Effects of high-pressure cooling in the flank and rake faces of WC tool on the tool wear mechanism and process conditions in turning of alloy 718

Downloaded from: https://research.chalmers.se, 2019-09-13 17:04 UTC

Citation for the original published paper (version of record):

Tamil Alagan, N., Hoier, P., Zeman, P. et al (2019)
Effects of high-pressure cooling in the flank and rake faces of WC tool on the tool wear mechanism and process conditions in turning of alloy 718
Wear, 434-435
http://dx.doi.org/10.1016/j.wear.2019.05.037

N.B. When citing this work, cite the original published paper.

research.chalmers.se offers the possibility of retrieving research publications produced at Chalmers University of Technology. It covers all kind of research output: articles, dissertations, conference papers, reports etc. since 2004. research.chalmers.se is administrated and maintained by Chalmers Library

(article starts on next page)

Wear 434-435 (2019) 102922

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Effects of high-pressure cooling in the flank and rake faces of WC tool on the tool wear mechanism and process conditions in turning of alloy 718

Nageswaran Tamil Alagan[a,*], Philipp Hoier[b], Pavel Zeman[c], Uta Klement[b], Tomas Beno[a], Anders Wretland[d]

[a] Department of Engineering Science, University West, Trollhättan, Sweden
[b] Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden
[c] Department of Production Machines and Equipment, Faculty of Mechanical Engineering, Center of Advanced Aerospace Technology, Czech Technical University in Prague, Czech Republic
[d] GKN Aerospace Engine Systems AB, Trollhättan, Sweden

ARTICLE INFO

Keywords:
Alloy 718
Cemented tungsten carbide
High-pressure coolant
Tool wear mechanism
Crack
Coolant-boiling

ABSTRACT

The exceptional properties of Heat Resistant Super Alloys (HRSA) justify the search for advanced technologies that can improve the capability of machining these materials. One such advanced technology is the application of a coolant at high pressure while machining, a strategic solution known for at least six decades. The aim is to achieve extended tool life, better chip control and improved surface finish. Another aim is to control the temperature in the workpiece/tool interface targeting for optimum cutting conditions. In most of the existing applications with high-pressure coolant media, the nozzles are positioned on the rake face side of the insert and they are directed towards the cutting edge (the high-temperature area). The coolant is applied at high-pressure to improve the penetration of the cooling media along the cutting edge in the interface between the insert and workpiece material (chip) as well as to increase chip breakability. However, the corresponding infusion of coolant media in the interface between the flank face of the insert and the work material (tertiary shear zone) has been previously only scarcely addressed, as is the combined effect of coolant applications on rake and clearance sides of the insert. The present work addresses the influence of different pressure conditions in (flank: 0, 4 and 8 MPa; rake: 8 and 16 MPa) on maximum flank wear, flank wear area, tool wear mechanism, and overall process performance. Round uncoated inserts are used in a set of face turning experiments, conducted on the widely used HRSA "Alloy 718" and run in two condition tests with respect to cutting speed (45 (low) and 90 (high) m/min). The results show that an increase in rake pressure from 8 to 16 MPa has certainly a positive impact on tool life. Furthermore, at higher v_c of 90 m/min, cutting edge deterioration: due to an extensive abrasion and crack in the wear zone were the dominant wear mechanism. Nevertheless, the increase in coolant pressure condition to 16 MPa reduced the amount of abrasion on the tool compared to 8 MPa. At the lower cutting speed, no crack or plastic deformation or extensive abrasion were found. When using 8 MPa pressure of coolant media on the flank, the wear was reduced by 20% compared to flood cooling conditions. Application of high-pressure cooling on the flank face has a positive effect on tool life and overall machining performance of Alloy 718.

1. Introduction

Heat resistant super alloys have a self-evident place in the material shelf of the aerospace industry, in particular for various engine applications. Almost 50% of the high-performance components used in the hot sections of a jet engine are made from nickel-based super alloys [1]. Their exceptional material characteristics, such as retained mechanical and thermal properties at elevated temperatures and further, their corrosive and creep resistance, make them very attractive for many high temperature applications as compared to other alloys. Consequently, as the air transportation industry expands, the volumes of advanced materials (such as HRSA) increases. Despite the superior properties of nickel-based superalloys for various specific applications and the contemporary advancements in machining technologies, the material is still regarded as difficult to machine.

The "Alloy 718" – the fifty-year-old "workhorse" material for gas turbine applications – is one such alloy. Alloy 718's ability to retain its mechanical properties at elevated temperatures and good welding

* Corresponding author.
E-mail address: nageswaran.tamil@hv.se (N. Tamil Alagan).

https://doi.org/10.1016/j.wear.2019.05.037
Received 7 April 2019; Received in revised form 28 May 2019; Accepted 29 May 2019
Available online 01 June 2019
0043-1648/ © 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/BY/4.0/).

properties makes it the natural “first choice” for jet engine components. However, when it comes to machining, Alloy 718 generally exhibits low machinability indexes. This is mainly due to its ability to retain hardness and strength at high temperatures, and its low thermal diffusivity, work hardening and presence of hard abrasive carbides. As a result, accumulated heat in the cutting zone leads to intense tool wear and machining parameters have to be restricted in order to keep the service life of the tools and the material removal rate at industrially reasonable levels.

Various aspects of the heat balance in the cutting zone have been researched. One aspect that is frequently investigated is the effect of elevated temperatures – thermal softening of the chip – which is beneficial to the cutting process due to the lowered cutting forces. However, most research in the field has been directed towards efficient heat transport rather than optimized heat conditions in and around the cutting zone. For the most commonly used chip removing methods (milling, turning and drilling) several means of heat transport concepts have been explored, among which concepts such as Compressed Air; Cryogenic Cooling; Minimum Quantity Lubrication (MQL) and application of conventional cutting coolant under extraordinary pressures, are among the most commonly discussed in literature [2].

Since the machining system (cutting tools, machine tools and fixtures combined) suffers from various forms of heat driven instabilities, the industrial incentive of improved heat transfer rather than optimized heat conditions in and around the cutting zone is obvious. Thus, geometrical shift and drift of the process, driven by thermal effects are considered more significant to achieve a robust production concept than the lowest possible mechanical stress imposed on the system. Despite the fact that a reduced cutting force due to thermal softening is rarely achievable if a certain heat level is not maintained in the cutting zone, thermal effects are considered a more significant driver towards achieving a robust production concept than the lowest possible mechanical stress.

With the exception of the application of conventional coolant as means for heat transfer, most of the mentioned applications have failed in their industrial application. The contribution to the overall process robustness – perceived or real – is frequently expressed as insufficient. The reason is far from scientific: even though all of these cooling methods are potential moderators of the heat flux in the cutting zone and *per se* contribute to controling the temperature of the cutting tool, most of them usually fail to address the additional requirements of “applied” machining system such as thermal stability of the machine-tool structure and chip transport.

It is therefore clearly justifiable to include application techniques of conventional cutting coolant in a system approach when to machine HRSA. In particular, when the process includes traditional tool materials, like cemented carbide (and where applicable high speed steel). Thus, the imminent question is how and where to apply the coolant media in order to reach the most significant effect on lowering tool wear and process capability.

The concept of focussing pressurized coolant to the cutting edge was experimented in 1952 by R J.S. Pigott and A.T. Colwell [3]. They built a high-pressure coolant delivery system with a maximum pressure of about 4 MPa, which improved tool life by about 7–8 times compared to flood cooling. They experimented on the flank face with the aim to bring the coolant in under the chip. Since then, the development of high-pressure technologies (pumps, delivery systems, tools and control units) has led to a considerable increase in available coolant media pressures for machining applications. A notable improvement was Jet-Break technology by Sandvik Coromant. In 1979 they introduced high-pressure coolant in turning operations of Titanium specifically for aerospace applications. Results showed significant improvement in the surface properties and MRR for difficult to cut materials by reaching the upper limits of the cutting speed for these materials [4]. During the latter part of the 20th century, coolant media pressure reached values as high as to 360 MPa (and even further) based on equipment used for water jet cutting. However, in later studies typical high pressure applications seem to have settled at 10–50 MPa based on work piece materials, cutting conditions, machine tools and tool holder designs.

The current state of the art, referred to in appendix A, elucidates that most of the scholars have directed their research interests and investigated the impact of the media jets on heat transfer from the cutting zone, when directed towards the rake face (the secondary shear zone). Thus, most aspects of the influence from high pressure media applied to the rake side of the cutting tool has been under scrutiny. Cutting conditions, nozzle diameters/positions, flow rates and cutting tool materials have been investigated with respect to their impact on tool wear, cutting force, chip morphology, surface finish, temperature, machinability, etc.

However, reports on effects from media applied to the additional high-temperature regions of the cutting tool like i.e. the relief side of the cutting edge (the tertiary shear zone) are rare. Thus, the relief side of the cutting edge is one such area that is not yet thoroughly investigated with respect to advanced heat transfer. In particular, the understanding of the fundamental mechanism of using high-pressure cooling on both tool faces (rake and flank – secondary and tertiary shear zones), Fig. 1 (a), is still an existing knowledge gap.

In addition, while machining HRSA using high-pressure coolant, only a limited number of researchers have hypothesized and reported on the formation and existence of the vapour barrier film acting as a barrier for the coolant to reach the vicinity of the cutting edge [5–8].

This paper aims for a more thorough explanation of the influence of high-pressure coolant pointed to the flank face of the cutting edge in combination with high-pressure cooling applied to the rake face and the resulting tool life and related wear mechanisms, see Fig. 1 (b). Furthermore, emphasis is directed towards thermal effects (such as the vapour barrier) along the flank face and their variations due to changes in pressure conditions.

2. Experimentals

2.1. Workpiece material and cutting insert description

Cast Alloy 718 with an average hardness of 381 ± 21.8 HV was used as the workpiece material for this investigation. A feed rate of 0.2 mm/rev and a depth of cut of 1 mm was kept constant during the machining tests. The spiral cutting length, SCL, as calculated from Eq (1), was approximately 90 m (based on a machined length, l_m, of approx. 8 mm). Conditions were kept constant for the entire experimental campaign, where D_m – machined diameter and D_1 – initial diameter. The outer diameter of the ring was 742 mm and the inner diameter was 672 mm. The setup can be seen [9].

$$SCL = \left[\frac{D_1 + D_m}{2}\right] \times \left[\frac{\pi}{1000}\right] \times \left[\frac{l_m}{f_n}\right] \quad (1)$$

Round cemented uncoated carbide inserts with the ISO designation RCMX 12 04 00 and grade of H13A were used. These inserts are commercially available with a measured hardness of 1545 ± 14 HV30. In rough machining, round cutting tools play a vital role when machining HRSA, due to their high edge strength and their versatility (number of cutting edges that can be extracted through clever indexing). The insert has a negative face land and is made from cemented tungsten carbide (WC) embedded in a Co-binder.

2.2. Machine setup, cutting and high-pressure coolant conditions

A 5-axis vertical CNC machine was used for the face turning operations of the Alloy 718 ring. The machine was programmed for constant cutting speed (the spindle speed increases as the cutting tool

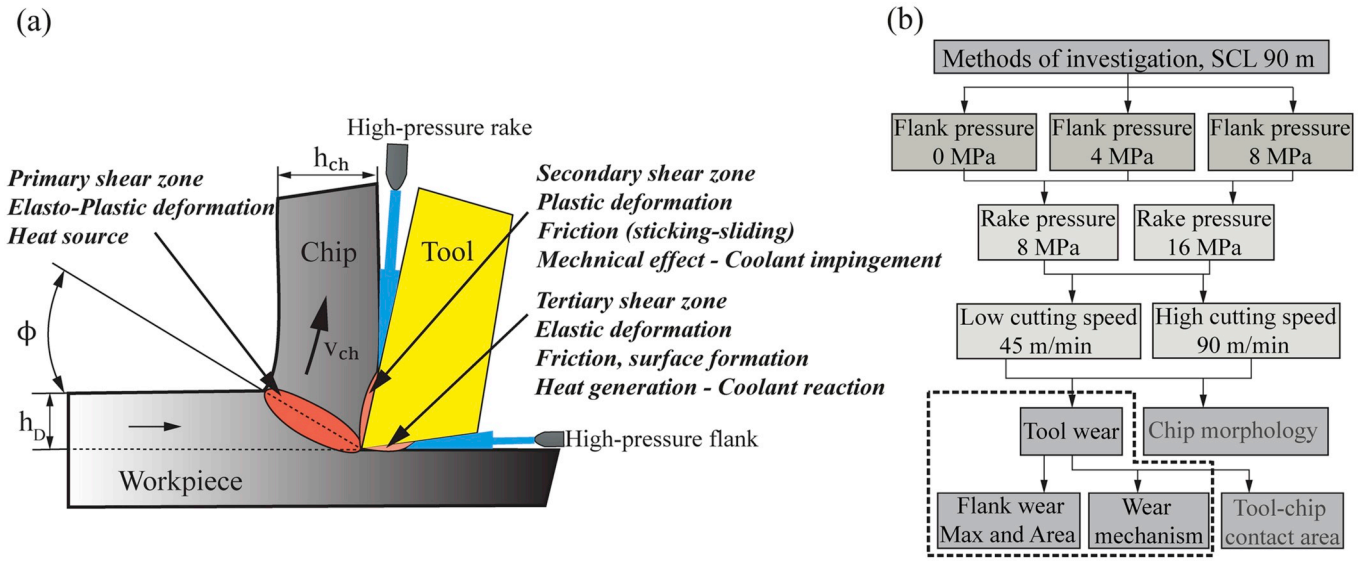

Fig. 1. (a) Illustrates three shear zones with focus of high-pressure coolant and (b) Overview of the research methodology incorporating investigation methods and process conditions focussed on tool wear.

moves towards the spindle centre), a more detailed description of the setup can be seen in Ref. [9]. High-pressure coolant was supplied to both the rake face and the flank face through a specially designed tool holder which allows precise focus of the coolant to the cutting edge (Fig. 2(b–c)). An emulsion consisting of water mixed with 5% oil was used as a coolant at room temperature, recommended by the coolant supplier.

The cutting parameters and pressure conditions are based on the experimental conditions and results discussed in literature given in Appendix A "Current State of the Art". Experiments were restricted to three different flank pressure conditions 0, 4 and 8 MPa (Fig. 1(b) for the detailed methodology). Two different rake pressures of 8 and 16 MPa were used. Currently, 8 MPa is the basic commercial setup readily sold by different machine tool manufacturers to the end user. Pressures of 16 MPa and above are customized to specific needs and used widely when machining HRSA to reach improved tool life, chip breakability and surface finish.

Since the cutting temperature rises drastically with increased cutting speeds, two cutting speeds 45 (low) and 90 (high) m/min were chosen to investigate the wear behaviour at two distinct levels of process heat generation. The coolant application was arranged through three nozzles with a diameter of 0.8 mm on the rake side and two nozzles with a diameter of 1.2 mm on the flank side.

The cutting parameters and pressure conditions are provided in Table 1. Feed rate, depth of cut, spiral cutting length (SCL) and material removed was kept constant. The cutting conditions were replicated two times, to ensure repeatability and were randomized before experimenting.

Table 1
Cutting parameters for facing operation of Alloy 718.

Parameter	Value
Spiral cutting length, SCL	90 m
Feed rate, f_n	0.2 mm/rev
Depth of cut, a_p	1 mm
Material removed, MR	18 cm^3
Cutting speed, v_c	45, 90 m/min
Rake pressure, RP	8, 16 MPa
Flank pressure, FP	0, 4, 8 MPa

2.3. Investigation methodology

Different methods were used for tool wear investigation. Light optical microscope, LOM, and scanning electron microscope, SEM, were used to measure and examine the flank wear, material adhesion and wear mechanisms. Moreover, 3-D scanning microscope based on InfiniteFocus variation [10] was used in measurement of maximum flank wear, flank wear area and volume difference measurement. Energy dispersive X-ray spectroscopy, EDX, was used to estimate the chemical composition. The measurement of maximum width of the flank wear land was conducted based on the ISO 1993:3685 standard [11]. For the round insert, a need to set a standard for how to establish the depth of cut line and corresponding wear land had to be established can be seen in Ref. [12]. In addition, the flank wear area was calculated for precise evaluation of the flank wear land for each cutting insert. Evaluation of notch wear and tool-chip contact area was measured based on the contact angle of 34° on the rake face [12].

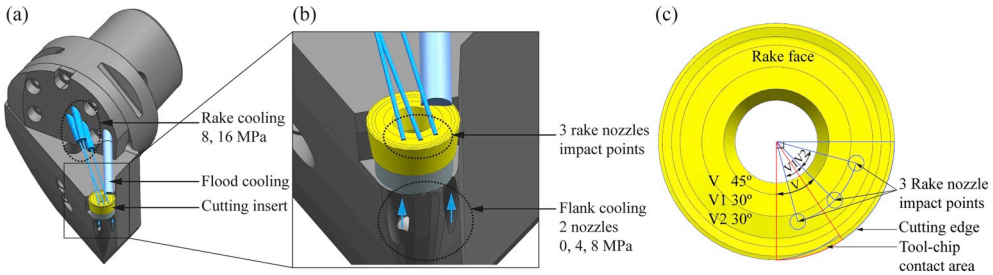

Fig. 2. (a) CAD model of special tool holder with internal delivering of high-pressure coolant to rake and flank extracted from Ref. [9]; (b) Magnified close to the cutting tool and impact directions; and (c) Illustration of the impact points of the coolant on the rake face as extracted from Ref. [9].

Analysis by electron backscatter diffraction (EBSD) was performed on cross sections of selected worn cutting tools. A low speed saw with a diamond wafering blade was used to section the tools at about the maximum chip thickness were the maximum width of flank wear was observed. Conventional metallographic methods were applied to polish the cross sections until a deformation-free surface was achieved (0.04 μm colloidal silica was used during the final polishing). The polished cross sections were examined using a LEO Gemini 1550 scanning electron microscope (SEM) equipped with a Nordlys EBSD detector. EBSD maps with 50 nm step size were acquired using an acceleration voltage of 20 kV. Post processing of the datasets was done with Oxford's HKL Channel 5 software [13].

3. Tool wear investigation

The investigations were focussed on the maximum flank wear (VB_{max}), flank wear area (VB_{area}) and wear mechanism observed on the WC cutting tools, by varying flank pressures conditions (0, 4 and 8 MPa) for rake pressure 8 and 16 MPa at cutting speeds 45 and 90 m/min (Fig. 1(b)). The findings are explained in the corresponding subsections.

3.1. Maximum flank wear and flank wear area

The maximum flank wear is a widely used reference for both research and industry to calculate the service life of the cutting tool. In industrial applications, the VB_{max} is utilized as a fast and reliable way to determine the need for tool replacement. The high-pressure coolant is extensively used with the main purpose to improve the tool life by lowering temperature in the cutting zone and the mechanical effect to break the chips in the rake face, thus, lowering the friction.

The tool failure criteria in this work was set to be the tool breakage, due to that the intention is to understand wear mechanism for the constant cutting conditions. However, according to ISO 1993:3685 standard, the recommendation is VB_{max} as 0.6 mm [11]. The maximum flank wear for v_c 45 m/min was observed close to the minimum chip thickness zone, see Fig. 3 (a) and the flank wear was evenly distributed for all the pressure conditions. In case of v_c 90 m/min, flank wear wasn't

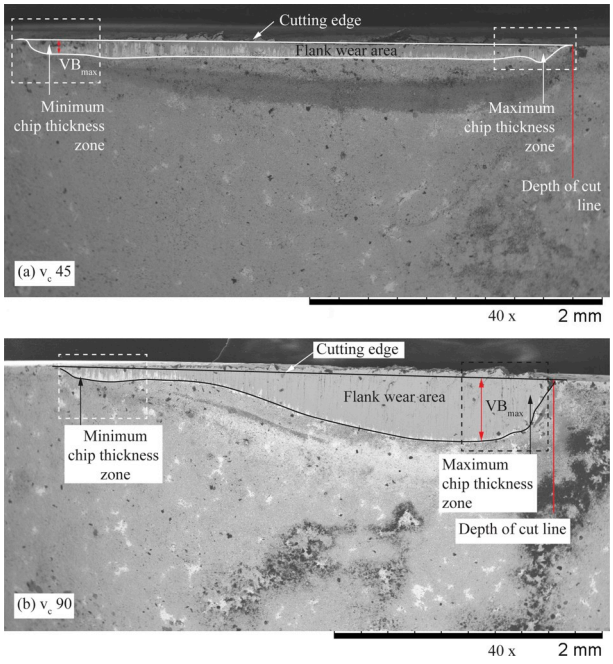

Fig. 3. Flank face of the WC cutting tool for rake pressure 16 MPa and flank pressure 8 MPa and a cutting speed v_c of (a) 45 m/min and (b) v_c 90 m/min.

Table 2
Measurement results of maximum flank wear and flank wear area with standard deviation.

S.no	v_c (m/min)	Rake pressure, RP (MPa)	Flank pressure, FP (MPa)	VB_{max} ± SD (mm)	VB_{area} ± SD (mm^2)
1	45	8	0	0.18 ± 0.01	0.43 ± 0.06
2	45	8	4	0.18 ± 0.01	0.40 ± 0.03
3	45	8	8	0.18 ± 0.02	0.46 ± 0.08
4	45	16	0	0.14 ± 0.04	0.40 ± 0.08
5	45	16	4	0.17 ± 0.04	0.41 ± 0.08
6	45	16	8	0.14 ± 0.04	0.38 ± 0.08
7	90	8	0	0.69 ± 0.05	1.48 ± 0.26
8	90	8	4	0.65 ± 0.11	1.42 ± 0.31
9	90	8	8	0.70 ± 0.08	1.39 ± 0.16
10	90	16	0	0.78 ± 0.04	1.45 ± 0.12
11	90	16	4	0.64 ± 0.12	1.25 ± 0.35
12	90	16	8	0.58 ± 0.07	1.17 ± 0.14

uniformly distributed and VB_{max} was measured in the region the maximum chip thickness zone and as shown in Fig. 3 (b). In addition, VB_{area} was measured to increase the understanding and avoid just one single number (VB_{max}) value to describe the flank wear. Values of the reached wear levels, extracted from a 3-D scanning microscope, can be found in Table 2.

The maximum flank wear was measured for all the cutting trials (including the replicates, which is shown by the error bar), see Fig. 4. In addition, the flank wear area of the worn zone was measured and values are plotted as shown in Fig. 5. While comparing the effects of varying v_c, the difference in mean value of VB_{max} and VB_{area} can be readily seen. The numbers have increased significantly (by approx. 3 to 4 times) for all the cutting conditions. Despite using a high-pressure coolant, the increase in cutting speed reduced the tool life significantly. This is in line with the theory that increased cutting speed leads to rises in the temperature at the cutting edge due to the heat generated in tool-chip and tool-workpiece shear zones, which consequently accelerates tool wear and lowers tool life [6,14].

For v_c 45 m/min, an increase in rake pressure from 8 to 16 MPa for constant flank pressure of 8 MPa led to a reduction of the mean values for VB_{max} and VB_{area} by approx. 20 and 17%, respectively. The corresponding wear levels were not significantly influenced by similar cutting conditions by flank pressures of 0 and 4 MPa. For a v_c of 90 m/min and a rake pressure of 8 MPa, an increased flank pressure did not lead to a reduction of the maximum flank wear and flank wear area (Fig. 4 (a) Fig. 5 (b)). However, if the rake pressure is increased to 16 MPa (Figs. 4 (b) and Fig. 5 (b)) the mean VB_{max} and VB_{area} are reduced by approx. of 25 and 20%. The wear levels were not influenced when no flank coolant was used and when the flank pressure was 4 MPa. Finally, at a flank pressure of 8 MPa, the downward wear rate trend was regained.

Based on the obtained tool life, the industrial implication of the results is to rather remain at the lower cutting speeds (at very low tool wear rate) than to increase the cutting speed (at the cost of frequent tool changes).

Observed wear mechanisms from the investigated WC tools used in machining Alloy 718 are elaborated with respect to cutting speed (low and high).

3.2. Wear mechanism of WC at low cutting speed

Abrasion and adhesion were observed to be the dominant wear mechanisms on the WC tools disregarding the rake and flank coolant conditions. Increase in rake and flank pressure had no influence on wear mechanism, see Fig. 6. However, the amount of adherence of Alloy 718 and abrasion of WC tools varied due to different coolant pressure conditions on the rake and flank. With all the cutting tools, a more uniform abrasion wear was observed in the form of flank wear.

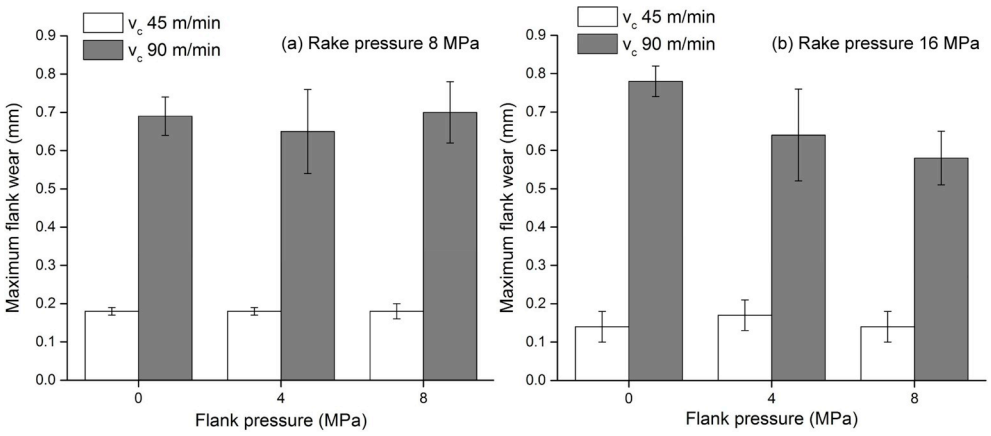

Fig. 4. Comparison of measured maximum flank wear for different cutting speeds and flank pressures; (a) Rake pressure 8 MPa (b) Rake pressure 16 MPa.

Further analysis by SEM and EDX revealed the adherence of the workpiece material, Alloy 718 as a uniform grey region on the flank wear land as shown in Fig. 6 (a, b and e), while the white regions (varying spikes) were identified as the WC tool material.

Adhesion wear mechanism is observed in all the cutting tools on both flank wear region and tool-chip contact area at the rake face. Considering the mechanical and thermal properties of Alloy 718, the amount of heat and mechanical stress applied to the cutting tool during machining can lead to the frequent chemical bonds between the tool and workpiece materials. This also stands as cause of micro welds to the tool rake face due to thermally controlled diffusion process. Formation and growth of build-up edges is due to adhesion where the material moves from workpiece to cutting tool. Cobalt is widely used as a binder for WC due to its exceptional properties of adhesion and carbide wetting. Cobalt has two allotropic forms. Below 417 °C it is hexagonally closed packed and above 417 °C cobalt has a face centred cubic, which has positive influence on the adhesion process [15–17].

When the coolant touches a heated surface i.e. the cutting tool, temperature higher than the coolant boiling point, the liquid vaporizes immediately and forms an insulating vapour layer. This layer protects the remaining coolant from boiling. This is known as the Leidenfrost effect. The vapour layer acts as barrier for the coolant to reach the proximity of the cutting edge for improved cooling. Traces of vapour layer are seen as a dark region in Fig. 6 (b and c). It is identified by EDX analysis as calcium and sulphur containing layer stemming from the coolant.

The coolant-boiling region formed as a continuous layer below the flank wear region for flank pressure conditions between 4 and 8 MPa, Fig. 6 (b and c). However, continuous formation of the coolant-boiling region did not occur when there was no flank pressure. Instead, the coolant-boiling regions were scattered and did not follow the flank wear pattern. By focussing, the high-pressure coolant media at clearance face so called Leidenfrost effect can be suppressed. Concurrently, increase in flank pressure had a positive impact on the tool life by lowering the flank wear and moving the coolant precipitate layer closer to the cutting edge. Application of high-pressure coolant in the clearance face led to the formation of different zones on the flank face of the tool. The zones can be seen from the cutting edge in Fig. 6 (c) starting from flank wear marked as (1), the no boiling region (2) (visibility of Co and W), followed by the coolant-boiling region (3) (dark region). These zones illustrate the temperature gradient along the cutting tool.

Abrasion and adhesion are the primary and interrelated wear mechanisms observed with rise in temperature. During the machining process, initial stage of wear begin with mechanical wear, abrasion due to the relative interaction of the WC tools with Alloy 718 carbides present in the material. Abrasion is also caused by the burr due to work hardening found on the surface generated in the previous pass due to the side flow of material [15,16] as can be seen in Fig. 6. There was no fracture or cracking observed on any of the tools.

The rake face of all the cutting tools had the build-up layer (BUL) on the tool-chip contact area; one of the tools is shown in Fig. 7 (a). In addition, build-up material (BUM) formation was observed in different areas along the contact zone, as seen Fig. 7 (b) is not the build-up edge (BUE). Normally the BUE is non-stable, breaks periodically and takes away a small amount of tool material, which in turn leads to deterioration of the cutting edge [18]. In this case, the BUM can be from the chips adhered to the tool during the cutting tool disengagement from the workpiece. BUM is scattered along the tool-chip contact area, it

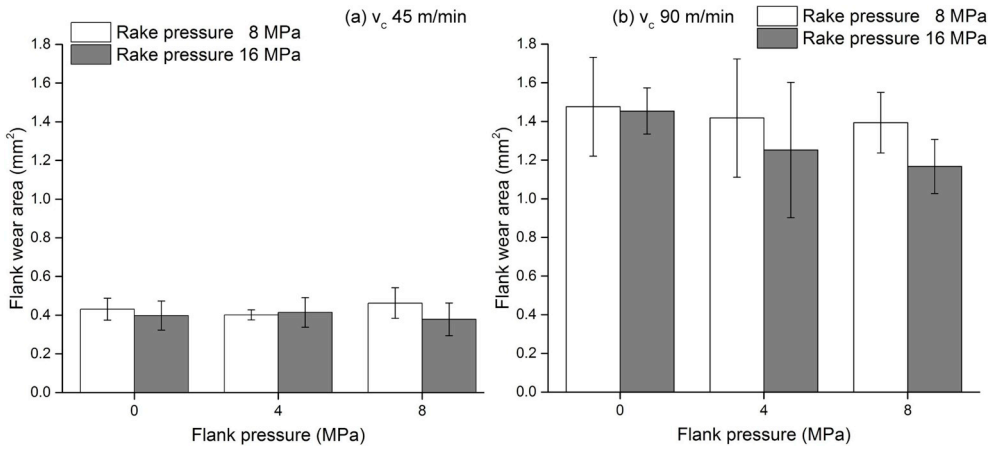

Fig. 5. Comparison of measured flank wear area for different flank and rake pressures at cutting speeds of (a) v_c 45 m/min, and (b) v_c 90 m/min.

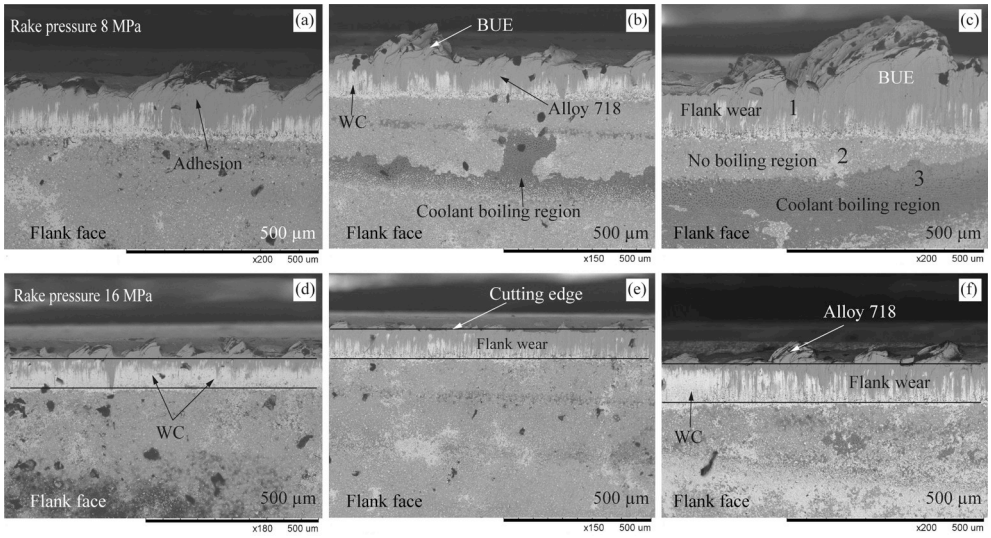

Fig. 6. Wear observation on the selected tool at v_c 45 m/min for rake pressure of 8 MPa and flank pressure of (a) 0 MPa, (b) 4 MPa, and (c) 8 MPa and for rake pressure of 16 MPa and flank pressure of (d) 0 MPa, (e) 4 MPa, and (f) 8 MPa.

does not represent traditional BUE formation. However, intense formation of BUL could lead to negative effects of the tool life by acting as barrier for the heat to dissipate through the tool. Fig. 7 (c) shows the region of BUM, adhesion of alloy 718 and WC at higher magnification. By use of a 3-D microscope, volume difference analysis was conducted and the resultant micrograph clearly shows the volume adhered to the tool-chip contact area along the cutting edge (Fig. 7 (d)). The colour variation orange and red being the highest level of material adhered and cyan colour showing the build-up layer on the tool.

3.3. Wear mechanism of WC at high cutting speed

Increasing the cutting speed can be beneficial in the production aspect to remove the material at higher rates. Due to the thermal resistance and work hardening property of Alloy 718, it is a disadvantage to machine at higher cutting speeds. Normally, chips carry away most of the heat when machining materials like aluminium and steel. However, chips from Alloy 718 do not dissipate the heat from the tool-chip contact zone at the same rate. In addition, the energy created due to friction in the tool-chip contact zone is directly proportional to the cutting speed, hence creating an intense temperature load on the tools [19].

The observed tool wear mechanisms were similar independent of the cutting speed. Nevertheless, the amount of wear such as VB_{max}, VB_{area}, cutting edge deterioration due to extensive abrasion on the tool increased significantly. Apart from BUL, BUM and flank wear, the dominant wear found was the growth of crack in both rake and flank face, disregarding the high-pressure cooling in the rake and flank face almost all the tools showed cracks. These cracks can be seen in the premature stage of the tool breakage. The tools were intensively damaged compared to the lower cutting speed. As shown in Fig. 8, for the rake pressure of 16 MPa and flank pressure of 8 MPa, the crack propagates from the cutting edge across the flank wear zone as can be seen in Fig. 8 (b and c). A grey area can be seen on the flank wear land, which was found to be adhered Alloy 718 material.

When investigating the cutting tool in SEM, it was not possible to see a crack before etching the sample (Fig. 9(a)). Since the adhered workpiece material obscured the actual flank wear land, the tools were investigated after etching (Fig. 9(b)). After removing the adhered workpiece material from the flank face, the presence of the cracks was revealed see Fig. 9 (b &c). This could be seen as a kind of confirmation that the cracks are actually present in the tool and are not just part of the adhered layer.

Selected cutting tools from different flank pressure conditions were investigated for cracks in flank wear zone using SEM, micrograph showing the crack propagation for all three conditions can be seen in Fig. 10. For 4 and 8 MPa of flank pressure, the maximum flank wear and area were measured to be lowered compared to no cooling conditions. However, cracks exist in the tools as can be seen in Fig. 10. In addition to adhesion of Alloy 718 and cracks, abrasion in form of sliding led to

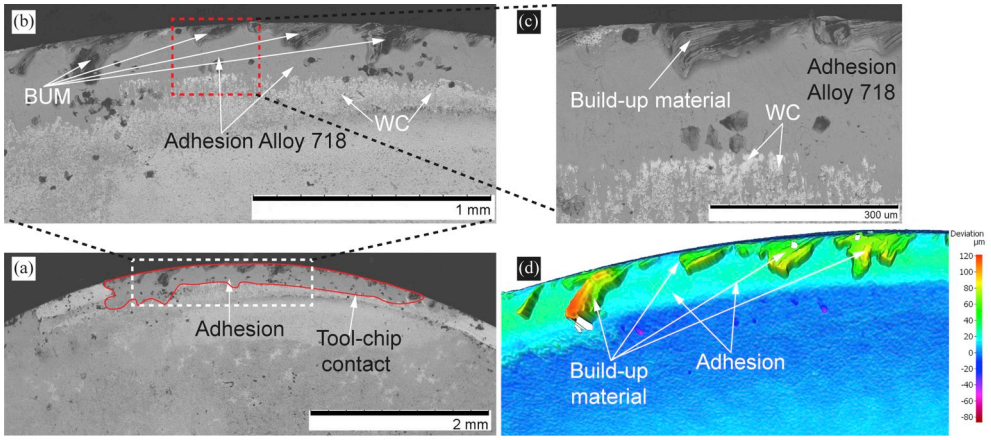

Fig. 7. Wear mechanism observed on rake face of the tool for v_c 45 m/min with rake pressure of 8 MPa and no flank cooling.

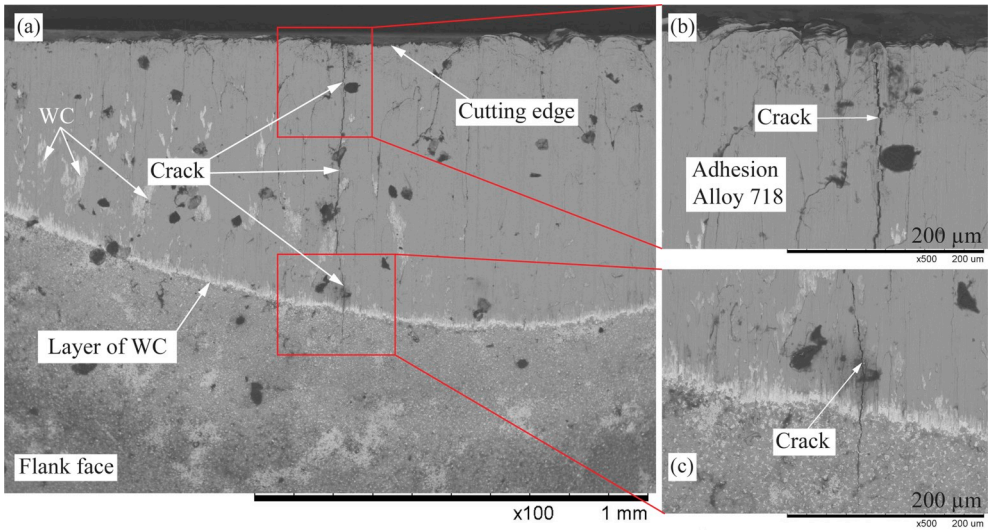

Fig. 8. Flank face of the cutting tool at rake pressure of 16 MPa and flank pressure of 8 MPa (a) Flank wear focussed on the crack (b) crack from the cutting edge, and (c) propagation of crack across the flank wear area.

removal of cobalt exposing the WC as white zones. Altintas [19], stated that tools start to crack once the principle tensile stress reaches the ultimate tensile strength (UTS) of the tool material. WC has an approx. of 650 MPa as UTS. Furthermore, one needs to consider the accumulation of heat with increase in cutting time, tool wear and in combination with coolant cooling; leads to a thermal gradient on the tool. The cracks found on these tools can be seen as an early stage of plastic failure of the cutting tool. From the results, it can be assumed that by further increase of the cutting speed or SCL, the tool is prone to catastrophic failure.

The cutting edge deformation was identified as a common problem in machining HRSA [19]. On the rake face, tool-chip contact area was filled with Alloy 718 material. The cutting edge deterioration due to extensive abrasion and fracture were observed, Fig. 11. Increase in wear occurs as the cutting tool exceeds the deformation resistance due to the thermomechanical stress and at elevated cutting temperature. At this condition, the cutting edge cannot withstand the compressive stress. In case of carbide tools, plastic deformation mechanism occurs due to the increase in the cutting temperature (increase in cutting speed), under high cutting forces.

Machining of Alloy 718 at increased cutting speed induces higher forces and a rise in temperature in the contact zone, which in turn affects structural strength of the cutting tool, thus leading to deteriorate the cutting edge at a faster rate. It is important to retain the strength of the cutting edge at elevated temperatures to avoid a blunt tool, which can change the cutting conditions and damage the workpiece. The loss in structural integrity and edge strength of the tool, could lead to an intense tool wear rate and cause tool breakage in form of cracks, as seen in Fig. 11 (c).

3.4. Notch and crater wear

Various researchers like Ezugwu et al. [20, 21], Machado and Wallbank [22], and Suárez et al. [23] have investigated machining with the use of high-pressure coolant and reported increases in tool life by lowering flank wear compared to flood cooling or even dry cutting conditions. However, the dominant depth of cut notch wear was observed in their research work for both carbide and ceramic tools. This failure mode was reported to be the most prominent cause for tool failure while machining Alloy 718. Shalaby and Veldhuis [24] mentioned that the probable cause of notch wear can be caused by one effect or a combination of the following: adhesion effects, work-hardened surfaces, stresses, adverse chip flow conditions with chip curling, and temperature gradients. Further, notch wear is the dominant tool failure criterion when machining at higher cutting speeds. However, in some cases notch wear was identified even at lower cutting speeds [23]. In this experiment, no such observation of groove shape or notch wear were found for any of the cutting tools at the depth of cut line (at approx. 3.6 mm as shown in Figs. 3 and 12).

Diffusion wear mechanism is commonly found on the cutting tool in form of crater wear due to the high temperature in the tool-chip contact region. Many studies observed crater wear to be another common tool wear form observed during machining Alloy 718. This was reported by various experts and researchers in the area of machining disregarding

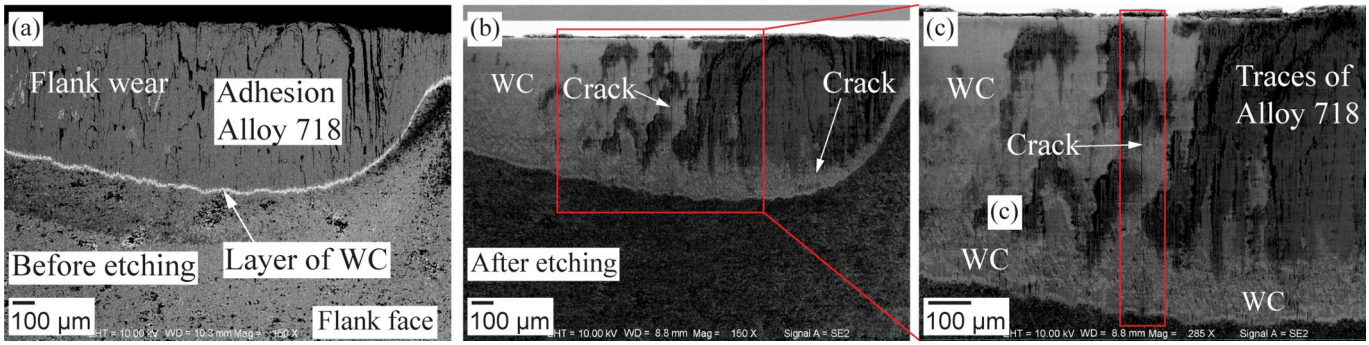

Fig. 9. SEM micrographs of the flank face of selected tool machined with a rake pressure of 16 MPa and no flank cooling (a) before etching, (b) after etching, and (c) higher magnification showing the crack.

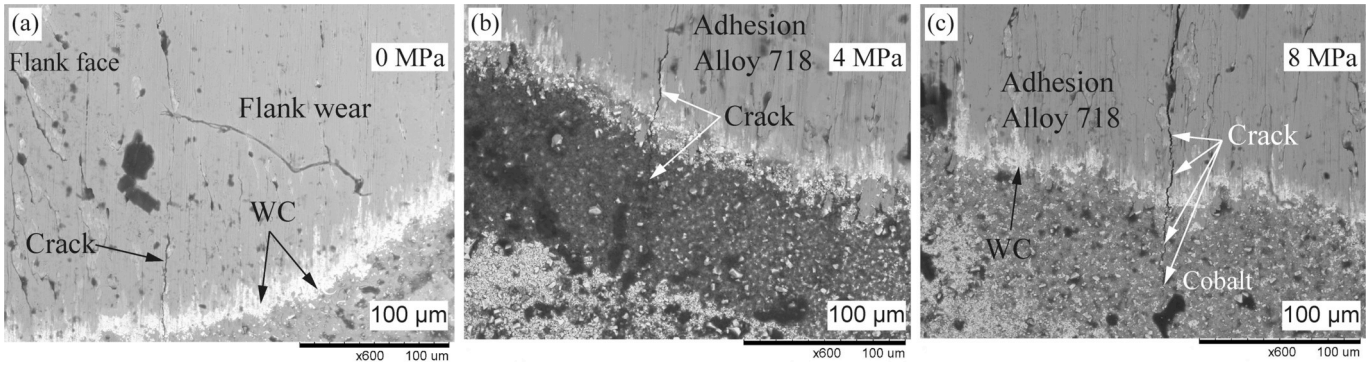

Fig. 10. For a rake pressure of 16 MPa selected tools SEM micrograph of flank face at higher magnification on the crack for different flank pressures condition (a) 0 MPa (b) 4 MPa (c) 8 MPa.

the tool geometry and material such as carbide, ceramics, [25–28]. In this experiment, none of the tools in tool-chip interface for low cutting speed of 45 m/min showed any form of crater wear. This could be attributed to the insert geometry. The round shape is creating a varying tool-chip area see Fig. 2 (c), thus, reduces the mechanical contact in the secondary shear zone.

At higher cutting speed of 90 m/min and disregarding the strength of insert geometry and flank pressure conditions, the tool wear mechanism changed between 8 and 16 MPa. Instead of crater wear, which is one of the common wear mechanism in machining Alloy 718, loss of material was observed on the cutting edge (see Fig. 12 a, b and c), in form of abrasion. However, the shape looks like a “crater valley” than a localized crater wear. For the cutting tools machined with a rake pressure of 16 MPa, abrasion rate and flank wear area were less. In addition, the tool-chip contact area was more constrained and showed less abrasion compared to the tools with a rake pressure of 8 MPa (see Fig. 12).

This result can be correlated to the findings by Ezugwu and Bonney [5] that an increase in the coolant pressure creates access for the coolant jet to penetrate the tool-chip interface. This leads to an efficient cooling and lubrication. Physical formation of coolant wedge due to pressure in the secondary shear zone lowered the tool–chip contact length, cutting force and coefficient of friction. The results show that applying coolant media at a high pressure of 16 MPa on the rake face has a significant effect on the mechanical force to penetrate close to the cutting edge, therefore, reducing the thermo-mechanical load on the rake face, leading to lower the tool wear.

At higher cutting speed in machining Alloy 718, it is highly recommendable to use the maximum available pressure on the rake face. Flank cooling places a vital role in decreasing the tool wear rate. Hence, it is important to have at least a pressure of 8 MPa on the flank face of the tool for improved tool life.

3.5. EBSD wear characterization of WC tools at low and high cutting speeds

In order to study the tool wear and its underlying mechanisms in dependence of the machining and coolant conditions, cross sections of four worn inserts were prepared and examined with EBSD regarding the plastic deformation of WC grains. Local misorientation maps of EBSD datasets acquired at the cutting edge can be seen in Fig. 13. The colour of every pixel represents its average orientation difference with a set of surrounding pixels [13]. According to the colour code in Fig. 13 (a), undeformed regions with low/no local misorientation are therefore shown in blue while higher misorientations due to deformation of the WC grains are shown by green, yellow, and red. As can be seen, the majority of all four maps are coloured blue indicating that these areas are free of deformation. However, close to the worn surfaces on the rake and flank faces, green and yellow coloured pixels show significant local misorientation (deformation) within WC grains. The affected zones extend a few rows of WC grains into the tools (below 5 µm). The examined part of the rake face in Fig. 13 (c) shows an exception where no local misorientations can be seen in close vicinity to the worn tool surface. As indicated by the significantly different geometry of the cutting edge (compare with e.g. Fig. 13 a), it is believed that this tool exhibited local chipping of the cutting edge in the region where the tool was sectioned. Brittle fracture of the tool material due to chipping instead of gradual wear might explain the absence of deformation in Fig. 13 (c).

Interestingly, no significant differences between the low and high coolant supply pressures can be observed for the two cutting speeds: The majority of deformation reaches to about the same depth beneath the worn rake and flank face when comparing Fig. 13 (b with d) and when comparing the flank face in Fig. 13 (c with e). The observed reduction in tool flank wear for constant cutting speed when using higher coolant supply pressures (see Figs. 4 and 5) are therefore not likely due to a significant reduction of plastic deformation of WC grains. Instead, the increased cooling is expected to affect other wear mechanisms such as diffusion/dissolution or abrasion, which lead to the reduced overall flank wear.

An increase in cutting speed has an impact on the observed misorientation: Significantly more WC grains which are comparably far from the worn tool surfaces (> 10 µm) exhibit local misorientation for

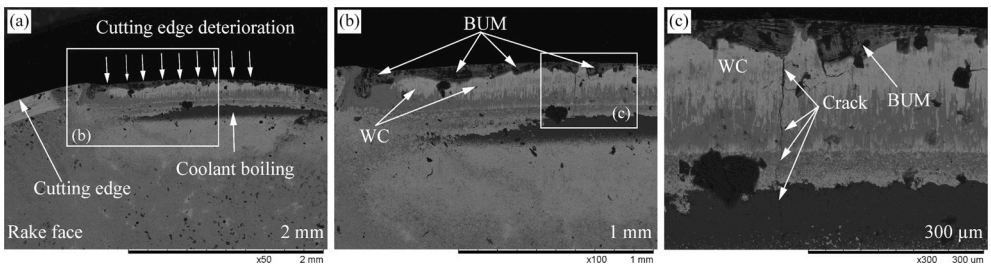

Fig. 11. Rake face of the cutting tool machined with rake pressure of 16 MPa and flank pressure 4 MPa (a) cutting edge deterioration (b) BUM on the cutting edge, and (c) crack initiation from the cutting edge crossing the tool-chip contact area.

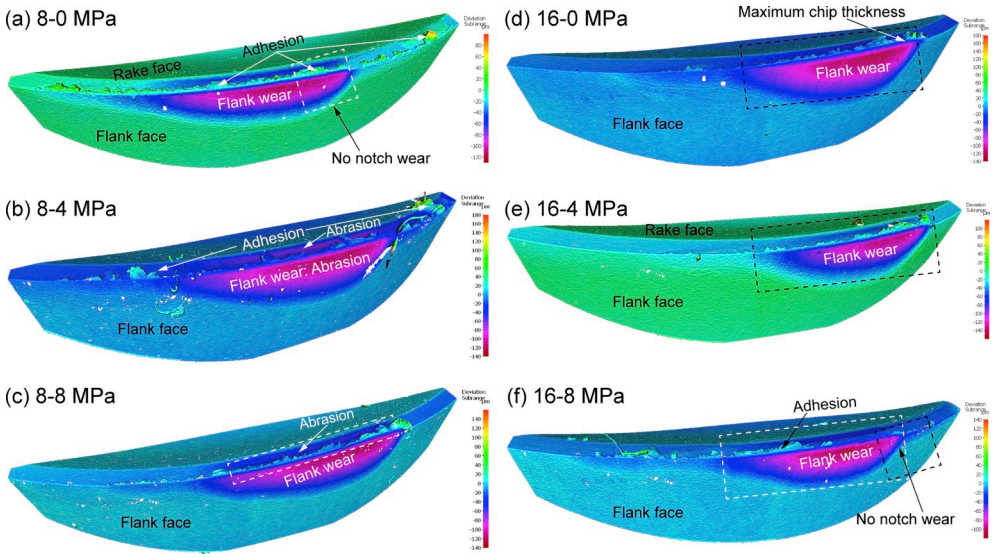

Fig. 12. Volume difference measurement of the cutting tools at different pressure conditions for v_c 90 m/min.

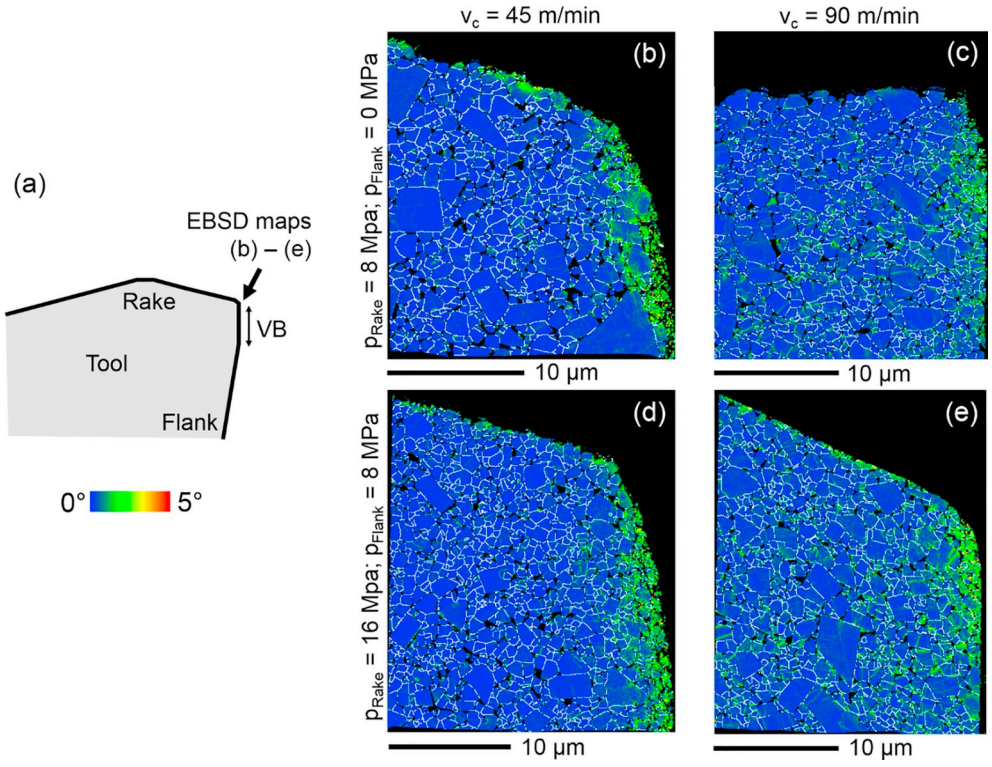

Fig. 13. EBSD results of worn cutting tools: (a) schematic representation of cross section through worn tools with location of EBSD maps indicated; (b)–(e) EBSD local misorientation maps of WC grains for low cutting speed (left column) and high cutting speed (right column) with low and high coolant supply pressures to rake (p_{Rake}) and flank (p_{Flank}) in the upper and lower row respectively. The local misorientation maps were generated using 3 × 3 pixel filter size, 5° subgrain exclusion angle. Grain boundaries (> 10°) are shown in white.

the tools used with the higher cutting speed of 90 m/min as compared with the tools used for 45 m/min cutting speed (compare Fig. 13 (c and e) with Fig. 13 (b and d). This is likely to be the result of higher thermal and mechanical loads, which are expected to act on the cutting edge when for the higher cutting speed, resulting in a larger zone of the network of WC grains to be deformed during cutting.

4. Conclusions

This research work has presented the findings from the influence of using flank high-pressure cooling on the cutting tool. Tool wear investigations were focused in different areas such as maximum flank wear, flank wear area, wear mechanism in machining Alloy 718 with cemented tungsten carbide tools. The following conclusions can be drawn:

At low cutting speed (45 m/min) with a maximum pressure on the both rake (16 MPa) and flank (8 MPa) reduced the mean VB_{max} and VB_{area} by approx. 22 and 12% compared to 8 MPa of rake pressure and "no cooling" on the flank.

At high cutting speed (90 m/min), with a rake pressure of 16 MPa, mean VB_{max} and VB_{area} reduced by approx. 25 and 19% with a flank pressure of 8 MPa compared to no flank cooling condition.

No depth of cut notch wear was observed in any of the cutting tools including the repetitions.

At the high cutting speed, 3-D measurement results of the tools showed the formation of a crater in the shape of a valley on the cutting edge at a rake pressure of 8 MPa condition. By increasing the rake pressure to 16 MPa significantly decreased the rake wear and abrasion.

At the low cutting speed, abrasion and adhesion were common wear mechanisms; no crack and cutting edge deterioration were observed.

At high cutting speed, drastically increased the tool wear rate (VB_{max}, VB_{area} and rake wear). Cracking of the tool and cutting edge deterioration due to extensive abrasion were dominant tool wear mechanisms.

The EBSD results in the flank face of the tools for high cutting speed indicated significant local misorientation of WC grains as far from the worn tool surfaces ($> 10\,\mu m$) compared to low cutting speed. Increase in coolant pressure did not have an influence on the WC grain misorientation.

Higher traces of coolant precipitate were found on the tools, machined with a flank cooling. At 8 MPa of pressure on the flank face moved the vapour barrier film to the cutting edge. Thus, enhanced the coolant reachability close to the cutting edge.

Flank coolant at 8 MPa had a substantial positive effect on the tool life.

Based on the investigation, results point in the direction to machine Alloy 718 at low cutting speed with maximum available pressure for both rake and flank to increase the service life of the tool.

Acknowledgement

The authors would like to thank the funding organization Västra Götalandsregionen in association with the PROSAM project. We would also like to thank Sandvik Coromant for the support with cutting inserts. Special thank go to Andreas Gustafsson at University West and Andreas Lindberg at GKN Aerospace Engine Systems AB for helping with experiments. Sauruck Clemens, Alicona Imaging GmbH, Austria, André Prando Lidström and Joakim Bonér from Mytolerans AB, Sweden are thanked for helping with 3-D measurements. The authors gratefully acknowledge the financial support from the corporate research school SiCoMaP, funded by the Knowledge Foundation, Dnr20140130 and the ESIF, EU Operational Programme Research, Development and Education, and from the Centre of Advanced Aerospace Technology (CZ.02.1.01/0.0/0.0/16_019/0000826), Faculty of Mechanical Engineering, Czech Technical University in Prague to publish in open access.

Appendix A. Current state of the art

Findings from different researcher's over decades in high-pressure coolant application, during machining Ni-base alloy Inconel 718 also known as “Alloy 718” focused mainly on single point cutting tool operations has been discussed below (Inconel 901 was used in the 1990's experiments). Comparisons were made based on the cutting conditions, cutting tool material, high-pressure coolant conditions, the position of the coolant, followed by evaluation and findings, see Table 3.

Table 3
Summary of various researchers' investigation in machining Ni-base alloy with high-pressure coolant.

Year	Authors	Workpiece/Cutting tool	Process conditions	Coolant position/conditions	Evaluation/Findings
1991	Ezugwu. E. O, Machado. A. R, Pashby. I. R and Wallbank. J [20]	Inconel 901 Carbide: CNMP 12 04 12/08 and CNMA 12 04 12/08 Ceramic: CNMG 12 04 12, CNMP type are 5° positive, with chip breaker grooves	Turning f_n = 0.127 and 1.18 mm/rev, a_p = 1.25 and 2.5 mm Carbide, v_c = 47 and 55 m/min Ceramic, v_c = 150, 215 and 300 m/min.	Overhead flood cooling had a flow rate of 5.2 l/min. High-pressure coolant pressure were at 14 MPa with a flow rate of 15.1 l/min. Tool holder was specially designed to direct the coolant through into the region where the chip breaks contact with the tool.	Small segmented chips were produced. Using high-pressure coolant severe wear mechanism the premature fracture was suppressed in both carbide and ceramic inserts Notch wear was dominant tool wear found in carbide tools led lower the tool life.
1992	Wertheim. R, Rotberg. J and Ber. A [29]	Inconel 718 Uncoated ISO P40	Grooving v_c = 30 m/min, f_n = 0.16 mm/rev	Internal flushing-coolant through the rake face of the tool at pressure of 1.62 MPa.	Tool life improved from 3 min to 14 min with high-pressure coolant.
1994	Machado. A. R and Wallbank. J [22]	Inconel 901 CNMP 12 04 08 CNMP 12 04 12 CNMA 12 04 08 CNMA 12 04 12	Turning v_c = 32 and 55 m/min. f_n = 0.067, 0.127, 0.25 and 0.38 mm/rev a_p = 2.5 mm.	Special tool holder to deliver coolant in the rake face at a pressure of 14.5 MPa at the tool-chip interface. Hysol G used as coolant with a concentration of 4%.	Notch wear was dominant. Cutting forces did not change significantly. In some of the experimental conditions, tool-chip contact was reduced by 44% with high-pressure cooling. Surface finish had a minor improvement.
1999	Öjmertz. K. M. C and Oskarson. H. B [25]	Inconel 718 Silicon carbide whisker reinforced ceramic	Turning v_c = 150 m/min f_n = 0.1 mm/rev a_p = 1.5 mm Rake angle −6°; Approach angle 75° and cutting edge inclination angle 6°.	Three jets targeted tool-chip interface. 1. Notch wear region through a 0.15 mm diameter sapphire orifice, 2. Mid region through a 0.25 mm diameter orifice. 3. Parallel to the cutting edge where notch wear emanates through a 0.15 mm diameter orifice. Pressure: 80, 240, 320 and 360 MPa. For orifice diameter of 0.15 the corresponding flow rates were 0.30, 0.52, 0.60 and 0.64 l/min. For orifice diameter 0.25 mm the flow rates were 0.84, 1.45, 1.67 and 1.78 l/min.	Notch wear increased with coolant pressure. The predominating wear mechanism influenced the tool life was thermal wear. Thermal wear mechanism obstructs the formation of a protective build-up layer. Shorter tool-chip contact, slightly improved surface finish and chip breakability. High-pressure cooling did not work as expected with SiC-whiskers reinforced alumina inserts compared to carbide tools.
2000	López de Lacalle, L. N., J. Pérez-Bilbatua, J. A. Sánchez, J. I. Llorente, A. Gutiérrez, and J. Albóniga [30]	Inconel 718 under study was to AMS 5662 annealed (hardness 200 HBN) Ceramic cutting tools RNG 12 07 00 and CNGN 12 07 12	Turning Round A (v_c/f_n/a_p) 850/0.4/0.2 Rhomb 80° B 850/0.1/0.35 Rhomb 80 °C 750/0.1/0.35	Coolant pressure 11 MPa with a flow rate of 10 l/min. A stainless steel nozzle was used to deliver the coolant on the rake face at a distance of 7–10 mm with at an angle of 10°.	The round inserts can withstand a higher feed than the rhombic inserts. The round tools had positive results, more stable, due to lead angles produced thinner chips. Ceramic tools can be used for machining Inconel 718

(*continued on next page*)

Table 3 (*continued*)

Year	Authors	Workpiece/Cutting tool	Process conditions	Coolant position/conditions	Evaluation/Findings
2003	Ezugwu. E.O and Bonney. J [31]	Cast Inconel 718 SiC whisker reinforced ceramic inserts RNGN 12 07 00	f_n = 0.15 & 0.25 mm/rev, a_p = 1.5–2.5 mm, v_c = 200, 250, 300 m/min.	Coolant was directed via a nozzle to the region where the chip breaks contact with the tool. At pressures: 11, 15 & 20.3 MPa. Coolant concentration used was 6%.	Increase in coolant pressure lowered the tool life. Accelerated the notch wear with increase in the cutting conditions. In addition, water jet impingement lead to erosion on ceramic tools. Chips, were well segmented and did not significantly affect the surface finish.
2004	Ezugwu. E.O and Bonney. J [5]	Cast Inconel 718 Triple PVD coated, $TiCN/Al_2O_3/TiN$ carbide tool SNMG 12 04 12	f_n = 0.25 & 0.3 mm/rev, a_p = 2.5–3 mm, v_c = 20, 30 & 50 m/min.	Conventional coolant used at the cutting interface at an average flow rate of 5 l/min. The high-pressure coolant was directed via a nozzle on the tool holder to the region where the chip breaks contact with the tool. At a pressure of 11, 15 and 20.3 MPa with an average flood rate of 20–50 l/min. Coolant concentration 6%.	Tool life increased up to seven folds with rise in high-pressure cooling. However, there is a critical pressure where the tool life is marginal. Tool-chip contact was reduced which lead to lower the coefficient of friction, cutting temperature and forces. At higher v_c of 50 m/min with 20.3 MPa, the tool life increased by 740% and also produced well segmented C-shape chips.
2005	Ezugwu. E.O, Bonney. J, Fadare. D. A and Sales. W. A [21]	Cast Inconel 718, Whisker reinforced ceramic insert, RNGN 12 07 00	Finishing operation f_n = 0.1 & 0.2 mm/rev, a_p = 0.5 mm, v_c = 200, 270, 300 m/min.	Concentration of the coolant 6% Flood cooling at the cutting interface had an average flow rate of 5 l/min. Pressure used: 11, 15 and 20.3 MPa. High-pressure coolant had flow rate ranging 20–50 l/min. Nozzles were focussed in the region where chip breaks contact with the tool.	Increase in coolant pressure improved cooling, lubrication at the cutting interface, effective chip segmentation that lead to lower the cutting forces. Chip curl radius depends on the coolant pressure and flow rate. At v_c = 250 and 270 for f_n = 0.2, at a critical pressure of 15 MPa improved tool life by approx. 70% Increasing the pressure further to 20.3 MPa caused rapid notch wear.
2009	Courbon. C, Kramer. D, Krajnik. P, Pusavec. F, Rech. J and Kopac. J [32]	Inconel 718, HRC (36–38). PVD TiAlN coated carbide tool (gradeP25) SNMG120408-23	Rough turning f_n = 0.2, 0.224 & 0.25 mm/rev, a_p = 2 mm, v_c = 46, 57, 63, 74, 81 & 127 m/min.	Coolant pressure: 50, 90 & 130 MPa. Coolant through nozzle diameter of 0.25, 0.3, 0.4 mm and the emulsion was with a concentration of 5.5% Coolant focussed on the rake face, at the tool-chip contact zone. The distance between the impact point of the jet and the cutting edge were 0, 1.5 and 3 mm.	Able to increase the cutting speeds and feed rate for a fixed pressure by increasing the nozzle diameter. Lower contact length observed at low cutting speed. Excellent chip breakability were found at a pressure of 130 MPa and v_c 127 m/min. Reduced the build-up edge formation. Extended process window range of operability of the cutting tool.
2012	Oguz Colak [26]	Inconel 718 (Ti,Al)N + TiN coated carbide cutting tool CNMG 0812	Turning process Taguchi L18 orthogonal array. f_n = 0.05, 0.10, 0.15 mm/rev, a_p = 0.5 & 1 mm, v_c = 50, 70 & 90 m/min.	A pressure of 0.6 MPa used as a reference conventional cooling. High-pressure were at 10 and 30 MPa. The coolant was focussed on the rake face, between the cutting tool and formed chip back surface, at a low angle about 5–6°. Water-soluble oil coolant of 5% concentration.	Flank wear and cutting forces considerably decreased with the high-pressure cooling. Crater wear was observed on the rake face. High-pressure at the tool-chip interface enhanced the chip fragmentation and decreased cutting force due to the mechanical effect of high pressure coolant. Lowered rake wear and tool-chip contact, which in turn contributed to longer tool life and improved surface quality.
2013	Kramer. D, Sekulic. M, Jurkovic. Z and Kopac. J [33]	Inconel 718, HRC (36–38). TiAlN coated carbide tool SNMG120408-23	Hard turning f_n = 0.2 mm/rev, a_p = 2 mm, v_c = 16, 40, 50, 63, 81,101 & 127 m/min.	Emulsion of 5.5% used as concentration focussed at the tool-chip contact zone. The jet was directed normally to the cutting edge at a low angle with a distance of 22 mm from the rake face. The nozzle diameter of 0.25 mm delivered pressure of 50 and 130 MPa. The corresponding flow rate was 0.6 and 2.61 l/min.	Dry machining of Inconel 718 with carbide tools was not possible, due to the rapid tool wear. Chip breakability was improved with the high-pressure coolant. In addition, increasing the cutting speed and pressure, chip breakability can be further improved. The tool life was improved significantly and consumption of coolant reduced up to 10 times by high-pressure cooling.
2014	Klocke. F, Lung. D, Cayli. T, Döbbeler. B, and Sangermann. H [7]	Inconel 718, Cemented carbide cutting tool	Grooving, facing and longitudinal turning. f_n = 0.10–0.25 mm/rev, v_c of 20–35 m/min (flood cooling) & 80–100 m/min (high-pressure cooling).	Flood cooling at 0.6 MPa. High-pressure coolant ranged between 7 and 30 MPa was directed onto the rake face of the tool. Maximum flow rate of 22 l/min.	Evaluated the process in the economic and ecological point of view. High-pressure pump uses electrical energy at higher power consumptions. But it can trade-off by improving the productivity in machining Inconel 718 at higher cutting speeds is of huge advantage. Apart from the improvement in tool life, evaluating all non-productive times due to removal of chips, high-pressure coolant supply might be able to favour the chip breakage problem.

(*continued on next page*)

Table 3 (*continued*)

Year	Authors	Workpiece/Cutting tool	Process conditions	Coolant position/conditions	Evaluation/Findings
2014	Krämer. A, Klocke. F, Sangermann. H, and Lung. D [34]	Inconel 718 Cemented carbide CNMA 12 04 08 (HC) Ceramic RCGX 12 07 00	Turning Carbide: f_n = 0.2 mm/rev, v_c = 35 and 60 m/min a_p = 1 mm Ceramic: f_n = 0.15 mm/rev, v_c = 200 and 500 m/min a_p = 1.5 mm	Flood cooling pressure 0.6MPa/flow rate 12 l/min, High-pressure on the rake face through three nozzles at a pressure of 7, 15 and 30 MPa, corresponding flow rate 16, 23 and 31 l/min An emulsion concentration of 7%	Inconel 718 led to mechanical wear mechanisms. Increase pressure led to increase notch wear compared to TiAl6V4. Increase coolant pressure decreased the flank wear by 50%. Positive impact of lowering tool temperature improved tool life. At a pressure of 30 MPa the specific tool load increased by 45% compared to flood cooling.
2016	Suárez. A, López de Lacalle. L. N, Polvorosa. R, Veiga. F & Wretland. A [23]	Wrought Inconel 718 Uncoated carbide cutting tool TCMW 16T304 – H13A. Modified tool holder STFCR 25 × 25 M 16	Rough face turning f_n = 0.10 mm/rev a_p = 2 mm v_c = 30 m/min. SCL = 727 m	One nozzle in clearance face and two nozzles in the rake face of diameter 0.8 mm, estimated jet speed of 127 m/s. Coolant was oil based emulsion of 10–12% Conventional cooling was set at 0.6 MPa, high-pressure cooling at 8 MPa.	Flank wear decreased more than 30%, cutting force by 10%, and temperature by 50% compared to conventional cooling. Notch wear at the DOC line was the dominant damage to the tool with high-pressure coolant.

References

[1] R. Polvorosa, A. Suárez, L.N.L. de Lacalle, I. Cerrillo, A. Wretland, F. Veiga, Tool wear on nickel alloys with different coolant pressures: comparison of Alloy 718 and Waspaloy, J. Manuf. Process. 26 (Apr. 2017) 44–56.

[2] E.O. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aero-engine alloys, J. Mater. Process. Technol. 134 (2) (Mar. 2003) 233–253.

[3] R.J.S. Pigott, A.T. Colwell, Hi-jet System for Increasing Tool Life, SAE Tech. Pap., 1952.

[4] Manoucheh Vosough, Effect of high-pressure cooling on the residual stress in Ti-alloys during machining, (2005) Licentiate Thesis-Luleå Univ. Technol. http://ltu.diva-portal.org/smash/record.jsf?pid=diva2%3A990963&dswid=591.

[5] E.O. Ezugwu, J. Bonney, Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools, J. Mater. Process. Technol. 153 (154) (Nov. 2004) 1045–1050.

[6] R.B. da Silva, Á.R. Machado, E.O. Ezugwu, J. Bonney, W.F. Sales, "Tool life and wear mechanisms in high speed machining of Ti–6Al–4V alloy with PCD tools under various coolant pressures, J. Mater. Process. Technol. 213 (8) (Aug. 2013) 1459–1464.

[7] F. Klocke, D. Lung, T. Cayli, B. Döbbeler, H. Sangermann, Evaluation of energy efficiency in cutting aerospace materials with high-pressure cooling lubricant supply, Int. J. Precis. Eng. Manuf. 15 (6) (Jun. 2014) 1179–1185.

[8] H. Jäger, N.T. Alagan, J. Holmberg, T. Beno, A. Wretland, EDS analysis of flank wear and surface integrity in machining of alloy 718 with forced coolant application, Procedia CIRP 45 (2016) 271–274.

[9] N.T. Alagan, P. Zeman, P. Hoier, T. Beno, U. Klement, Investigation of micro-textured cutting tools used for face turning of alloy 718 with high-pressure cooling, J. Manuf. Process. 37 (2019) 606–616.

[10] R. Danzl, F. Helmli, P. Rolland, S. Scherer, Geometry and volume measurement of worn cutting tools with an optical surface metrology device, Transverse Disciplines In Metrology, John Wiley & Sons, Ltd, 2010, pp. 373–382.

[11] ISO 3685:1993, Tool-life Testing with Single-point Turning Tools-ISO 3685:1993, (2011).

[12] N. Tamil Alagan, T. Beno, P. Hoier, U. Klement, A. Wretland, Influence of surface features for increased heat dissipation on tool wear, Materials 11 (5) (Apr. 2018) 664.

[13] Oxford Instruments, HKL Channel 5 EBSD Post-processing Software, (2011).

[14] E.M. Trent, Metal Cutting, Butterworth-Heinemann, Burlington: Burlington, MA, USA, 2000.

[15] W. Akhtar, J. Sun, P. Sun, W. Chen, Z. Saleem, Tool wear mechanisms in the machining of Nickel based super-alloys: a review, Front. Mech. Eng. 9 (2) (May 2014) 106–119.

[16] F. Klocke, Manufacturing Processes 1: Cutting, Springer-Verlag, Berlin Heidelberg, 2011.

[17] S. Ndlovu, The Wear Properties of Tungsten Carbide-Cobalt Hardmetals from the Nanoscale up to the Macroscopic Scale, (2009).

[18] J.L. Cantero, J. Díaz-Álvarez, M.H. Miguélez, N.C. Marín, Analysis of tool wear patterns in finishing turning of Inconel 718, Wear 297 (1–2) (Jan. 2013) 885–894.

[19] Y. Altintas, Manufacturing Automation, second ed., Cambridge University Press - M.U.A, United Kingdom, 2012.

[20] E. Ezugwu, A. Machado, I. Pashby, J. Wallbank, The effect of high-pressure coolant supply when machining a heat-resistant nickel-based superalloy, Lubr. Eng. 47 (9) (1991) 751–757.

[21] E.O. Ezugwu, J. Bonney, D.A. Fadare, W.F. Sales, Machining of nickel-base, Inconel 718, alloy with ceramic tools under finishing conditions with various coolant supply pressures, J. Mater. Process. Technol. 162 (May 2005) 609–614.

[22] A.R. Machado, J. Wallbank, The effect of a high-pressure jet on machining, Proc. Inst. Mech. Eng. 208 (1994).

[23] A. Suárez, L.N. López de Lacalle, R. Polvorosa, F. Veiga, A. Wretland, Effects of high-pressure cooling on the wear patterns on turning inserts used on alloy IN718, Mater. Manuf. Process. 32 (6) (Apr. 2017) 678–686.

[24] M.A. Shalaby, S.C. Veldhuis, Wear and tribological performance of different ceramic tools in dry high speed machining of Ni-Co-Cr precipitation hardenable aerospace superalloy, Tribol. Trans. 0 (0) (Jul. 2018) 1–16.

[25] K.M.C. Öjmertz, H.-B. Oskarson, Wear on SiC-whiskers reinforced ceramic inserts when cutting Inconel with waterjet assistance, Tribol. Trans. 42 (3) (Jan. 1999) 471–478.

[26] O. Çolak, Investigation on machining performance of Inconel 718 under high pressure cooling conditions, Strojniski Vestnik J. Mech. Eng. 58 (11) (2012) 683–690.

[27] Fritz Klocke, Manufacturing Processes 1: 1,Turning, Milling, Drilling, Springer Verlag, 2011.

[28] A. Altin, M. Nalbant, A. Taskesen, The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools, Mater. Des. 28 (9) (2007) 2518–2522.

[29] R. Wertheim, J. Rotberg, A. Ber, Influence of high-pressure flushing through the rake face of the cutting tool, CIRP Ann. - Manuf. Technol. 41 (1) (1992) 101–106.

[30] L.N. López de Lacalle, J. Pérez-Bilbatua, J.A. Sánchez, J.I. Llorente, A. Gutiérrez, J. Albóniga, Using high pressure coolant in the drilling and turning of low machinability alloys, Int. J. Adv. Manuf. Technol. 16 (2) (Feb. 2000) 85–91.

[31] E.O. Ezugwu, J. Bonney, Effect of high-pressure coolant supplies when machining nickel-base, Inconel 718, alloy with ceramic tools, Tribol. Trans. 46 (4) (Jan. 2003) 580–584.

[32] C. Courbon, D. Kramar, P. Krajnik, F. Pusavec, J. Rech, J. Kopac, Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: an experimental study, Int. J. Mach. Tool Manuf. 49 (Nov. 2009) 1114–1125.

[33] D. Kramar, M. Sekulic, Z. Jurkovic, J. Kopac, The machinability of nickel-based alloys in high-pressure jet assisted (hpja) turning, Metalurgija 52 (Dec. 2013) 512–514.

[34] A. Krämer, F. Klocke, H. Sangermann, D. Lung, Influence of the lubricoolant strategy on thermo-mechanical tool load, CIRP J. Manuf. Sci. Technol. 7 (1) (Jan. 2014) 40–47.