub&gt;p&lt;/sub&gt;=0.2 mm, Rake angle 7.5° and clearance angle 5°</td>
<td>Pressure: 68.9 MPa, Coolant through tool in tool-chip interface. Heating and cooling of workpiece.</td>
<td>Both heating and cooling of workpiece and cooling of the cutting tool reduced the cutting energy compare to dry machining. It was an initial step to understand the effects of heating and cooling on the properties of the workpiece material and on tool-chip friction.</td>
</tr>
<tr>
<td>1971</td>
<td>Sharma. C. S., Rice. W. B. and Salmon. R [18]</td>
<td>SAE 1040 steel</td>
<td>High-speed steel</td>
<td>a&lt;sub&gt;p&lt;/sub&gt; = 0.508 mm, v&lt;sub&gt;c&lt;/sub&gt; = 23 m/min, rake angle = 7°</td>
<td>Pressure: 68.9 MPa, nozzle diameter: 0.25 mm hole on the rake face for the coolant</td>
<td>Chip diameter reduced from 100 mm to 12-25 mm. Tool-chip friction reduced by 40 pct. An increase in the fluid temperature, improved the cooling.</td>
</tr>
</tbody>
</table>
Overview from 1952 to 1989, evolution of the high-pressure coolant technology and how the researchers carried out various methods and ideas to improve the tool life. The study showed researcher’s primary interest was to improve the cooling of the cutting tool followed by to create a better interface for the coolant to reach closer to the cutting edge. Thus, to improve the cutting conditions, surface finish and MRR.

In Table 2, summarizes the findings from 1990 to 2000, also expounds the researcher’s interest and contributions to improve the technology and its application. In 1991, Ezugwu. E. O, took an initial step to conduct research in the application of high-pressure coolant technology in machining HRSA material (Inconel 901) in collaboration with Rolls Royce UK. The impelling cause was the rapid expansion in 1990’s the aerospace industries considerably increased the numbers of commercial flights, airports and passengers. The potential interest was to make components from superalloys for aircraft engine application which could improve the engine efficiency. During that time aircraft manufacturers were majorly depended on Aluminium. Which were machined at very high speed led to high productivity rate. The changeover to superalloys created a state to machine

<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher</th>
<th>Methodology</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Nappal B. K. and Sharma C.S</td>
<td>Pressure: 0.69 MPa to 2.06 MPa. Water soluble oil</td>
<td>Temperature and cutting forces were reduced.</td>
</tr>
<tr>
<td>1977</td>
<td>Hood M</td>
<td>Two jets at a pressure of 68.9 MPa directed to centrally/corners of the cutting tool.</td>
<td>Doubled the depth of cut with reduced force exerted on the tool, when the coolant jets were directed at the corners of the tool.</td>
</tr>
<tr>
<td>1979</td>
<td>Sandvik Coromant Jet-Break™</td>
<td>Introduced in turning operations, main application was to machine Titanium for aerospace applications.</td>
<td>To improve the surface properties and MRR for difficult to cut materials by reaching the upper limits of the cutting speed for these materials.</td>
</tr>
<tr>
<td>1986</td>
<td>Yankoff G. K</td>
<td>Patented tool holder with nozzle design to deliver the coolant closer to the cutting edge.</td>
<td>Intention is to have combination of orifice spacing, coolant velocity and feed rate within a critical range to improve chip control and tool life disregarding the type material and operation. Delivery of the coolant on the rake face at a velocity range of 75 to 300 m/s. The distance between the nozzle and cutting edge was set in the range of 1 to 10 mm. The feed rate was in axial direction varied from about 0.1 to 0.6 mm/rev.</td>
</tr>
</tbody>
</table>
CURRENT STATE OF THE ART

at much lower cutting speed due to their metallurgical characteristics, which in turn lowered the production rates [15].

Initially high speed steel tools were used for machining nickel alloys at a low cutting speed, 5 to 8 m/min. The introduction of carbide cutting tools revolutionized the machining of these materials by enabling to reach cutting speeds of approximately 30 m/min. In 1990’s carbide cutting tools have remained the best tool materials for machining superalloys, also considered to be an expensive tool on the market [15].

Contrariwise, cemented carbide tools can’t withstand the extreme conditions of the stresses and temperature generated in the cutting zone during high speed machining. It has therefore led to an extensive research and development of alternative tool materials. New super abrasive cutting tools from cubic boron nitride (CBN) and ceramic tools materials. Made from $\text{Al}_2\text{O}_3 + \text{ZrO}_2, \text{Al}_2\text{O}_3 + \text{TiC (+TiN)}$, Sialon and SiC whisker reinforced alumina based ceramic tool during same time with new tool-geometries enabled higher cutting speed in 1990’s. The intention of new cutting tool material developed was to retain their mechanical properties at elevated temperature while machining superalloys [15].

Table 2. An insight of the research contributions of various researchers from 1990 to 2000.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Workpiece/Cutting tool</th>
<th>Process conditions</th>
<th>Coolant conditions</th>
<th>Evaluation/Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>Ezugwu. E. O., Machado. A. R., Pashby. I. R and Wallbank. J [15]</td>
<td>Inconel 901</td>
<td>$f = \frac{0.127}{1.18}$ mm/rev, $a_p = 1.25/2.5$ mm</td>
<td>Flood cooling 5.20 l/min, Coolant pressure 14 MPa, flow rate 15.10 l/min.</td>
<td>Negative influence on the tool life. Small segmented chips were produced. The premature fracture of carbide and ceramic inserts suppressed while using high pressure coolant jet.</td>
</tr>
<tr>
<td>1991</td>
<td>Lindeke. R. R., Schoenig. F. C., Khan. A.K. and Haddad. J [21]</td>
<td>Titanium alloy Ti-6Al-4V, TPG 432 C2 carbide</td>
<td>$a_p = 2.54$ &amp; 3.81 mm, $f = 0.127$ &amp; 0.254 mm/rev. $v_c$ ranged from 40 to 183 m/min.</td>
<td>Tool holder had a sapphire jet nozzle of diameter 0.31 mm with a maximum pressure about 379 MPa at a</td>
<td>Coolant reaches underneath the chip at a point very close to the cutting edge of the insert. Better bending and floats the chip off the rake face. Lowered tool-chip contact and temperature of the cutting tool.</td>
</tr>
<tr>
<td>Year</td>
<td>Author(s)</td>
<td>Tool Material</td>
<td>Cutting Speed (m/min)</td>
<td>Feed (mm/rev)</td>
<td>Depth of Cut (mm)</td>
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<tr>
<td>1992</td>
<td>Wertheim, R., Rotberg, J and Ber. A [22]</td>
<td>AISI 4140, AISI 316, Inconel 718, Uncoated ISO P40 and coated ISO P20-P40</td>
<td>To develop and test a grooving tool with a chip former groove. Inconel</td>
<td>30</td>
<td>m/min, f = 0.16 m/min</td>
</tr>
<tr>
<td>1994</td>
<td>Machado. A. R and Wallbank. J [23]</td>
<td>Ti-6Al-4V, Inconel 901</td>
<td>Ti-6Al-4V</td>
<td>v&lt;sub&gt;c&lt;/sub&gt; = 14, 62, 75 &amp; 84</td>
<td>m/min, f = 0.18, 0.25, 0.35 &amp; 0.50 mm/rev.</td>
</tr>
<tr>
<td>1999</td>
<td>Öjmertz. K. M. C and Oskarson. H. B [24]</td>
<td>Inconel 718, Silicon carbide whisker reinforced ceramic</td>
<td>Tool-chip interface. Pressure: 80, 240, 320, 360 MPa. The flow rate for orifice 0.15 mm was 0.30, 0.52, 0.60 and 0.64 l/min. For orifice diameter 0.25 mm was 0.84,</td>
<td>v&lt;sub&gt;c&lt;/sub&gt; = 150 m/min, f = 0.1 mm/rev, a&lt;sub&gt;p&lt;/sub&gt; = 1.5 mm</td>
<td></td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Tool Material</th>
<th>Process Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Crafoord. R, Kaminski. J, Lagerberg, Ljungkrona. O and Wretland. A [25]</td>
<td>SS2258 (SAE 52100)</td>
<td>Pressure from 16 to 80 MPa, Nozzle diameter 0.35 to 0.8 mm.</td>
<td>The upcurl radius of the chip doesn’t depend only on the jet power, but also in correlation between flow rate and water pressure. Cutting forces were not influenced by the high-pressure coolant reason might be the low pressure &lt; 100 MPa, previous researchers have reported pressure in the range over 200 MPa has lowered cutting forces in particular, feed force. Jet coolant forming wedge between the tool rake face and chip has potential to control to the upcurl radius of the chip. For larger depth of cut was necessary to use more than one jet beam to have full chip control. This is due to the lack of momentum with one beam.</td>
</tr>
<tr>
<td>2000</td>
<td>Kaminski. J and Alvelid. B [26]</td>
<td>SS2541-03 Al2O3 coated carbide insert SPUN 19 04 12, 3015 K15 (P10), without chip breaker.</td>
<td>$v_c = 150, 225 &amp; 300$ m/min, $f = 0.1, 0.2, 0.3$ mm/rev and $a_p = 3$ mm. Thermocouples were considered new temperature measurements.</td>
<td>Between 20 and 70 MPa there was a significant decrease in temperature. Additional increases in pressure didn’t effect in lowering the temperature. Surface roughness improved with increase in pressure at 300 MPa. To improve cooling by 40-45% necessary to break through the steam with high pressure concentrated water jet.</td>
</tr>
</tbody>
</table>
From 1990 to 2000, researchers focussed on developing new tool holders, increase the coolant pressure, which reached up to 360 MPa to investigate the tool-chip interface, chip formation, chip curl radius, tool wear mechanism and etc. Meanwhile, new cutting tools were experimented with HRSA materials with primary importance to improve the cutting conditions and tool life. Thermocouples were used for temperature measurements. Kaminski. J and Alvelid. B stated “Steam generated around the hot surface of the insert and chip preventing the coolant to reach closer to the cutting zone” concluded it is necessary to further increase the pressure to break through the steam. This steam phenomenon in the world of physics is known as Leidenfrost effect which is discussed in this thesis about its traces and influence on the machining process. Instead of increasing the pressure, which leads to increase the energy inputted into the process, there lays a possibility to work on the cutting tool and its interface with coolant that is included in this work.

From 2000 to 2016 the research focus turned in the direction of the cooling fluids and application strategies. Residual stress got its interest at this time to understand the effect of the coolant in different process such as roughing and finishing. In the 20th century begun with high interest on the cryogenic cooling in particular applied in machining components from HRSA.

Table 3. An insight of the research contributions of various researchers from 2000 to 2016.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Workpiece /Cutting tool</th>
<th>Process conditions</th>
<th>Coolant conditions</th>
<th>Evaluation/Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Hong. S. Y, Markus. I and Jeong. W.C [27]</td>
<td>Ti-6Al-4V</td>
<td>f = 0.254 mm/rev, ap = 1.27 mm, vc = 60, 90, 120, 150 m/min.</td>
<td>Liquid Nitrogen, LN2, applied at tool-chip interface through an innovative micro nozzle.</td>
<td>Tool life with cryogenic cooling increased up to five times longer than conventional method at vc of 150 m/min. Carbide tool behaved as close to the ceramic tool with cryogenic cooling also improved the machinability of Ti-6Al-4V.</td>
</tr>
<tr>
<td>2002</td>
<td>Dahlman P [28]</td>
<td>SS 2258 SS 2541 Ti-6Al-4V</td>
<td>f = 0.3 mm/rev, a_p = 3 mm, Steel v_c = 300 m/min, Titanium v_c = 50 m/min.</td>
<td>Convectional cooling: 0.5 MPa, 30 l/min. High-pressure cooling: 80 MPa, 13 l/min, nozzle diameter = 1 mm. Synthetic cooling emulsion Sintolin 86.</td>
<td>SS 2541 high pressure and low flow rate had highest temperature reduction. But for SS 2248 the opposite reduces temperature. High-pressure coolant reduced about 50% in contact length for both steel grades. Cooling is very important when turning Ti-6Al-4V, is effective when applied along the cutting edge.</td>
</tr>
</tbody>
</table>
### CURRENT STATE OF THE ART

<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Material</th>
<th>Tool Type</th>
<th>Feed Rate</th>
<th>Depth of Cut</th>
<th>Cutting Speed</th>
<th>Pressure</th>
<th>Coolant</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Ezugwu. E.O and Bonney. J [29]</td>
<td>Inconel 718</td>
<td>SiC whisker reinforced ceramic inserts</td>
<td>$f = 0.15 &amp; 0.25$ mm/rev, $a_p = 1.5\text{--}2.5$ mm, $v_c = 200, 250, 300$ m/min.</td>
<td>Pressure: 11, 15 &amp; 20.3 MPa.</td>
<td>Coolant concentration: 6 pct.</td>
<td>Increase in coolant pressure lowered the tool life due to severe notching and generated component forces. The high-pressure coolant reduces the temperature at the cutting zone below a critical level. Didn’t significantly affect the surface finish.</td>
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<tr>
<td>2003</td>
<td>Vosough. M, Liu. P and Svennings son. I [30]</td>
<td>Ti-6Al-4V</td>
<td>Uncoated round cemented carbide tool</td>
<td>Roughing: $f = 0.4$ mm/rev, $a_p = 3$ mm, $v_c = 70$ m/min.</td>
<td>Finishing: $f = 0.2$ mm/rev, $a_p = 0.3$ mm, $v_c = 250$ m/min.</td>
<td>Coolant was 5% soluble oil.</td>
<td>Pressure: 28 MPa.</td>
<td>Effect on residual stress using x-ray diffractometry</td>
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<td>High-pressure cooling has increased the tool life up to 50% compared to conventional cooling. Compressive residual stresses in the transversal and longitudinal directions of the cut, was about -300 MPa. Stress decreased with an increase in the cutting time and flank wear. Feed direction has higher compressive residual stresses than in the cutting direction. During finishing operation, high pressure increase compression stresses with 100 MPa. Residual stress during finishing operations affected more than roughing by high-pressure cooling.</td>
</tr>
<tr>
<td>2004</td>
<td>Ezugwu. E.O and Bonney. J [31]</td>
<td>Inconel 718</td>
<td>Triple PVD coated, TiCN/Al2O3/TiN carbide tool</td>
<td>$f = 0.25 &amp; 0.3$ mm/rev, $a_p = 2.5\text{--}3$ mm, $v_c = 20, 30 &amp; 50$ m/min.</td>
<td>Pressure: 11, 15, 20.3 MPa.</td>
<td>Coolant concentration 6 pct.</td>
<td>Increase in coolant pressure showed a general increase in tool life. High-pressure led to a reduction of the tool-chip contact, thus lowering the coefficient of friction coefficient therefore reduces cutting temperature and component forces. At higher $v_c \geq 50$ m/min with 20.3 MPa was able to increase the tool life by 740 pct. also produced well segmented C-shape chips. Further increase in pressure above a critical point the coolant pressure doesn’t have a significant increase in tool life.</td>
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</tr>
<tr>
<td>2005</td>
<td>Ezugwu. E.O, Da Silva. R.B, Bonney. J</td>
<td>Ti-6Al-4V</td>
<td>Three grades of Cubic</td>
<td>$f = 0.15$ mm/rev, $a_p = 0.5$ mm,</td>
<td>Pressure: 11 and 20.3 MPa.</td>
<td>Increase in CBN content in the cutting tool tend to accelerate the notch wear rate, consequently lowering the tool life. T1 grade was more</td>
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<tr>
<td>Year</td>
<td>Author(s)</td>
<td>Material</td>
<td>Tool</td>
<td>Velocity</td>
<td>Coolant</td>
<td>Notes</td>
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<tr>
<td>2006</td>
<td>Bareggi, A, Torrance, A and Donnell, G</td>
<td>AISI 1020 steel with tungsten carbide tool</td>
<td>( f = 0.095 ) mm/rev, ( a_p = 0.5 ) mm, ( v_c = 270 ) m/min.</td>
<td></td>
<td>Intention to replace the high-pressure coolant and Minimum Quantity Lubrication, MQL with supersonic air-jet as a coolant. Inlet pressure: 0.6 MPa directed tool-chip contact</td>
<td>Infrared camera was used to monitor the temperature of the cutting tool with and without coolant. Surface roughness values had less impact with air jet cooling. The results showed the supersonic air jet has reduced the temperature and cutting forces and modified chip shape, requires further investigation with air jet assisted cooling.</td>
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<tr>
<td>2006</td>
<td>Sorby, K and Tønnesen, K</td>
<td>Ti-6Al-4V, 36 HRC, Grooving Uncoated carbide tool Two geometries N123G2–0400–RM, round insert and N123G2–0500–0003–GM, neutral insert</td>
<td>( f = 0.12 ) mm/rev, ( a_p = 6 ) mm, ( v_c = 120-160 ) m/min.</td>
<td>Coolant jet on both rake and flank face. Rake nozzle 1.4 mm, 10-30 MPa and flank nozzle 0.6/1.1 mm, 5-30 MPa. Flood cooling 0.7 MPa at 26 l/min.</td>
<td>High-pressure 10-30 MPa in the rake face can increase 200-300 percent in tool life, the application of high pressure coolant on the tool flank face increases tool life by 50-100 percent compared to flood flushing. The chips were well segmented in shorter lengths. At high pressure on the rake face may cause an adverse effect on the other parts of the workpiece surface by chip flow. There was no damage observed on the workpiece surface. Surface alteration was observed with rake face cooling not with flank face cooling. Cooling in flank face is highly recommended in order to increase the productivity by improving the tool life. It was concluded high-pressure cooling on the both faces is of primary importance.</td>
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</tr>
<tr>
<td>2007</td>
<td>Kamata, Y and</td>
<td>Inconel 718 3 different grades of</td>
<td>( f = 0.1 ) mm/rev, ( a_p = 0.1 ) mm,</td>
<td>MQL, Biodegradable synthetic ester as</td>
<td>For ( v_c ) 60 m/min, Coating A with MQL showed the best performance: was second in</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**CURRENT STATE OF THE ART**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Process</th>
<th>Tool</th>
<th>Coating</th>
<th>Feed</th>
<th>Depth of Cut</th>
<th>Cutting Speed</th>
<th>Pressure</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Courbon, C., Kramer, D., Krajnik, P., Pusavec, F., Rech, J., Kopac, J.</td>
<td>Rough turning of Inconel 718</td>
<td>PVD coated carbide tool (grade P25 SNMG120404-23)</td>
<td>TiAlN</td>
<td>f = 0.2, 0.224 &amp; 0.25 mm/rev, a_p = 2 mm, v_c = 46, 57, 63, 74, 81 m/min.</td>
<td>0.2, 0.224 &amp; 0.25 mm/rev, a_p = 2 mm, v_c = 46, 57, 63, 74, 81 m/min.</td>
<td>Pressure: 50, 90 &amp; 130 MPa. Nozzle diameter: 0.25, 0.3, 0.4 mm</td>
<td>For the fixed jet pressure, increase in nozzle diameter permitted to reach higher feed rates and cutting speed. Able to yield a 20% increase in the cutting speed and feed rate with a 250% increase in nozzle diameter. Excellent chip breakability, reduction in build-up edge, extension of process range of operability of the cutting tool has been proven.</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Obikawa, T., Funai, K., Kamata, Y.</td>
<td>Finish turning of Inconel 718</td>
<td>Uncoated carbide tool CNMG120404 and PCLN R2525</td>
<td>Ti6Al4V+(Ti,Al)N+TiN coated carbide cutting tool CNMG 0812</td>
<td>f = 0.1 mm/rev, a_p = 0.3 mm, v_c = 108, 126 &amp; 150 m/min.</td>
<td>Air assisted machining. Cutting fluid concentration 6.7%, nozzle diameter inner diameter 1.1 mm, pressure: 0.54 MPa measured flow rate of 61.7 l/min exit velocity 175.4 m/s</td>
<td>Extended tool life by 20, 27 and 11% for respective cutting speed 108, 126 and 150 m/min. Surface finish didn’t have significant influence. Air jet promotes turbulence of the cutting fluid between the cutting tool flank face and machined surface. Thus, contributing to reduce the thickness of the thermal boundary layer resulting in enhancing the heat transfer from the insert to the cutting fluid.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Oguz Colak, [38]</td>
<td>Inconel 718 with (TiAl)N+T iN coated carbide cutting tool CNMG 0812</td>
<td>Taguchi L18 orthogonal array. f = 0.05, 0.10, 0.15 mm/rev,</td>
<td>Convective cooling pressure 0.6 MPa. High-pressure 10 and 30 MPa. Swisslube Blaser</td>
<td>Convectional cooling pressure 0.6 MPa. High-pressure 10 and 30 MPa. Swisslube Blaser</td>
<td>Coolant application in the tool-chip interface decreases cutting force due to the mechanical effect of high pressure coolant. It has improved the chip breakability, reduced the tool-chip contact, and contributed to</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flank wear was reduced, though the high-pressure coolant was applied on a rake face. High-pressure coolant technology improved the productivity of hard-to-cut material by increasing the tool life, lowering the cutting force and reducing the energy consumption.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Material</th>
<th>Coolant</th>
<th>Pressure</th>
<th>Concentration</th>
<th>Tool life</th>
<th>Wear Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>Ayed, Y,</td>
<td>Ti17, uncoated WC, CNMG</td>
<td>BCool 650 5% concentration</td>
<td>15 and 20 MPa</td>
<td>6.7%</td>
<td>Tool life can be increased by a factor of five. Important wear mechanisms found were adhesion, diffusion and plastic deformation of the cutting edge. Results showed that wear mechanisms were different between conventional and high-pressure cooling. The percentage of alloying element for conventional cooling was about 45%, reduced to 21%. The titanium deposit rate on the cutting tool decreased about 25% with 10 MPa and 55% with 25 MPa. Adherent layers was reduced with increase from 10 MPa to 25 MPa. Cutting forces were lowered about 10% at 25 MPa for the roughing operation most likely was due to the decrease in the coefficient of friction.</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Obikawa, T and Yamaguchi, M</td>
<td>Inconel 718, SiC whisker reinforced alumina ceramic tool</td>
<td>Conventional</td>
<td>0.1, 0.2, 0.3 MPa</td>
<td>6.7%</td>
<td>Tool life was only 190 m with dry machining, 1290 m for ordinary wet machining. With Air jet assisted at a pressure of 0.2 MPa extended to 1850 m. Reduction of the rate of the notch wear in AJA machining was related to the formation of the tribo film through tribochemical reaction between Sic and coolant, which might be activated by the oxygen supplied with air jet. CFD analysis of coolant flow around the tool tip added better understanding to the wear mechanism.</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Krajnik, P, Rashid, A</td>
<td>Tool steel (45 HRC)</td>
<td>MQL with nCLFs</td>
<td>0.1, 0.2, 0.3 MPa</td>
<td>6.7%</td>
<td>Results showed MQL with nCLFs lowered tool wear by 10-15% compared to MQL</td>
<td></td>
</tr>
</tbody>
</table>
### CURRENT STATE OF THE ART

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Tool Type</th>
<th>Cutting Parameters</th>
<th>Cooling Type</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhenglon g Fang, Toshiyuki Obikawa [42]</td>
<td>Inconel 718 (568 HV) PVD coated carbide tools</td>
<td>$f = 0.1$ mm/rev, $a_p = 0.5$ mm, $v_c = 120$ m/min.</td>
<td>Micro textured flank face in combination with high-pressure coolant. 5 shapes Fin parallel, perpendicular, pit, dot and cross hatch. Flank pressure 13 MPa, flow rate 9.2 l/min, 8 mm away from the tool-tip. CFD simulations.</td>
<td>All the five types of micro-textures tool had better cutting performance compared to the non-textured tool. Cooling capability of the micro-textured tools was influenced by the height and array of microfins and micropits. In contrary, plate type microfins exhibited the fairly good performances regardless of their arrays and heights. The change of pit depth altered the distribution of turbulent kinetic energy of main flow as well as the flow pattern in the flank clearance.</td>
</tr>
</tbody>
</table>

Research in high-pressure coolant commenced in the direction to investigate the coolant pressure, exit velocity and flow rate. New tool holders were introduced to bring the coolant to the proximity of the cutting edge. Optimization of coolant pressure and impingent locations on the cutting tool, different types of chemicals used as coolants were investigated along with chip formation, temperature measurement techniques, tool wear mechanism, tribological effect, etc.

In later year’s focus was to develop new cooling strategies such as cryogenics, MQL, $\text{CO}_2$, air assisted cooling to investigate the possibility to minimize/alternate for conventional coolant to be replaced by eco-friendly cooling methods. Since long exposure of coolant by the operator could result in health issues and disposal/recycling of used coolant is of high importance. Another dimension is to visualize the interaction of coolant and the insert is to use Computational Fluid Dynamics, CFD. In 2013 Obikawa. T and Yamaguchi. M [43], conducted two phase CFD analysis of coolant and air to visualize the flow of coolant around the tool tip. In parallel during the development of high-pressure coolant there has been investigations conducted on the tool geometries and micro texturing features in the form of dimples, pits or linear grooves either on a rake or flank. Results of this has shown decrease in the cutting forces, friction coefficient, tool temperature and increase in service life of the tool [44].
The study of the current state of the art of high pressure coolant, in addition with texturing on the tools provides the fundamental knowledge for this research work. In the aspect of relating between tool life, cooling phenomenon, tribological properties and pressure. Different methods of evaluation included tool life based on the flank wear, ISO 3685:1993. Tool-chip contact area and chip breakability to evaluate the effects of coolant pressure on tool life and tool wear, temperature and cutting force measurements.

2.1 CONCLUDING REMARKS

From the literature study, the knowledge gap which was interesting to focus on in this thesis work was the physics behind the heat dissipation phenomenon in combination with high-pressure coolant. Most of the research done in the area of machining with high-pressure coolant were empirical and rather less focussed on the fluid mechanics and thermodynamics underlying in the process. The focus of this research is to investigate the process based on the physics involved.

Focus of the coolant pressure to increase the heat dissipation rate is important. On the other hand, an alternative research interest is to increase the surface area by texturing on both faces of the cutting tool where high temperature exits to influence the heat dissipation rate. Correspondingly, to find a geometry with the maximum increased surface area for a constant volume removed. Further to continue with surface features on the cutting tool to create a better interface for the coolant to reach the proximity of the cutting edge. To investigate the conditions behind the coolant boiling and vapor formation, acting as a barrier for coolant and how to eradicate it. Mentioned research interests have been investigated and presented in the upcoming chapters.

The future direction of research is to find the optimized pressure of the coolant in combination with the texture interface and cutting temperature. To understand the relation between the texturing, coolants boiling and vapor pressure of the fluid to improve the cutting conditions in machining superalloys.
MACHINING

CHAPTER 3. MACHINING

Machining is a traditional cutting process to cut a piece of workpiece material into a desired shape through guided movement of the cutting tool. Today, almost all products, particularly those containing metals, undergo machining at some point of their manufacturing. There are three main cutting operations used in industrial production, turning, drilling and milling. In the following section, the turning operation is discussed in detail.

3.1 TURNING PROCESS

Turning is a basic machining operation that may be divided into two different types, based on the tool movement [9]:

I. Longitudinal turning – the tool moves in the axial direction, see Fig. 10a.

II. Facing – the tool moves in the radial direction, see Fig. 10b.

During longitudinal turning, the workpiece material is rotating. A single point cutting tool is moved along the axis of rotation, i.e., in the axial direction, shearing away layers of material in the form of chips to create a new surface on the workpiece [9] Fig. 10.

During facing, the workpiece material is also rotated while a single point cutting tool moves towards the centre of the face, in the radial direction. The feed rate is measured in the radial direction and the depth of cut is measured parallel to the axis of rotation. During a facing operation, the cutting speed varies continuously as a function of the radius and approaches zero at the centre of the workpiece [9].

Fig. 10. (a) Longitudinal turning and (b) Facing.
3.1.1 Orthogonal and Oblique cutting

Orthogonal cutting:
In orthogonal cutting, see Fig. 11, the cutting edge is parallel to the uncut surface, where the cutting edge inclination angle is zero and the cutting edge is at right angle to the direction of the cutting velocity. The direction of the chip flow is perpendicular to the cutting edge. This is commonly known as a two-dimensional cutting process [45].

Oblique cutting:
In oblique cutting, see Fig. 12, the cutting edge is inclined to the uncut surface, where the cutting edge inclination angle, $\lambda$, is non-zero. The direction of the chip flow is at an angle to the cutting edge. This causes the chip side flow angle to be non-zero [45].

In a turning/facing operation, the cutting tool moves along the material at a cutting speed, $v_c$, with a depth of cut, $a_p$, and feed, $f_n$. The cutting speed is the rate at which the uncut surface of the workpiece passes the cutting edge of the tool. $v_c$, expressed in m/min is defined as the product of $\pi$, the initial diameter, $D_1$, in mm and the spindle speed, $n$, in rev/min divided by 1000.

$$v_c = \frac{\pi D_1 n}{10^3}$$ (1)

The feed rate is the distance advanced by the tool in axial or radial direction based on the process at each revolution of the workpiece. $f_n$ is generally expressed in mm/rev. The depth of cut is the thickness of the material removed from the workpiece, which is measured in mm in the radial direction for longitudinal turning and in the axial direction for facing operations.
The product of cutting speed, feed rate and depth of cut results in material removal rate, MRR, expressed in cm$^3$/min, and it is a parameter often used to measure the efficiency of a cutting process [9].

$$MRR [Q] = v_c f_n a_p$$  \hspace{1cm} (2)

The theoretical chip area, $A_D$, can be defined as the product of the $a_p$ and $f_n$ expressed in Eq. (3).

$$A_D = a_p f_n$$  \hspace{1cm} (3)

The chip compression ratio, $\lambda_h$, is defined as the ratio of $h_2$ to $h_1$, where $h_1$ is the theoretical chip thickness and $h_2$ is the actual chip thickness expressed in Eq. (4), and as shown in Fig. 13 [46].

$$\lambda_h = \frac{h_2}{h_1}$$  \hspace{1cm} (4)

The intersection of the rake and the flank face of the tool forms the cutting edge, nomenclature during an orthogonal cutting operation is illustrated in Fig. 13. The chip flows over the surface of the tool, which is known as the rake face. The flank face of the cutting tool is the one in contact with the workpiece during the machining operation [46]. Clearance/relief angle is the angle between the flank face of the cutting tool and the virgin surface of the workpiece. In most of the cases, the inserts are designed with a clearance angle ranging from 6° to 10° in order to avoid contact with the virgin surface created.

![Fig. 13 Nomenclature during orthogonal cutting process.](image)

When the cutting tool penetrates into the workpiece, the workpiece material undergoes shear deformation and is removed in the form of chips along a plane named the shear plane. The concept of a shear plane is also a simplification,
assuming that the chip forms along the shear plane. In fact, the shearing takes places in a zone around the shear plane called the shear zone [9]. The resulting chip is restrained by frictional forces in the tool rake face, see Fig. 14. As a consequence, chip velocity, \( v_{ch} \), is lower than the cutting speed [46].

![Fig. 14. Chip thicknesses, \( h_1 \) and \( h_2 \), chip velocity, \( v_{ch} \) and reactive forces between the cutting tool and chip material [46].](image)

The major part of the energy used in the cutting process is transformed into heat through plastic deformation in the primary shear zone. Friction is generated between the tool-chip on the rake face and tool-workpiece on the flank face, characterized as the secondary and the tertiary shear zones, see Fig. 15 [9].

![Fig. 15. Three shear zones.](image)

- In the Primary shear zone, the workpiece material is deformed under compression and sheared in the form of chips.
• In the Secondary shear zone, the formed chip creates sliding action on the rake face of the cutting tool, creating friction in the chip-tool interface.

• In the Tertiary shear zone, the virgin surface created is exposed to the clearance face of the cutting tool, causing workpiece-tool friction.

### 3.2 Workpiece and Cutting Tool

The low machinability of heat resistant superalloy materials has an adverse influence on the economy of the process. The term machinability has been in discussion for many decades due to its ambiguity. Most commonly, it is used to express easiness to cut a material with an acceptable finish at a low cost. The machinability for different materials was evaluated by M. P. Groover [47], based on tool life, cutting forces, power required, cutting temperature and material removal rate. This was achieved by taking a base steel, B1112, as the standard material and rate its performance as 1.00. Then, the machinability of different materials were compared with this reference and tabulated together with the corresponding Brinell hardness values [47].

Table 4. Approximate values of Brinell hardness and typical machinability rating for selected work materials [47]:

<table>
<thead>
<tr>
<th>S.no</th>
<th>Workpiece material</th>
<th>Brinell hardness</th>
<th>Machinability rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base steel: B1112</td>
<td>180-220</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>Low carbon steel: C1008, C1010, C1030</td>
<td>130-170</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>Medium carbon steel: C1020, C1025, C1030</td>
<td>140-210</td>
<td>0.65</td>
</tr>
<tr>
<td>4</td>
<td>High carbon steel: C1040, C1045, C1050</td>
<td>180-230</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>Tool steel (unhardened)</td>
<td>200-250</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>Cast iron, soft</td>
<td>60</td>
<td>0.70</td>
</tr>
<tr>
<td>7</td>
<td>Cast iron, medium hardness</td>
<td>200</td>
<td>0.55</td>
</tr>
<tr>
<td>8</td>
<td>Cast iron, hard</td>
<td>230</td>
<td>0.40</td>
</tr>
<tr>
<td>9</td>
<td>Inconel</td>
<td>240-260</td>
<td>0.30</td>
</tr>
<tr>
<td>10</td>
<td>Inconel X</td>
<td>350-370</td>
<td>0.15</td>
</tr>
<tr>
<td>11</td>
<td>Waspaloy</td>
<td>250-280</td>
<td>0.12</td>
</tr>
<tr>
<td>12</td>
<td>Titanium plain</td>
<td>160</td>
<td>0.30</td>
</tr>
<tr>
<td>13</td>
<td>Titanium alloy</td>
<td>220-280</td>
<td>0.20</td>
</tr>
<tr>
<td>14</td>
<td>Aluminium 2-S, 11-S, 17-S</td>
<td>Soft</td>
<td>5.00</td>
</tr>
</tbody>
</table>
3.2.1 Heat resistant superalloys

When it comes to machining, heat resistant superalloys, HRSA are considered to be ‘difficult to cut’ materials due to their ability to retain mechanical and thermal properties at elevated temperatures, which is favourable for applications in jet engines. HRSA are usually grouped into three major categories [48]: Ni-base, Fe-base and Co-base.

In particular, Ni-base superalloys are widely used in hot sections of the aircraft engines. Approximately 80 pct. of the superalloys are utilized in the aerospace sector. In today’s advanced aircraft engine up to 50 pct. of the weight is made up by Ni-base and Ni-Fe-base superalloys [49].

A comparison of temperature-dependent strengths and oxidation resistance properties for different materials is shown in Fig. 16 [48]. Alloys based on W and Mo are stronger at higher temperature, but do not possess good oxidation resistance properties. Pt alloys possess higher oxidation resistance properties, but they are inferior in strength. Ni-base alloys occupy a key position, due to their key combination of oxidation resistance and ability to retain strength at higher temperature and in particular their weldability.

![Comparison of Stress rupture and oxidation resistance property of different alloys, reconstructed from [48].](image)

Fig. 16. Comparison of Stress rupture and oxidation resistance property of different alloys, reconstructed from [48].
3.2.2 Alloy 718

Alloy 718 is a Ni-base material with high strength, corrosion resistant and thermally resistant properties, which is necessary in the hot zones, such as combustion chambers and turbines of the aircraft engines. With outstanding weldability and creep resistance properties at elevated temperature, Alloy 718 is a natural choice for making components for jet engines. In some engines of Pratt and Whitney, Alloy 718 components account 50% of all superalloys used [50]. Typical chemical composition of Alloy 718 is given in Table 5.

Table 5: Nominal chemical composition (%wt) of Alloy 718 [51]:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Ni</th>
<th>Cr</th>
<th>Nb</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Co</th>
<th>Si</th>
<th>Mn-Cu</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt. %</td>
<td>53.4</td>
<td>18.8</td>
<td>5.27</td>
<td>2.99</td>
<td>1.02</td>
<td>0.50</td>
<td>0.17</td>
<td>0.12</td>
<td>0.07</td>
<td>0.03</td>
<td>Bal</td>
</tr>
</tbody>
</table>

There has been extensive research conducted since 1960’s with regard to improving the machining process and also into metallurgical improvements to the machinability of Alloy 718 [52]. Even though the material has been used for more than five decades, it is still considered as ‘difficult to cut’.

Alloy 718 possesses several advantageous properties. However, when it comes to machining, it has a poor machinability factor due to its ability to retain high strength and hardness at elevated temperatures. During machining, work hardening of the workpiece leads to rapid tool wear, which affects the tool life. Due to the low thermal conductivity and thermal diffusivity properties of Alloy 718, there is accumulation of heat in the proximity of the cutting edge. The workpiece material will act as a thermal insulator on the cutting edge which leads to an increase in the steady state temperature [53]. Thus, the properties which make Alloy 718 preferable for high temperature applications is also negative for the machining process.

3.2.3 Cutting tool

Typical problems faced with cutting tools are rapid and intense tool wear during the machining of HRSA materials. This leads to short tool life, which contributes to an increase in the number of tool changes, which increases the non-productive time of the machine tool. Cutting tool materials commonly used for machining operations are high speed steel, cemented carbides, ceramic, polycrystalline cubic boron nitride. The softening point temperature of different cutting tool materials is tabulated in Table 6.
<table>
<thead>
<tr>
<th>Tool Material</th>
<th>Softening point temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed steel</td>
<td>600</td>
</tr>
<tr>
<td>Cemented carbide, WC</td>
<td>1100</td>
</tr>
<tr>
<td>Aluminium oxide, Al₂O₃</td>
<td>1400</td>
</tr>
<tr>
<td>Cubic boron nitride, CBN</td>
<td>1500</td>
</tr>
</tbody>
</table>

The selection of cutting tool material and geometry plays a key role in a successful machining operation. In order to enter a region of high MRR, a cutting tool with a combination of high toughness and high hardness at elevated temperature is necessary. The hardest material is diamond, followed by cubic boron nitride, CBN and other technical ceramics as cutting tools. Although they are hard materials, they are relatively fragile and exhibit both low toughness and low thermal resistance, see Fig. 17 [54]. The cemented carbide is an interesting material since it has a wide range of combined hardness and toughness. To machine HRSA materials, both ceramics and cemented carbide tools are used. Ceramics are able to machine at higher MRR regions. However, when it comes to tool life predictability, cemented carbides are more consistent than ceramic tools. Considering today’s advancement in materials and manufacturing technology, one challenge that still remains is to move the conditions of carbide cutting tools into the region of high MRR where, so far, only ceramic tools can be used to machine Alloy 718.

Fig. 17. Different cutting tool material hardness versus toughness properties [54].
In addition to the tool material strength, both the insert shape and micro geometry also influence the strength of the cutting tool. It is important to choose the insert shape according to the operation, since it influences the tool life. As the number of useable cutting edges of the tool increases, the tool cost decreases. As a rule of thumb, an increase in the included angle increases the strength and heat dissipation. As shown in Fig. 18, here is a trade-off between the strength of the insert and the versatility [55].

The round insert is a combination of maximum edge strength and the number of cutting edges. By rotating an angle of the available 360° on the inset to get a new edge. Round inserts are preferably used in roughing operations, but are less suitable in finishing operations, due to their tendency to vibrate and create chatter [55]. Also, a round insert reduces the chip thickness due to the longer cutting edge in contact with the workpiece, which is engaging radially. The inscribed circle, \( IC \), for the round insert is the same as the insert diameter. Larger \( IC \) inserts are used for heavy interrupted cuts and similar roughing operations [55].

![Fig. 18. Different insert shapes and properties [55], [56].](image)

The entry angle, \( \kappa_p \), is the angle between the main cutting edge of the insert and the workpiece surface, and it depends on the depth of cut. Based on cutting depth variations, \( a_p \), the entering angle ranges from 0° to 90°, altering the cutting force direction along the edge radius [56].

---

**Fig. 18. Different insert shapes and properties [55], [56].**
In round inserts, the depth of cut determines the entry angle, which is the same as the contact angle in the insert edge in Fig. 19, given by Eq. (5). When the depth of cut is equal to the radius of the insert, an entry angle of 90° is created. As the depth of cut decreases, the entry angle decreases as shown in Eq.(5) [56].

\[ \cos \kappa_r = \frac{(0.5 iC - a_p)}{0.5 iC} \]  

(5)

The maximum chip thickness, \( h_{ex} \), varies with round inserts, and depends on the entering angle and is calculated using Eq. (6) [56].

\[ h_{ex} = f_n \times \sqrt{\frac{4a_p}{iC} - \left(\frac{2a_p}{iC}\right)^2} \]  

(6)
CHAPTER 4. THERMAL AND COOLING ASPECTS IN THE MACHINING PROCESS

The thermal and cooling aspects of the machining process, i.e., heat generation and heat transfer in the cutting zone are of vital importance in influencing the tool life. Introducing high-pressure cooling will influence and improve the heat dissipation from the cutting zone to the fluid, as discussed in the following section.

4.1 HEAT GENERATION AND DISSIPATION IN THE CUTTING ZONE

The power input to the machining process is, to a large extent, converted into heat in the cutting zone. According to Trent [9], “Most of the economic and technical problems of machining are caused directly or indirectly by this heating action”. The productivity of the machining process strongly depends on the MRR, which can be improved by increasing the cutting speed/feed/depth of cut or any combination of these. But one restriction is that the tool life shortens drastically due to increase in either cutting speed and or feed rate [9]. It was stated by Kitagawa [57] that, in general, it is not the mean cutting tool temperature, but local edge temperatures that govern tool wear.

Heat generation and heat dissipation in the cutting process are shown in Fig. 21 (a). The isothermal distribution on the cutting tool wedge during machining of steel at a cutting speed of 60 m/min is shown in Fig. 21 (b), [58].

![Fig. 21. Heat generation and temperature distribution on the cutting tool adapted and reconstructed from Vieregge. G [59]](image)

In particular, low thermal conductivity of the Ni-base superalloys leads to increase and insulates the heat at the cutting edge. That means that heat will accumulate close to
the cutting edge. In addition, Ni-base superalloys exhibit strong work hardening that influence the machinability further. Thus, a small increase in the cutting speed/feed rate leads to negative effects on the tool life [9].

4.2 Heat Transfer in the Cutting Zone

Heat transfer is the exchange of thermal energy between physical systems at different temperatures. Heat fundamentally transfers from a high temperature region to a lower temperature region to attain a thermal equilibrium. The three basic modes of heat transfer are conduction, convection and radiation [60].

In machining, the two modes of primary interest are conduction and convection. In conduction, \( Q_{\text{cond}} \), transfer of heat energy occurs via solid media between tool/chip/workpiece. The three main regions, where heat is generated in the cutting process, are shown in Fig. 15. Primary, secondary and tertiary shear zones influence the cutting tool life and tool wear mechanisms.

In Eq. (7), \( Q_{\text{cond}} \) is the rate at which heat is transferred by conduction, which is proportional to the temperature gradient \( dT/dx \) times the area, \( A \), through which heat is transferred. The local temperature is denoted by \( T(x) \), where \( x \) is the distance in the direction of the heat flow [60].

\[
Q_{\text{cond}} \propto A \frac{dT}{dx}
\]  

(7)

The heat transfer depends on the thermal conductivity, \( k \), which is the physical property of the medium. Considering a homogeneous medium for conduction, the rate of the heat transfer can be described by Eq. (8). According to the second law of thermodynamics, heat must flow in the direction from higher to lower temperature region, which is indicated by the minus sign [60].

\[
Q_{\text{cond}} = -k A \frac{dT}{dx}
\]  

(8)

The heat transfer during the dry machining process is shown in Fig. 22. Heat generation in the machining process is governed by the combination of cutting conditions, geometry of tool and workpiece, physical and chemical properties of the cutting tool and the workpiece material.

Thermal boundary regions of interest are the cutting edge, shearing away the workpiece materials, the tool-chip contact where sliding and friction occurs and the tool-workpiece interface. Most of the heat generated is transferred through conduction between chip, tool and workpiece material. As mentioned above, in the case of a low thermal conductivity workpiece material, the heat is sealed in the cutting edge causing the process temperature to increase drastically. The focus of development is to improve the heat dissipation in the hot cutting zone. Gen I
inserts are designed based on increasing the surface area. According to Eq. (8), this is directly proportional to the heat transfer rate of conduction.

![Thermal boundary conditions](image)

Fig. 22. Occurrence of different heat transfer modes in dry machining.

Convection, $Q_{\text{conv}}$, is classified as *natural* or *forced* convection, depending on how the fluid motion was initiated. Convection is considered as heat transfer through a fluid in the presence of bulk fluid motion and in its absence, the heat transfer occurs by conduction [61].

Looking closer into the machining process with the assistance of coolant, Fig. 23 shows the occurrence of both heat transfer mechanisms, conduction through a solid medium and forced convection by a coolant.

The convection heat transfer mechanism is seen as a complicated process due to the fact that it involves fluid motion as well as heat conduction. The fluid motion enhances the cooling effect and the heat transfer rate when it gets in contact with a hot surface, since it attempts to achieve thermal equilibrium between two medium. The convection heat transfer strongly depends on the fluid properties, such as thermal conductivity, $k$, dynamic viscosity, $\mu$, density, $\rho$, specific heat, $C_p$ and fluid velocity, $U$. In addition, it is governed by the type of fluid flow (laminar or turbulent), and also roughness and geometry of the solid surface over which the fluid flows. However, it is observed that the rate of convection heat transfer is proportional to the temperature difference, as expressed by Newton’s law of cooling, Eq. (9) [61].

$$Q_{\text{conv}} = h A_s [T_s - T_\infty]$$  \hspace{1cm} (9)
The convection heat transfer coefficient $h$, is defined as the rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference [61]. Following the reasoning above, this is hence dependent on the roughness of the surface, fluid properties and type of fluid flow. In machining with coolant assistance, the dominant mode is convection heat transfer in addition to the conduction between the workpiece, tool and chip, as shown for dry machining see Fig. 22. The coolant influence in enhancing the convection heat transfer, and this turns in turn leads to an improved cooling of the cutting zone, see Fig. 23. The application of high-pressure coolant on the rake face naturally forms a hydraulic wedge shape between tool and chip, see Fig. 23. At high pressure, the coolant transmits the mechanical force needed to penetrate deeper into the sliding zone and to bend the chip. Thus, it lowers the tool-chip contact length, which in turn influences the heat generated by friction in the secondary shear zone and shear plane angle [24], [31].

![Fig. 23. Occurrence of different heat transfer modes in machining with coolant.](image)

The boundary regions of the chip, tool, workpiece and coolant can be seen in Fig. 23. Both conduction and convection occur in the process at the same time while low thermal conductivity of the workpiece material restricts the rate of conduction. Consequently, cooling of the cutting zone is mainly dependent on the coolant in the rake and flank face and by forced convection. However, in the convection heat transfer between fluid and hot surface. There exists a conduction region, where the fluid velocity is zero on the wall of the hot surface's thermal boundary layer. To gain insight into the forced fluid flow over a hot surface, it is important to look at the fluid boundary layer, since both convection heat transfer and fluid mechanics are united [61].
4.2.1 Velocity boundary layers

The laminar and turbulent flow of the fluid is of vital importance since it has a direct relation with convection heat transfer. Laminar flow is highly ordered fluid motion characterized by smooth streamlines. Turbulent flow is highly disordered fluid motion that usually occurs due to velocity fluctuations [61]. Consider a flat plate with a fluid approaching in X-direction with a uniform upstream velocity, $U_\infty$, as shown in Fig. 24.

![Fig. 24. The development of a boundary layer for flow over a flat plate and different flow regimes, adapted and reconstructed from [61].](image)

The boundary layer of a fluid consists of several adjacent layers on top of each other. In particular, the fluid layer closest to the plate has zero velocity due to the no-slip condition, then the velocity of the fluid increases according to a profile, see Fig. 25, creating different relative velocities between fluid layers.

![Fig. 25. Development of a boundary layer on a flat surface due to the no-slip condition and friction, shows laminar region, adapted and reconstructed from [61].](image)

The boundary layer thickness, $\delta$, as shown in Fig. 25, is defined as the distance from the plate in the Y-direction to where the velocity of the fluid reaches 99 pct. of $U_\infty$. The region above this point is known as undisturbed free stream, Fig. 24. In the boundary layer region viscous effects and velocity changes are significant.
and in the inviscid flow region, the velocity remains basically constant and the frictional effects are negligible [60], [61].

When the fluid flows over the surface, the initial boundary layer formed is laminar. The thickness of the boundary layer, \( \delta \), increases with increasing distance along the x direction, as shown in Fig. 24. At a critical distance, inertial effects become significantly large compared to viscous effects, leading to the development of small disturbances in the flow.

As these disturbances increase, the regular viscous flow is disturbed and a transition occurs from laminar to turbulent flow. Looking closer into the boundary layer in the region of turbulent flow there exists a thin layer known as laminar or viscous sublayer. However, this layer is much thinner compared to regular laminar flow, thereby providing improved convection heat transfer as shown in Fig. 24 [60].

The Reynolds number, \( \text{Re} \), is a dimensionless factor that quantitatively relates the viscous and inertial forces and the value helps to determine the transition from laminar to turbulent flow [60]. \( \text{Re} \) is defined as

\[
\text{Re} = \frac{\rho U_\infty x}{\mu} = \frac{U_\infty x}{v} \tag{10}
\]

where \( U_\infty \) is the free stream velocity, \( x \) the distance from the leading edge, \( v = \mu/\rho \) is the kinematic viscosity, \( \rho \) is density of the liquid and \( \mu \) the dynamic viscosity of the fluid.

### 4.2.2 Thermal boundary layers

Consider a fluid having an inlet temperature of \( T_\infty \), that flows over a hot surface of temperature \( T_S \), where \( T_S > T_\infty \), see Fig. 26. As soon as the fluid at a velocity \( U_\infty \) interacts with the hot surface, it creates a no-slip condition, \( i.e., \) the relative velocity of the fluid is zero. Due to the temperature difference between fluid and hot surface, heat transfer takes place in order to attain a thermal equilibrium [61].
In regions where no relative motion between the fluid and the hot surface takes place, only conduction heat transfer occurs. Heat moves towards the remaining fluid layers until the surface reaches the inlet temperature of fluid $T_\infty$, forming a thermal equilibrium between the hot surface and fluid. During cooling a temperature gradient from $T_s$ to $T_\infty$ is created and this layer is called the thermal boundary layer [61], see Fig. 26 & Fig. 27.

Thickness of the thermal boundary layer determines the efficiency of convective heat transfer, \textit{i.e.} thinner the layer higher the efficiency. We can consider the thermal boundary layer as an insulation layer between the fluid and solid restricting the convection heat transfer rate.

In the machining process, both on the rake and flank faces of the inserts, there are areas where high temperature gradient exists. To decrease the thermal boundary layer thickness, turbulent fluid flow and interrupted structures of the tool surface can be used to enhance the convective heat transfer.
Development of the velocity boundary layer in relation to thermal boundary layers will have a strong influence on the convective heat transfer rate. It is described by the Prandtl number, $Pr$, a dimensionless ratio of the thickness of velocity boundary layer to the thickness of the thermal boundary layer. If $Pr$ is greater than one, the thermal boundary layer is thinner than the velocity boundary layer, and vice versa if it is less than one. If $Pr$ is one, then both layers are of the same thickness. To enhance the convective heat transfer, $Pr$ has to be greater than one [61].

The Nusselt number, $Nu$, is a dimensionless indicator that relates the enhancement of heat transfer through convection to conduction across the same fluid layer.

$$Nu = \frac{Q_{conv}}{Q_{cond}} = \frac{hL}{k} \quad (11)$$

Where $k$ is the thermal conductivity of the fluid, $L$ the characteristic length and $h$ the convective heat transfer coefficient. Thus, a larger Nusselt number, the more effective convection heat transfer. When $Nu$ is one, it means that the heat transfer across the layers occurs through conduction.

### 4.3 LEIDENFROST EFFECT

When a liquid touches a heated surface hotter than the liquid’s boiling point, it vaporizes immediately and forms an insulating vapor layer which protects the remaining part of the liquid from boiling, known as the Leidenfrost effect.

![Image of Leidenfrost effect](image)

Fig. 28. The Leidenfrost effect, formation of a vapor layer protecting the water droplet.

The gas pressure from this vapor prevents the rest of the fluid from reaching the hot surface due to the low thermal conductivity of the vapor film in comparison to the liquid, leading to a lower rate of heat flux in this region, see Fig. 28. As shown in Fig. 29, the boiling of water begins from point A. As the temperature
increases, water reaches its maximum heat transfer rate at point C. The region A to C is known as the nucleate boiling region. A further increase in temperature will force heat transfer rate to decrease. This is due to a large fraction of the hot surface being covered by a vapor film, which then acts as an insulating layer.

The point D, where the heat transfer rate is at a minimum, is known as Leidenfrost point. In the transition boiling region, both nucleate and film boiling occurs partially. In the film boiling region, the hot surface is completely covered by a continuous stable vapor film. Upon further increase in temperature, the heat transfer rate increases from the heated surface of the liquid through the vapor by radiation.

Fig. 29. Typical boiling curve for the water adapted and reconstructed from Yunus A. Çengel [61].

4.4 HIGH-PRESSURE COOLING

High-Pressure cooling has the capability to remove heat and extend tool life. Aiming the coolant at a precise location with the right pressure and flow rate on the cutting tool will help to achieve these goals. According to Bernoulli’s law, considering a streamline flow of a fluid with constant density and conservation of volume, a fluid passing from the larger diameter to a smaller diameter result in higher velocity of the fluid exiting the nozzle, see Fig. 30.

---

1 In honor of J. C. Leidenfrost, who observed in 1756 that liquid droplets on a very hot surface jump around and slowly boil away [61].
Bernoulli’s law states that a decrease in the area leads to a simultaneous decrease in fluid pressure with the increase in velocity [62]. This is beneficial for reducing the thermal boundary layers.

High-pressure coolant increases the localized pressure on the targeted locations, delaying the formation of the vapor by increasing the boiling point of the fluid. In Fig. 31, the steam pressure is shown as a function of temperature, obtained from tables of thermodynamic properties of steam. For instance, if the temperature on the flank face is 300°C, the hi-jet cooling pressure should be higher than 8.6 MPa in order to avoid the formation of the vapor film [34]. The film boiling temperatures of conventional cutting fluids are about 350°C [2].
CHAPTER 5. TOOL WEAR

The economy of the cutting process greatly depends on the cutting tool life [63]. Tool life can be estimated in many different ways. Most common is the time frame a cutting tool can be used to remove workpiece material until reaching its tool-wear criteria. The key parameters influencing the cutting tool life are: the tool material, tool geometry, cutting conditions, type of operation, workpiece material and the presence of coolant [10].

Tool failure arises as a premature or gradual failure. Excessive principle cutting force on the tool leads to a premature, brittle failure. Elevated cutting temperatures can also lead to a thermal failure of the tool. Thus the use of coolant, leading to lower temperatures, contributes to extending the tool life. A gradual failure of the cutting tool allows the cutting tool to be used for longer time, hence this is the preferred tool failure mode [10].

Fig. 32 shows the case of gradual failure of a cutting tool, based on flank wear, in relation to cutting time. When the tool engages with the workpiece it has an initial rapid tool wear, a break-in period. Then, the tool enters a zone of uniform wear rate, a steady state condition. Finally, the wear accelerates to a tool failure region [10]. The most widely used tool life criteria is the flank wear. For instance, in the case of carbide cutting tool the flank wear criteria ranges between 0.2 and 0.4 mm depending on the operation, such as finishing or roughing [64].

![Fig. 32 Tool wear rate as a function of cutting time and flank wear, adapted and reconstructed from Bonilla Hernández [10].](image)
A comparison of gradual tool wear curves with increasing cutting speed is shown in Fig. 33. The time taken for the tool to reach the severe tool wear regime decreases with increased cutting speed, thus lowering the time the tool spent in the steady wear region, see Fig. 33. Through experiments, it is found that the reduction in tool life depends less on feed rate than cutting speed and even less on the depth of cut [65].

![Fig. 33. Progression of Flank wear with time for incremental cutting speed \(v_{c1} < v_{c,2} < v_{c,3}\) [65].](image)

### 5.1 TOOL WEAR MECHANISM

Several types of tool wear mechanisms are observed during the interaction of the cutting tool and workpiece material in machining process. This is illustrated in Fig. 34. Different wear mechanisms appear and they are linked to cutting temperatures raised in the cutting zone, thus affecting the tool life.

![Fig. 34. Different tool wear mechanism as a function of temperature adapted and reconstructed from Vieregge. G [59].](image)
5.1.1 Adhesive wear

Adhesive wear is caused by the adhesion of workpiece material sticking to the cutting tool surface in some sort of cold welding process. This occurs within a limited temperature range. Due to the high pressures and temperature, workpiece material gets cold-welded onto the rake face of the tool in the form of a build-up edge, BUE, acting as a superimposed cutting edge. The BUEs formed are unstable and continually torn away by the chips, with small fragments of the tool material removed from the cutting edge.

On the flank face, under certain conditions, a build-up layer, BUL can be found in the contact zone [66]. This represents the sticking friction zone. It is observed, at low cutting speeds, that the temperature is not high enough to have adhesion. On the other hand, at higher cutting speed, the rise in temperature is well over the temperature when adhesion can occur. Adhered material is observed on the rake face, even at recommended cutting speeds, when machining Ni-base superalloys [66].

5.1.2 Abrasion wear

Abrasive wear is the most common and predictable wear found on the cutting tool. It is the simplest way to determine when an insert has been worn out. Primarily, it creates a wear land on the flank face of the tool. It is caused by predominantly hard particles, present in the workpiece material, that abrade the cutting tool by chipping, micro-ploughing or cracking and thereby plucking off particles from the tool substrate [67]. The abrasive wear morphology is characterized by parallel grooves on the flank and rake faces and by notching at the depth of cut point. During machining of Ni-base superalloy with uncoated cemented carbide as cutting tool material, it was observed that abrasive wear usually resulted in a depth of cut notching [66]. Abrasive wear is frequently observed when machining Ni-base superalloys, for all types of tool materials [66].

5.1.3 Diffusion wear

Diffusion wear occurs at the atomic level in the crystal lattice, where atoms move from regions of high concentration towards low concentration, governed by Fick’s law of diffusion [61]. The loss of material due to the diffusion of tool material atoms into the workpiece is observed at high temperatures, mainly on the tool-chip interface, around the secondary shear zone [67]. Diffusion wear is dominant at higher cutting speeds because of the elevated temperature in the contact zone. According to Kalpakjian [64], “crater wear generally attributed to a diffusion wear mechanism in the tool-chip interface”. Crater wear increases with a rise in the cutting temperature.
It has been stated in a literature review by Akhtar et al. [66], that diffusion wear has been reported by many researchers during the machining of Ni-base superalloys. According to the same review, Ezugwu et al. [68] have investigated different sets of tool materials following the machining of Ni-base superalloys. They reported that evidence of the diffusion wear mechanism was found on all types of tool materials, such as carbides, ceramics or CBN, upon machining such alloys.

The wear rate depended on the cutting temperatures and chemical composition of both the tool and the workpiece materials. At higher cutting speed, the temperature rises, thus accelerating the diffusion process. It was claimed that Ti and Cr displayed a stronger effect than Ni and Fe as workpiece materials. When machining a Ni-base alloy with a carbide tool, diffusion occurred in the tool-chip interface as cutting speed increased beyond 30 m/min due to the carbide tool’s poor thermochemical stability. This was observed at cutting speeds of 35 m/min, where carbide particles were diffusing into the cobalt binder phase by means of grain boundary diffusion [66].

5.1.4 Plastic deformation

When plastic deformation of the cutting tool is observed, this is due to the forces acting on the cutting edge in combination with high cutting temperatures. Ni-base superalloys can retain their hardness and strength at elevated temperature which contributes to a further rise in temperature and forces acting on the cutting tool. Once the softening temperature of the cutting tool materials is reached, it cannot withstand the pressure on the tool any longer, which results in plastic deformation. Plastic deformation is usually accompanied by micro-crack growth on the tool surface, which consequently causes chipping and flanking failure [66].

Investigations by Ezugwu et al. during machining of Ni-base alloys with a carbide cutting tool found that the temperature generated in the tool-workpiece interface could exceed 1100°C, which is the softening temperature of WC. For a cutting speed of 30 m/min, immediate bonding and high stresses at this temperature caused tool failure by cratering and/or plastic deformation of the cutting edge [66].

5.2 Tool wear types

Depending on the active tool wear mechanism, wear patterns, such as flank wear, crater wear and notch wear are found on the cutting tool. As shown in Fig. 35, the nomenclature and region to measure are guided by the international standard ISO 3685:1993.
Flank wear is seen on the flank face of the tool, as shown in Fig. 35. Flank wear land, VB, with average and maximum, is caused by abrasive, adhesive and diffusion wear mechanism [67]. Flank wear progresses with increased cutting speed, as shown in Fig. 33, thus lowering the tool life.

Crater wear is seen as a crater formation on the rake face of the cutting tool, observed at very high temperatures. Crater wear is caused by one or more combined wear mechanisms, such as abrasion, diffusion, etc. Fig. 35 (top view and section view) shows how to measure crater depth, width and distance from cutting edge [67]. Crater wear can weaken the cutting edge to the point of tool fracture. According to Kalpakjian [64], “the location of maximum crater depth, KT, coincides with the location of the maximum temperature at the tool-chip interface”.

Notch wear, VB_N, as shown in Fig. 35, is found on the depth of cut line in the contact between the tool and the workpiece, where sliding contact conditions prevail. The active wear mechanism is the abrasion and adhesion and to great extent includes chemical interaction at high temperature. Tool fracture and plastic deformation are two failure mechanisms, which are consequences of high compressive stress acting on the cutting edge at elevated temperatures [67].
CHAPTER 6. EXPERIMENTALS

This chapter discusses the experimental methods, conditions and setup used to investigate the regular, Gen I and Gen II inserts. The evaluation of inserts was based on a tool wear perspective.

6.1 INSERTS

6.1.1 Regular

Round inserts with an ISO nomenclature of RCMX 12 04 00 of grade H13A is used as a regular insert, see Table 7. This is a commercially available insert in which the main material composition is tungsten carbide, WC, with cobalt, Co, as the binder phase. The melting point of WC is 2900 °C and for Co it is 1495 °C [51].

Table 7. Insert nomenclature.

<table>
<thead>
<tr>
<th>Insert</th>
<th>Regular</th>
<th>Gen I</th>
<th>Gen II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake</td>
<td>R</td>
<td>G I</td>
<td>G II</td>
</tr>
<tr>
<td>Flank</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insert thickness [mm]</td>
<td>4.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle diameter [mm]</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rake angle [°]</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clearance angle [°]</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of insert</td>
<td>Uncoated carbide insert</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insert shape</td>
<td>Round</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip breaker</td>
<td>No</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The sectional view of a regular insert, see Fig. 36, illustrates the rake and flank faces. In Fig. 37 (a), a light optical microscope, LOM, image shows the top view, called as rake face. In Fig. 37 (b), the rake face is shown at higher magnification using a scanning electron microscope, SEM. In this micrograph, the cutting edge is visible, where WC appears as a white region.
Fig. 36. Sectional view of the regular insert.

Fig. 37. (a) LOM and (b) SEM images of rake face of regular insert.

In Fig. 38 (a), a LOM image shows the insert flank face whereas Fig. 38(b) shows the corresponding SEM image at higher magnification, where WC appears as white.

Fig. 38. LOM and SEM images of flank face of regular insert.
In Fig. 39, a SEM image at even higher magnifications shows the microstructure of an unused carbide insert, which has two distinctive phases, tungsten carbide as white and cobalt as dark. SEM images were taken of an unused insert as a reference for the evaluation of worn inserts after machining.

![Fig. 39. SEM images of the regular insert at higher magnification.](image)

### 6.1.2 Gen I

The Gen I insert was a reengineering of a regular insert, with the purpose to increase the surface area in regions of high temperature. During the design process, the criterion was to choose a geometry that could yield the largest surface area.

Calculations were performed, based on removing a constant volume of 48 µm$^3$ for three possible geometries. This was done to extend the surface area in relationship to the removed material, which are tabulated in Table 8. For instance, a square pyramid of height 9 µm and base edge length 4 µm results in 48 µm$^3$ of a volume removed and the corresponding surface area generated will be 73.76 µm$^2$ from the base surface area, BSA, 16 µm$^2$. The square pyramid geometry has led to an increase of approx. 5.6 times in surface area.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Geometry</th>
<th>Input [µm]</th>
<th>Total Surface area [T.S.A] [µm$^2$]</th>
<th>Results [µm$^2$] [TSA-BSA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Square pyramid</td>
<td>a = 4; h = 9</td>
<td>$A = a^2 + 2a\sqrt{\frac{a^2}{4} + h^2}$</td>
<td>89.76-16=73.76</td>
</tr>
<tr>
<td>2</td>
<td>Cone</td>
<td>r = 2.2567; h = 9</td>
<td>$A = \pi r(r + \sqrt{h^2 + r^2})$</td>
<td>81.78-16=65.78</td>
</tr>
<tr>
<td>3</td>
<td>Cylinder</td>
<td>r = 2.2567; h = 3</td>
<td>$A = 2\pi rh + 2\pi r^2$</td>
<td>74.54-16=58.54</td>
</tr>
</tbody>
</table>
From the surface area analysis, a square pyramid geometry has the possibility to create the largest surface area compared to other geometries. Hence, square pyramid geometry was chosen as the pattern to be created by laser machining at a sector of 90 degrees on the rake and flank face of the regular insert, as shown in Fig. 40.

On the rake face, the first row of the indent pattern was placed at a distance of 0.2 mm from the cutting edge. Whereas on the flank face, patterns were kept at a distance of 0.1 mm from the edge. The depth of the indents increased with the distance from the cutting edge to avoid jeopardizing the structural integrity of the insert, weakening the cutting edge.

According to Table 8 and CAD calculations, individual square pyramid indents led to increase approx. of 1.4 times in surface area compared to the regular insert. A pattern on a sector of 90 degrees of the regular insert resulted in a 12% increase in the surface area, which is termed as Gen I insert. In addition to GEN I, two more variants of inserts were tested to understand the importance of heat dissipation in relation to the rake or flank face. In the first variant, texture was placed only on the rake face, whereas in the second variant, texture was placed only on flank face. These were consequently termed rake and flank insert, respectively.

**6.1.3 Gen II**

The Gen II insert was designed to create an interface for improved access by coolant through the introduction of multiple surface features in the contact zone on the rake face of a Gen I insert. These act as channels to enable the access of coolant in closer proximity to the cutting edge. It will also influence the chip
bending which in turn leads to reduce tool-chip contact length. Lowering the tool-chip contact length leads to lower friction and heat generation in the secondary shear zone. Based on the cutting conditions, the channel feature was placed at an arc of $30.2^\circ$ on the rake face, as shown in Fig. 41. The CAD calculations, were based on a depth of cut of 1 mm.

Fig. 41. Generation II insert, channel feature on the first row of rake face.

The comparison of regular, Gen I and Gen II inserts in contact with coolant is shown in Fig. 42. Gen I and Gen II insert interfaces can create improved access for the coolant to reach the high temperature zone. The proposed indent pattern design acts as an uneven surface, which creates the possibility to have a turbulent flow in patterned area. At the same time, the indent pattern design acts as reservoir which allows the retention of coolant.

Fig. 42. Orthogonal view shows the interaction between coolant and three inserts.
The five different cutting inserts, regular, Gen I, Gen II, rake and flank inserts were tested on cast Alloy 718 with an average hardness of $381 \pm 21.8$ HV10. The dimensions of the ring were: outer diameter 742 mm, inner diameter 672 mm, height 22.30 mm and width 35.08 mm, respectively. In Fig. 43, the microstructure of the cast Alloy 718 is shown.

![Microstructure of cast Alloy 718](image)

**Fig. 43. Microstructure of cast Alloy 718 used as workpiece material, from Hoier. P.**

### 6.2 Experimental Conditions

Facing operation was conducted using a 5-axis CNC machine, with a high pressure pump facility having a maximum capacity of 25 MPa. The coolant used had 5% emulsion. In Fig. 44, the tool holder mounted with high-pressure coolant supply and a turning table with Alloy 718 ring fitted to the fixture is shown.

![Experimental setup](image)

**Fig. 44. Experimental setup.**
The coolant for the rake face was aimed at the cutting edge through three nozzles 0.8 mm in diameter. The pressure was 16 MPa with a flow rate of 11.33 litres per minute. The flank face was cooled from two nozzles 1.2 mm in diameter at a pressure of 8 MPa and with a flow rate of 12.02 litres per minute.

Fig. 45. Tool holder with internal high-pressure coolant.

The experiments were conducted for three categories of constant Spiral Cutting Length, SCL. A depth of cut of 1 mm was kept constant for all experiments. The SCL is calculated as the product of the circumference and length of the cut to the feed rate. However, the SCL is inversely related to the feed rate for constant length of cut.

Fig. 46. Illustration of spiral cutting length in facing operation.
Three different SCLs were experimented for different cutting speeds. The cutting speed was chosen as a varying parameter since it has a direct correlation with the cutting temperature and the tool wear [65]. The SCL for facing operation calculated from Eq. (12) and Fig. 47 illustrates the description [70].

\[
SCL = \left( \frac{D_1 + D_2}{2} \right) \times \left( \frac{\pi}{1000} \right) \times \left( \frac{l_m}{f_n} \right)
\]

(12)

\( D_1 \) original diameter, \( D_2 \) final diameter, \( l_m \) length of cut, \( f_n \) feed rate.

The flank pressure was kept at zero for lower cutting speed. For the rest of the experiments, a rake pressure of 16 MPa and a flank pressure of 8 MPa were kept constant. In Table 9, the cutting conditions, coolant pressure and concentration of fluid used during the facing operation of Alloy 718 is shown.

Table 9. Cutting parameters for facing operation of Alloy 718

<table>
<thead>
<tr>
<th>Cutting speed [m/min]</th>
<th>30, 60, 90, 105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate [mm/rev]</td>
<td>0.1, 0.2, 0.3</td>
</tr>
<tr>
<td>SCL* [m]</td>
<td>565, 282, 188</td>
</tr>
<tr>
<td>Rake pressure [MPa]</td>
<td>16</td>
</tr>
<tr>
<td>Flank pressure [MPa]</td>
<td>0, 8</td>
</tr>
<tr>
<td>Depth of cut [mm]</td>
<td>1</td>
</tr>
<tr>
<td>Length of cut [mm]</td>
<td>25.08</td>
</tr>
<tr>
<td>Coolant concentration</td>
<td>5%</td>
</tr>
<tr>
<td>Fluid type</td>
<td>Synthetic</td>
</tr>
</tbody>
</table>

*corresponds to feed and length of cut
In Fig. 48, the experimental plan for different inserts that were tested is shown. Three different values of SCL for varying cutting speed were used.

![Diagram of experimental design based on SCL and cutting speed, v_c.]

An additional experiment was carried out for a SCL of 70 m particularly for the Gen I insert at the highest cutting speed of 120 m/min and at a feed rate of 0.3 mm/rev. The purpose of this test condition was to investigate the cutting tool and workpiece material behaviour at elevated temperatures with high-pressure coolant. This was done by means of tool wear characterization, using SEM and EDS, see Paper D [71].

**6.3 Cutting Conditions**

The experiments were outlined and conducted for three different spiral cutting lengths, correlated to three different feed rates, except for Paper D. The depth of cut was kept constant at 1 mm. The experimental conditions were conducted for a randomized DOE, as shown in Table 10, Table 11 and Table 12.

The first set of experiments were conducted for a feed rate of 0.1 mm/rev and a corresponding SCL of 565 m. The intention was to investigate the tool wear of a Gen I insert without flank cooling at a cutting speed of 30 m/min. The next experiments were conducted at a cutting speed of 60 m/min without flank cooling for the regular insert, and also with flank cooling, for both regular and Gen I inserts, see Table 10.

At higher cutting speed of 90 m/min, the regular, Gen I, rake and flank inserts were investigated. The Gen II insert was not investigated for a feed rate of 0.1 mm/rev, since the channels were located at a distance of 0.2 mm from the cutting
edge whereby these cooling channels by location could not influence the tool-chip contact zone.

Table 10. $SCL$ 565 m; $f_r$ 0.1 mm/rev; $a_p$ 1 mm

<table>
<thead>
<tr>
<th>S.no</th>
<th>$v_c$ [m/min]</th>
<th>Pressure [MPa]</th>
<th>Tests conducted</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>RP</td>
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<tr>
<td>3</td>
<td>60</td>
<td>16</td>
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</tr>
<tr>
<td>4</td>
<td>90</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

- No tests were conducted

A second set of experiments were carried out for a $SCL$ of 282 m and a corresponding feed rate of 0.2 mm/rev. Regular, Gen I and Gen II inserts were investigated for two different cutting speeds, with constant rake and flank pressure, see Table 11.

Table 11. $SCL$ 282 m; $f_r$ 0.2 mm/rev; $a_p$ 1 mm

<table>
<thead>
<tr>
<th>S.no</th>
<th>$v_c$ [m/min]</th>
<th>Pressure [MPa]</th>
<th>Tests conducted</th>
</tr>
</thead>
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<tr>
<td>2</td>
<td>90</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

- No tests were conducted

A third set of experiments were carried out for a $SCL$ of 188 m and a corresponding feed rate of 0.3 mm/rev. For a cutting speed of 60 m/min, all the five inserts were investigated and at the higher cutting speeds of 90 and 105 m/min, regular inserts were excluded, see Table 12.

Table 12. $SCL$ 188 m; $f_r$ 0.3 mm/rev; $a_p$ 1 mm

<table>
<thead>
<tr>
<th>S.no</th>
<th>$v_c$ [m/min]</th>
<th>Pressure [MPa]</th>
<th>Tests conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RP</td>
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<tr>
<td>1</td>
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<td>90</td>
<td>16</td>
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</tr>
<tr>
<td>3</td>
<td>105</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

- No tests were conducted
According to the ISO 3685:1993 Standard, tool failure criteria for carbide cutting tools of average flank wear is 0.3 mm and of maximum flank wear 0.6 mm [69].

The tool wear characterizations were performed with SEM and Alicona 3-D imaging technology and reported in the Results and Analysis section, in CHAPTER 7. Alicona 3-D was used for the measurement of the volume difference between worn and unworn cutting tools.

Due to the round geometry of the cutting tool, it was necessary to set a standard for measuring the tool wear on the flank face. For a depth of cut of 1 mm and for a 6 mm radius, the insert creates a contact angle of 34°. Thus creating an arc contact length of 3.56 mm and a linear contact length of 3.51 mm. For the flank wear profile and notch wear measurements, the linear contact length was approximated to 3.6 mm and kept constant, see Fig. 49.

Fig. 49. Standards for flank wear measurement.
CHAPTER 7. RESULTS AND ANALYSIS

In this chapter tool wear and tool life observed from the different generations of inserts are summarized as a results compilation from Papers [A – D]. Furthermore, an extended investigation of tool wear using SEM and Alicona 3D imaging is added to the existing results and reported in this chapter. The Gen I and Gen II inserts, see Fig. 50, were of primary interest to investigate and compare the tool wear and tool life with the regular insert.

![Fig. 50. Regular, Gen I and Gen II inserts.](image)

### 7.1 FLANK WEAR

The key results of regular, Gen I and Gen II inserts maximum flank wear at the SCL of 282 and 188 m are shown as an overview in the Fig. 51.

![Fig. 51. Comparison of maximum flank wear of Regular, Gen I and Gen II insert for SCL (a) 282 m (b) 188 m.](image)
In the upcoming section detailed investigation of the different generation inserts based on the individual cutting conditions, corresponding tool wear observation, elemental analysis (EDS) and volume difference measurements are discussed.

For SCL 565 m, at a cutting speed of 30 m/min without flank cooling, the tool wear observations showed that the Gen I insert led to reduction of flank wear by approximately 46% compared to the regular insert. In Fig. 52, the comparison of regular and Gen I insert flank wear profile is shown.

![Flank wear profile comparison](image)

**Fig. 52. Flank wear profile of Regular and Gen I insert.**

The flank wear profile was formed from the thirty six measurements of flank wear along the linear contact length of 3.6 mm. Industrial tool failure criteria of flank wear of 300 µm is shown as a solid line see Fig. 52. Significant notch wear was observed on the regular insert.

In case of the Gen I insert, groove pattern similar to regular insert was observed within the depth of cutline, 3.6 mm, see Fig. 53. On the contrary, there were traces of build-up edges than a crater on the rake face of the insert. Chipping and build-up edge were found on both the regular and Gen I inserts. However, Gen I insert showed an adherence of higher volume of workpiece material compared to the regular insert. The build-up edge formation and a lower flank wear in Gen I insert is more likely correlated with the existence of high thermal gradients in the contact zone compared to the regular insert.
RESULTS AND ANALYSIS

Fig. 53. Comparison of tool wear, (a) regular insert (b) Gen I insert.

Additionally, EDS analysis showed the traces of coolant boiling on the flank face as a precipitate (darker region) in SEM micrograph, see Fig. 54. The dark region was determined to be calcium (Ca), which was from the coolant fluid used, see Fig. 54. Furthermore, strong traces of workpiece materials such as nickel, chromium and iron on the flank wear region were observed. Traces of tungsten and cobalt were seen following the edge of flank wear land and boiling region.

Fig. 54. Regular insert – EDS analysis in tilted position showing rake and flank face.

In the case of Gen I insert, see Fig. 55, traces of coolant precipitate below the wear land is seen in less proportion, concurrently it led to the shifting of the coolant boiling region closer to the cutting edge. It can be correlated with better heat dissipation rate on the flank face compared to the regular insert.
For SCL 565 at $v_c \, 60 \, \text{m/min}$, the maximum flank wear of regular insert was 530 $\mu$m. With flank cooling, tool wear was reduced to 306 $\mu$m. Gen I insert was able to further decrease the flank wear to 200 $\mu$m, see Fig. 56.
RESULTS AND ANALYSIS

Lower flank wear results with high pressure coolant on flank face were coherent with Colak (2012), where reduction in flank wear with high pressure coolant was observed [38]. Crater wear and build-up edge was found on both the inserts at the depth of cut.

For SCL 565 m at \( v_c \) 90 m/min, the regular, Gen I, flank and rake inserts were investigated. As shown in Fig. 57, the regular insert had a catastrophic failure. Hence, further investigations at higher cutting condition were not conducted.

![Fig. 57. Regular insert – Catastrophic failure, region of coolant boiling.](image)

The Gen I, rake and flank inserts had an extensive flank wear without a tool breakage, as shown in Fig. 58. Maximum flank wear of the rake and flank insert were 1.9 and 2.2 mm respectively. Comparing with the insert thickness of 4.7 mm, flank wear extended about to half of the insert thickness whereas Gen I insert showed the least flank wear of 1.4 mm. Increase in tool life of Gen I can be attributed to the improved heat dissipation from the cutting zone. This provides a possibility to operate the insert at wide range of cutting conditions. The rake and flank insert were not evaluated for higher cutting conditions based on the severe tool wear results.

![Fig. 58. Comparison of flank wear (a) Gen I (b) Rake and (c) Flank insert.](image)

EDS analysis of the flank wear region see Fig. 59, showed traces of tungsten carbide on the flank wear region. Interestingly, the traces of tungsten carbide on
the flank wear region lowered with decrease in flank wear, lowest for Gen I followed by rake and flank insert as shown in Fig. 59. This observation could be related to the more participation of workpiece material adhered to the tool as a function of reduced heat transfer based on the different tool design investigated.

Fig. 59. Comparison of traces of tungsten carbide on the flank face, (a) Gen I (both rake and flank) (b) Rake and (c) Flank insert.

The traces of tungsten carbide particle has led to an understanding that the temperature has significantly influenced the tool life. Considering the existence of elevated temperature on the cutting tool, there is a higher possibility of cobalt which is a binder, could be removed from the tungsten carbide insert. In Fig. 60, shows the pure cobalt hardness and tensile strength values with temperature.

Fig. 60. Hardness and tensile strength of pure cobalt as a function of temperature, from Hoier et al, [71].

For SCL 282 m at a cutting speed of 60 m/min, maximum flank wear was found in regular insert, whereas the minimum flank wear was observed in Gen II [72]. The Gen II inserts also showed a reduced flank wear by 44 pct. compared to the
regular insert. Conducting a volumetric measurement on the rake faces revealed the presence of crater wear for the regular insert. Crater wear was not observed for the Gen I and Gen II inserts, Fig. 61. Volume removed from the regular insert rake face was concentrated to a low number of craters. In cases of Gen I and Gen II inserts, volume of adhered material was present, which was approximately twice the amount compared to the regular insert. Presence of build-up edge formation on the Gen I and Gen II inserts shows that the tools were used at low cutting speeds. The build-up edge formation on the Gen I and Gen II inserts and the absence of crater wear presents the possibility of improvement in heat dissipation compared to the regular insert.

Fig. 61. Comparison of volume difference measurement of three inserts.

EDS analysis of the three inserts are show in Fig. 62. Calcium traces showed a strong layer below the flank wear of the regular insert, for the Gen I insert the
layer has moved closer to the cutting edge compared to the regular insert. In case of Gen II insert, Ca traces are evenly distributed as shown in Fig. 62.

The Leidenfrost film acting as an insulator for coolant to reach closer to the cutting edge has been moved by the added surface features of Gen I insert. Gen II insert shows a wide area of precipitated calcium indicating that there is no strict boundary created by possible Leidenfrost film. However, this could in fact indicate that there is possibility that nucleate boiling exist in the region without creating an undesirable Leidenfrost film [73].

The tool wear analysis leads in the direction that the Gen II insert has effected the heat dissipation rate most, lowered the cutting edge deterioration compared to Gen I and Regular insert. Moreover, the entire region of insulating film has been moved closer to the cutting edge for the reengineered inserts. Thus leading the coolant to access the hot regions closer to the cutting edge. Hence, Gen II insert exhibits high temperature gradient on the flank face of the cutting tool, which has led to an improved the tool life compared to Gen I and Regular.

For SCL of 188 m at a cutting speed of 60 m/min, the regular, Gen I, Gen II, rake and flank inserts were investigated. Results from the flank wear analysis were ambiguous, as discussed in the Paper A [74] and Paper B [72]. Tool wear observations of five cutting inserts showed similar tool wear such as cutting edge deformation, adhesion of workpiece material and build-up edge at a different levels. Surprisingly, Gen II insert had the maximum flank wear compared to the other inserts, rake insert had the least flank wear.
Fig. 63. Volume difference result of Regular, Gen I, Gen II, Rake and Flank inserts.
Therefore, further investigations need to be made for this cutting condition in order to understand the tool wear mechanism. Results from the volume measurement of the five inserts are shown in the Fig. 63. Positive values in the scale represents volume added and negative values represents the volume removed from the cutting tool by wear.

Cutting speeds of 90 and 105 m/min, Gen I and Gen II inserts were investigated. Both Gen I and Gen II insert were able to machine Alloy 718 without tool failure. The flank wear profiles for \( v_c \) 90 m/min is shown in Fig. 64 (a), and for \( v_c \) 105 m/min is shown in Fig. 64 (b). Both the inserts had an extensive flank wear. In the case of Gen II insert for two cutting speeds 90 and 105 m/min, reduced the flank wear by 24 and 35 pct. approximately compared to the Gen I. Interestingly, flank wear of the Gen II insert for the cutting speed of 90 and 105 m/min was approximately the same. In the case of Gen I, flank wear was increased by 12.4 percent. In addition, an interesting observation was the shape of the flank wear profiles as shown in the Fig. 64.

![Flank wear profile of Gen I and Gen II inserts for (a) \( v_c \) 90 (b) \( v_c \) 105.](image)

Flank wear profile of the Gen I insert was peak shaped, whereas for the Gen II insert flank wear profile was more of a bell shape. The profiles were consistent for all different cutting speeds and SCL’s for Gen I and Gen II inserts. The linear contact length in the images below represents contact on the flank face from the conversion of contact angle see. Fig. 49. Increase in feed rate increases the tool-chip contact area on the rake face, as shown in Fig. 67. In the case of Gen II insert, the channel design creates the possibility for the coolant to reach closer to the proximity of the cutting edge where most heat generated. In this aspect, Gen II insert could have a more efficient heat transfer from the source of heat generation. Thereby reducing the amount of heat that is conducted into the tool.
Further, tool-chip contact length on the rake face can also be affected by bringing coolant beneath the chip which can be attributed to lower friction and heat generated in the secondary shear zone. Investigation of different feed rates and cutting speeds is needed to broaden the understanding of the flank wear profile of Gen II insert. Detailed analysis of tool-chip contact length is presented in the section 7.2.

Cutting speed was further increased to 120 m/min for the Gen I insert without catastrophic failure, Fig. 65. Previous researchers suggested that the safe operating conditions for uncoated WC were between 15 to 30 m/min and in the case of coated WC, the possibility was to reach 50 m/min and feed rate for longest tool life was 0.18-0.25 mm/rev in machining Alloy 718 [49]. This means that Gen I insert has moved the upper operating limit twofold with respect to cutting speed.

Fig. 65. SEM images of the cutting edge of the Gen I insert after test with $v_c=120$ m/min and $f_n=0.3$ mm/rev from Hoier et al [75].

7.2 CUTTING EDGE DETERIORATION

The Gen II insert with channel design on the rake face was to create an improved way for the coolant to reach the proximity of the cutting edge, where most heat is generated. It also creates a possibility for the coolant to penetrate beneath the chip which leads to lift the chip on the rake face, thus lowering the tool-chip contact length. Reducing the tool-chip contact length leads to lower heat generation from friction in the secondary shear zone.

Later Gen I and Gen II inserts from previous conducted experiments were investigated on the rake face. For SCL 282 and 188 m, both the cutting inserts Gen I and Gen II had the cutting edge deterioration at varying levels. CAD model, as shown in Fig. 66, was used to estimate the distance from the cutting edge to different rows of indents. In Fig. 67, the theoretical chip contact area for feed rate of 0.1, 0.2 and 0.3 mm/rev on the rake face in correlation with the channel design is shown.
Fig. 66. Distance distribution of cooling patterns from the cutting edge, Gen II.

Comparing the rake wear between (a) Gen I and (b) Gen II, Fig. 68, for feed rate 0.2 mm/rev with the theoretical chip contact area on the rake face, see Fig. 67, it was shown that the deterioration of the cutting edge of Gen II was less and follows to a greater extent the shape of the theoretical chip contact area as the wear progress. Additionally, it moves in the radial direction of the insert.

Fig. 67. Chip contact area on Gen II insert.

In the case of Gen I insert, cutting edge deterioration was not following theoretical chip contact area. It could be observed that the wear was significantly dominant with respect to chip thickness. Another difference observed between Gen I and Gen II inserts was the flank wear profile. In the case of Gen I insert more of a peak shape and for Gen II it was more evenly distributed flank wear as a bell shape. Overall results through all the inserts investigated showed a decreased rake and flank wear for Gen II inserts compared to other inserts.
RESULTS AND ANALYSIS

Fig. 68. Comparison of cutting edge deterioration for \( v_c \) 90 m/min, \( f_n \) 0.2 mm/rev, (a) Gen I rake face (b) Gen II rake face (c) Gen I flank face (d) Gen II flank face.

### 7.3 Summary of Tool Wear Observation

Tool wear results of regular, Gen I, Gen II, rake and flank inserts for three different spiral cutting length at varying cutting speeds are summarized in Table 13, Table 14 and Table 15.

#### Table 13. For SCL 565 m; \( f_n \) 0.1 mm/rev

<table>
<thead>
<tr>
<th>S.no</th>
<th>( v_c ) [m/min]</th>
<th>Pressure [MPa]</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( f_n )</td>
<td>T</td>
<td>Gen I</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>16 0</td>
<td>Chipping, Notch wear, Coolant boiling.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>16 0</td>
<td>Flank wear, Chipping, Crater wear, Small traces of build-up edge.</td>
</tr>
<tr>
<td>S.no</td>
<td>$v_e$ [m/min]</td>
<td>Pressure [MPa]</td>
<td>Insert</td>
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<tr>
<td></td>
<td>$v_e$</td>
<td>$P_R$</td>
<td>$P_F$</td>
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<tr>
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<tr>
<td>2</td>
<td>90</td>
<td>16 8</td>
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</table>
### RESULTS AND ANALYSIS

Tool–chip contact length 0.48 mm

* no experiments were conducted

Table 15. SCL 188 m; \( f_n \) 0.3 mm/rev;

<table>
<thead>
<tr>
<th>S.no</th>
<th>( v_c ) [m/min]</th>
<th>Pressure ( P ) [MPa]</th>
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<tr>
<td>3</td>
<td></td>
<td></td>
<td>Gen II</td>
</tr>
</tbody>
</table>

Rake and flank insert has same type of tool wear mechanism and Flank wear for five inserts were of different length.

* no experiments were conducted
CHAPTER 8. CONCLUSIONS

A series of facing operations of Alloy 718 were conducted for three different spiral cutting lengths and five different cutting speeds investigated for five different inserts (Regular, Gen I, Rake, Flank and Gen II insert). Two generations of inserts Gen I and Gen II were of primary interest. Gen I insert design increased the surface area by twelve percent. Gen II insert created an interface for coolant to reach closer to the proximity of the cutting edge.

Gen I insert had improved the tool life compared to the regular insert. It was evaluated based on the tool wear mechanism and coolant precipitate on the flank face of the inserts in relation to the heat. For instance, at a cutting speed of 90 m/min, the regular insert had a catastrophic failure, while the Gen I, rake and flank inserts did not fail. Gen I insert had a lower flank wear than both rake and flank inserts. An increase in surface area of the cutting tool indicates the enhancement in the heat transfer from the cutting zone, thus increasing the tool life. The results pointed out is vital to have an increased surface area on both rake and flank faces of the insert.

EDS analysis of the inserts exhibited the traces of calcium precipitate below the flank wear area. This may possibly be due to the existence of Leidenfrost film, acting as a barrier for the coolant to reach closer to the cutting edge.

Gen II insert (channel design on the rake face) had a better tool life compared to the Gen I insert. At higher cutting speeds, Gen II insert showed a lower flank wear of approximately 20 to 30 percent compared to the Gen I insert. However, tool wear mechanism observed for Gen I and Gen II inserts were similar to each other except in the flank wear patterns, where the Gen I insert had a peak shaped pattern, whereas Gen II had a bell shaped pattern. Magnitude of cutting edge deterioration and workpiece contact in the rake face of the Gen II insert was lower. Therefore, channel design on the insert has influenced the access of the coolant to the proximity of the cutting edge.

The calcium precipitate deposits show the Leidenfrost film moved closer to the cutting edge on the Gen I insert compared to the regular insert. In the case of Gen II insert, the film moved even closer to the cutting edge compared to Gen I insert. Comparing Gen I and Gen II, Gen II showed substantial improvement in the tool life by lowering the flank wear and abrasion of the flank face.

In this work it was shown that Gen I and Gen II inserts are capable of handling higher cutting conditions than the current state of the art industrial practice of machining Alloy 718. This re-design, thus has a potential to increase the productivity at an increased material removal rate.
CHAPTER 9. FUTURE WORK

This thesis work has demonstrated the potential of having surface features on the inserts which has improved the tool life, in addition, has moved upper operating limit twofold with respect to cutting speed. Concerning future work, there are many ways to continue investigation direction in the importance of the surface texturing of insert to promote heat transfer.

The following section will present some ideas for further investigations. It can be categorized as follows:

*Macro*, to focus on improving the structural design and integrity of the indents. By varying the indents size to further increase the surface area and also to introduce combination of different geometries combination on the rake face to study the tool-chip interaction. In aspect of structural integrity is important to find the optimized texture design with highest increase in surface area without compromising the structural strength of the insert. Is possible to conduct FEM investigation on the structural strength of the cutting tool to determine the best texture for the given conditions.

*Micro*, to investigate the adhesion and wettability of the coolant interaction with the surface texture of the cutting tool. Intention is to avoid hydrophobic surface of the tool instead to increase wettability of the coolant on the tool.

*Nano*, to achieve surface cavities in the Nano meter range to create nucleation points to promote pool boiling.

Besides the above one need to put in more research to investigate optimal aiming points for the jets in combination with surface texturing.
REFERENCES


REFERENCES


REFERENCES


Heat generated in a machining process is a common and critical obstacle faced in today’s machining industries. The heat generated in the cutting zone has a direct negative influence on the tool life which, in turn contributes to increase the manufacturing costs. Especially, in machining of Heat Resistant Super Alloys, HRSA this is a very limiting factor. HRSA are capable of retaining their mechanical strength and hardness at elevated temperatures. This property is advantageous in the application in e.g. aero-engines but also a disadvantage, since it also lowers the machinability significantly.

This work is an attempt to improve the heat transfer from the cutting zone, which would lead to an increase in the tool life. To achieve this goal, the cutting tool has been modified to create an improved interface between the coolant and tool in the high-temperature areas.

Two generations of inserts have been designed and investigated. Firstly, an insert with surface texture features has been created with the purpose of increasing the available surface area for heat dissipation: First generation, Gen I. Secondly, a Gen II was designed as a further improvement of Gen I. Here, several channel features on the rake face were added, reaching out from the contact zone to the near proximity of the cutting edge. This with the purpose of improving access of the coolant closer to the cutting edge.

The experiments were conducted in facing operations of Alloy 718 with uncoated round carbide inserts. All experiments were carried out with high-pressure coolant assistance, with a pressure of 16 MPa on the rake face and 8 MPa on the flank face, respectively.

The two generations of inserts, Gen I and Gen II, were experimentally evaluated by tool wear analysis in comparison with a regular insert. The results shows that the tool life increased significantly for the Gen I insert, compared to a catastrophic failure of the regular insert at the same conditions. Regarding the Gen II insert, an increase in tool life by approximately 30 to 40 percent compared to Gen I insert was observed.