State-of-the-art cooling and lubrication for machining Inconel 718

Andrea De Bartolomeis, first author
Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY,
United Kingdom
e-mail: A.De.Bartolomeis@bath.ac.uk

Stephen T Newman, second author
Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY,
United Kingdom
e-mail: S.T.Newman@bath.ac.uk

Dirk Biermann, third author
Institut für Spanende Fertigung,
Technische Universität Dortmund,
Dortmund, 44227, Germany
e-mail: dirk.biermann@tu-dortmund.de

Alborz Shokrani, fourth author
Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY,
United Kingdom
e-mail: A.Shokrani@bath.ac.uk

ABSTRACT

Inconel 718 is the most used nickel superalloys with applications in aerospace, oil&gas, nuclear and chemical industries. It is mostly used for safety-critical components where the condition of the surface is a significant concern. The combination of mechanical, thermal and chemical properties of Inconel 718, has made it a difficult-to-machine material. Despite recent advances in machining Inconel 718, achieving desired surface integrity with prescribed properties is still not possible. Different machining environments have been investigated for improving the machinability of Inconel 718 and enhance the surface integrity of machined components. This paper provides a new investigation and classification into recent advances in *the machining of Inconel 718 regarding surface integrity, mostly concentrated on turning applications. The major findings and conclusions provide a critique of the state-of-the-art in machining environments for Inconel 718 together with future directions for research. Surface integrity has been evaluated in terms of surface topology as well as mechanical and microstructural properties. The impact of various cooling and lubrication methods has been investigated. It has been found that surface integrity is affected by the thermomechanical conditions at the cutting zone which are influenced by the cutting parameters, cutting tool, tool wear and cooling/lubrication condition. The current technologies are incapable of delivering both productivity and sustainability whilst meeting surface integrity requirements for machining Inconel 718. High-pressure cooling has shown the potential to enhance tool wear at the expense of higher power consumption.*

Keywords: Machining, Cooling, Lubrication, Surface Integrity, Tool Wear, Inconel 718, Cryogenic Machining

1- INTRODUCTION

Inconel 718, also known as Alloy 718, belongs to the family of nickel-based superalloys, which are known for their high-temperature properties and are extensively used in aero-engines [1]. It is used in turbine engine discs for the connection elements between blades and the shaft [2]. Inconel 718 exhibits fatigue resistance up to 650 °C, which perfectly suits the high thermomechanical cyclic loads generated during take-off and landing phases [3]. Furthermore, excellent high temperature load-bearing capacity, up to 85% of its melting point [4], in combination with outstanding corrosion resistance in extreme environments [5], have made Inconel 718 the perfect fit for the vast array of applications. Apart from aerospace applications, Inconel 718 is used in power generation turbines, rocket engines, as well as in oil and gas, nuclear, automotive, and chemical processing industries [6].

Majority of Inconel 718 components require machining processes for manufacturing or finishing. Inconel 718 has been considered by many researchers as one of the most challenging materials for machining [7-11]. According to Dudzinski et al. [11], the seven physical properties which made Inconel 718 a difficult-to-machine material are:

- High material strength at elevated temperatures;
- Strain hardening;
- Presence of hard carbide particles in the microstructure;
- Low thermal conductivity;
- Chemical affinity to the majority of tool materials;
- Welding and adhesion tendency leading to frequent Built-Up Edge (BUE) formation;
- High machining forces and vibrations.

These properties can result in high cutting temperatures as high as 1200 °C and high tool wear rates [12] which can result in surface damage and increased power consumption [13, 14]. The tool wear induced surface damage is a primary concern as it can affect part reliability [15] and component fatigue life [16]. ISO 3685 [17] and ISO 8688 [18] recommend 300 µm flank wear as tool life criteria. In practice, tools are discarded before reaching their maximum wear in order to achieve required surface integrity for critical components [7]. In order to extend tool life, low cutting speeds are commonly employed, leading to poor productivity. Different cooling/lubrication technologies, high-performance tool materials, as well as engineered tool geometries, have been investigated as a means for improving productivity whilst maintaining surface integrity requirements. Nevertheless, even the most advanced technologies are today not able to guarantee productivity, sustainability, and surface integrity at the same time. Table 1 shows the previous review works in comparison to the current paper.

Given the importance of Inconel 718 and the issues encountered during machining, this paper presents a comprehensive, unbiased and critical overview of the state-of-the-art cooling and lubrication from a broader, technological point of view specific for Inconel 718 with regard to surface integrity and sustainability. It also offers a summary of all the issues related to conventional techniques, sustainable alternatives, and productivity concerns specific to Inconel 718 without generalizing to other materials e.g. titanium and nickel alloys. The paper is structured in 8 sections. After this introduction, the characteristic chemical and metallurgical composition of Inconel 718 is presented in section 2, and a brief illustration of tool wear behavior is followed in section 3. Section 4 investigates the three principal aspects of machining induced surface integrity extensively, highlighting their importance on the final applications of Inconel 718. C&L technologies are critically reviewed in Section 5, where the causes behind their failure are identified, and alternative strategies presented. Section 6 critically compares conventional technologies and their alternatives. Their effect on sustainability, productivity, and surface integrity when machining Inconel 718 is also discussed. Major findings, as well as research gaps, in combination with future research directions, are presented in section 7 with conclusions provided in section 8.

Table 1 - Previous related review works in comparison to the current paper.

Ref	Year	Effect of	On	Material
[19]	1998	Tool materials and tool wear	Machinability	Nickel-based superalloys
[20]	1999	Tool materials and tool wear	Machinability	Nickel-based superalloys
[21]	2000	Tool materials	Machinability	Nickel-based superalloys
[22]	2003	Tool materials, Water-based C&L, Environmentally conscious C&L	Machinability	Titanium and nickel-based superalloys
[11]	2004	High-speed machining, dry machining	Surface integrity and Machinability	Inconel 718
[1]	2011	Tool materials	Surface integrity	Titanium and nickel-based superalloys
[9]	2012	Tool materials, Water-based C&L, Environmentally conscious C&L, Dry machining	Sustainability and Machinability	Difficult-to-machine materials
[23]	2013	Tool wear, tool materials	Machinability	Nickel-based superalloys
[7]	2016	Tool materials, Water-based C&L, Environmentally conscious C&L, Dry machining, tool wear.	Surface integrity	Nickel-based superalloys
[24]	2016	Environmentally conscious C&L, tooling geometry.	Machinability	Difficult-to-machine materials
[25]	2017	High pressure and flood water-based cooling	Machinability and surface integrity	Inconel 718
[26]	2017	Tool materials, Water-based C&L.	Machinability	Nickel-based superalloys
[27]	2018	Tool structure, tool material	Surface integrity	Titanium and nickel-based superalloys
[8]	2019	Tool wear	Surface integrity	Titanium and nickel-based superalloys
Current paper		Water-based C&L, Environmentally conscious C&L, Dry machining, tool wear.	Surface integrity, Machinability, and sustainability	Inconel 718

2 - CHEMICAL AND METALLURGICAL COMPOSITION OF INCONEL 718

Inconel 718 is an alloy consisting of Nickel, Chromium, Niobium, Iron, Molybdenum, Titanium, and Aluminum [28]. The matrix of Inconel 718 consists of nickel as the principal element within which other elements are embedded. Chromium protects the bulk of the material from oxygen by forming a thin hard layer of Cr_3O_2 on the surface

[29]. Niobium is the most critical element in Inconel 718 responsible for generating the γ'' phase, which is the principal strengthening phase. Iron is responsible for the high weldability of the alloy and acts as a catalyst for γ'' aggregation [30]. Molybdenum strengthens the alloy through solid solution mechanism and forces formation of γ' phase [29]. Titanium and aluminum are γ' stabilizers, which contribute to the overall strength of the alloy. Table 2 presents the limiting chemical composition of Inconel 718 for aerospace applications.

Table 2 - Alloy 718, chemical composition for Aerospace [28]

Material	Symbol	Percentage	
Nickel[a]	Ni	50.0 - 55.0	%
Chromium	Cr	17.0 - 21.0	%
Iron	Fe	Remainder	%
Niobium[b]	Nb	4.75 - 5.50	%
Molybdenum	Mo	2.80 - 3.30	%
Titanium	Ti	0.65 - 1.15	%
Aluminum	Al	0.20 - 0.80	%
Cobalt[c]	Co	1.0 max	%
Carbon	C	0.08 max	%
Manganese	Mn	0.35 max	%
Silicon	Si	0.35 max	%
Phosphorus	P	0.015 max	%
Sulfur	S	0.015 max	%
Boron	B	0.006 max	%
Copper	Cu	0.3 max	%

[a]Plus Co. [b]Plus Ta. [c]If determined.

The strength and hardness of Inconel 718 are commonly realized through solid solution strengthening and precipitation hardening (aging) procedures prior to machining. The former consists of developing a single-phase crystal by replacing or inserting atoms of a different element in the matrix while precipitation hardening develops thin impurities homogeneously distributed in the structure. Both treatments aim at hindering the movement of dislocations resulting in strength development.

The following phases contribute to the specific material properties of Inconel 718:

- γ matrix: is the matrix of the alloy with an FCC structure made by Nickel and solid solution strengthening elements such as Cr, Fe, and Mo [30].
- γ' phase: is the metastable compound of $Ni_3(Al,Ti)$ with an FCC structure, which contributes to the strength. It has Ni atoms at cube faces in combination with either Al or Ti at the edges of the cube.
- γ'' phase: is the metastable compound of Ni_3Nb, which is responsible for the crucial strengthening mechanism. It has a body-centered tetragonal structure with an ordered disposition of Ni and Nb in the lattice. The structure mismatch between the matrix and γ'' leads the latter to aggregate in a lens-like disc shape and promote both order hardening and coherency hardening mechanisms [31].
- δ phase: is the undesirable stable compound of Ni_3Nb with an orthorhombic structure which is susceptible to formation when Inconel 718 is overaged [2]. Although a small amount of δ can control grain size, excessive quantities are harmful to fracture proprieties and creep endurance because of depleting the alloy from Nb and Ni. The δ phase aggregates at the expense of γ'' between 650°C and 980°C in acicular structures at grain boundaries. Beyond 700°C, its formation is combined with a rapid coarsening of γ'' [32].
- Carbides: hard-and-brittle NbC, TiC, and $Cr_{23}C_6$ carbide phases precipitate at grain boundaries. It is often argued that whilst they increase rupture life by inhibiting grain-boundary sliding [32], high amounts of carbides promote intergranular failure [33].

During machining, carbides are a source of anisotropy, which develops abrasive tool wear and workpiece surface cracking [34].

- Topologically close-packed (TCP) phases: undesirable μ, Laves, and σ phases can also occur in the microstructure of Inconel 718. These phases have detrimental effects on the mechanical proprieties of the alloy [35]. They form after long exposures at high temperatures, especially when the alloy is subjected to stress, commonly referred to as over-aged condition [20]. Figure 1 presents an electron channeling contrast image showing the grains of the γ matrix and δ plates. An NbC carbide is interspersed between γ grains. Both γ' and γ'' precipitates are shown inside the γ matrix in the top-right insert [36].

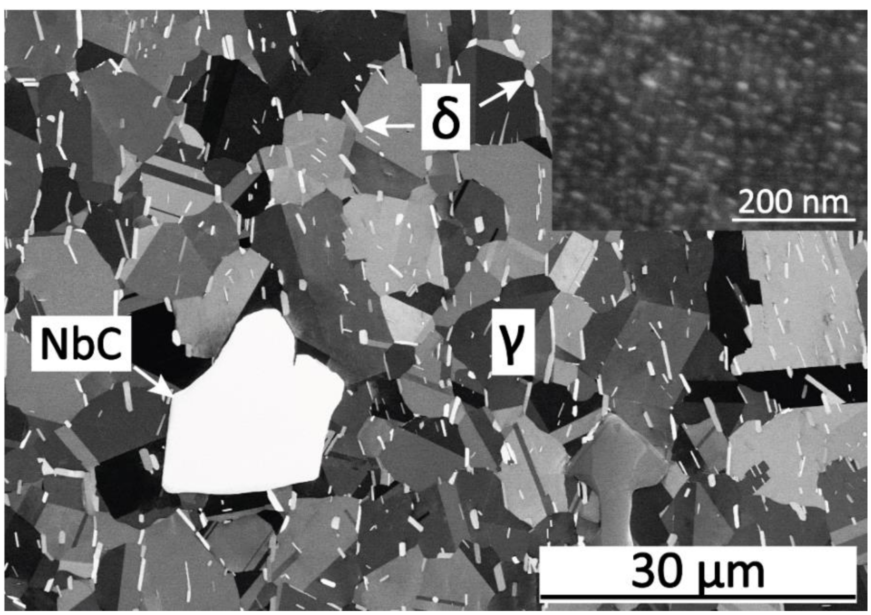


Fig. 1 - Electron channeling contrast image showing the microstructure of the aged Inconel 718 forging. It presents the equiaxed grains of the γ matrix, δ phase, and an NbC carbide. The insert shows γ' and γ'' precipitates inside γ. [36]

3 - TOOL WEAR

Tool wear has been considered as one of the influential parameters affecting surface integrity. For a detailed review on tool wear and its relation with surface integrity for nickel and titanium alloys, readers are referred to Liu et al. [8].

Zhou et al. [37] investigated the effect of tool wear on the subsurface deformation of Inconel 718 when turning in finishing conditions with whisker reinforced ceramic tools. They tested a new tool, a semi-worn tool and a worn tool, demonstrating that the surface damage is governed not only by process parameters but also by tool wear.

Higher thermomechanical loads are imposed on the machined surface when using worn cutting tools, resulting in poor surface integrity. Plastic deformation and even recrystallization in the immediate subsurface with grain size up to 200-300 nm were observed based on the level of tool wear.

However, the wear mechanism is greatly influenced by the cutting tool material, coating, and cutting parameters [38-46].

Cantero et al. [38] and Altin et al. [47] reported that the combination of high work hardening tendency and hard carbides resulted in significant notch wear at the Depth of Cut (DoC). Hoier [39] and Thakur et al. [40] pointed out that uncoated carbide tools presented chipping, plastic deformation, and abrasion as primary wear mechanism. Hoier [39] revealed that large NbC particles and TiN inclusion in Inconel 718 produced significant abrasive wear. Abrasion usually appeared as deep scratches [41] and severe grooving [42] on the flank of the tool. However, Grzesik et al. [43] pointed out that when machining Inconel 718, all wear mechanisms are intrinsically related. Xavior et al. [41] concluded that thermal softening, adhesion, diffusion, notching, and thermal cracking had a significant influence on tool wear. Moreover, they observed that adhesion resulted in BUE, which developed chipping on the cutting edge. They attributed BUE formation to low cutting speed and improper application of the coolant.

It is identified that tool wear is different for different cutting tool materials when using optimal machining parameters:

- Uncoated carbide - abrasion [44];
- Coated carbide - adhesion and abrasion [45];
- Cubic Boron Nitride (CBN) - adhesion and diffusion [46];
- Ceramic - diffusion, abrasion, and plastic deformation [47].

4- SURFACE INTEGRITY IN MACHINING INCONEL 718

The concept of surface integrity was firstly introduced by Field and Kahles in 1964 as "the condition of a surface produced by machining processes or other surface generation operations" [48]. Davin, in 2010, identified that surface integrity directly relates to material performance, longevity, and reliability [49]. Inconel 718 machined surface integrity can be classified into three categories, namely:

- Topological aspects: surface roughness, waviness, and visual defects.
- Metallurgical aspects: dynamic recrystallization, grain deformation, and thermally affected zone.

- Mechanical aspects: work hardening and residual stress.

4.1- Topological aspects

Topology involves geometrical features such as surface roughness, waviness, and visible defects. Surface roughness is defined as the high-frequency component of surface texture, while waviness is a more widely spaced component of the measured profile. General observations [13, 39, 41, 50, 51] reported that surface roughness and waviness are both dependent on thermomechanical deformation of the surface.

Fan et al. [50] analyzed substantial factors affecting the surface finish. Whilst BUE formation and chip plastic side flow were observed to have detrimental effects on surface roughness, the development of soft oxides showed the potential to reduce cutting forces and improve surface morphology. This is because of developing a boundary lubrication layer which inhibited BUE formation and resulted in tool wear equilibrium. The machining environment can minimize BUE [9]. Tool geometries may also alter surface roughness. Based on a number of references [7, 52-54]. Large nose radius is usually adopted due to reduced chipping and surface roughness to the detriment of cutting force increases. It has been observed that surface roughness decreased with increasing cutting speed [55] but, it becomes greater with increases in feed rate [56] and DoC [57].

D'Addona et al. [58] investigated the effect of cutting speed from 60 to 225 m/min on surface roughness and reported that surface roughness decreased from 1.2 to 0.3 μm as cutting speed increased from 60 to 190 m/min. However, at 255 m/min, surface roughness suddenly rose to 0.5 µm due to the notching of the cutting tool. This confirms that tool wear, as stated by Shokrani et al. [59], has a considerable effect on surface roughness and, in general, on surface integrity. Iturbe et al. [60] reported that flank wear influenced not only surface roughness but also developed microstructural and topological damage.

Nataraj et al. [61] investigated the influence of controllable parameters of cryogenic high-speed turning on surface roughness. Cutting speed, feed rate, and LN_2 pressure were found significant while the DoC, tool nose radius as well as cutting time were found negligible. At 0.15 MPa LN_2 pressure, chip brittleness resulted in poor surface roughness of the component.

Priarone et al. [62] criticized the measurement of surface roughness Ra as a key performance indicator. They pointed out that the average surface roughness is not enough to characterize the surface profile performance and suggested using statistical parameters such as skewness (RSk) and kurtosis (RKu). Visual defects on the machined surface of Inconel 718 appears as laps [63], plucking [64], material smearing [65], metal debris [56], grooves [66], surface cracking [67] and, tears [66]. M'Saoubi et al. [68] observed surface cracking near TiC and NbC carbides when machining Inconel 718. This carbide cracking phenomenon was investigated by Ranganath et al. [69]. They pointed out that feed rate and nose radius influences the behavior of surface carbide cracking. Zhou et al. [34] suggested that TiC and NbC cracking had their root in the passive force, which acts on the carbide particle resulting in breakage. As a result of being more brittle than the surrounding material, the carbide resulted in local anisotropy. Thus, when the passive force reached the carbide, a tangential status occurred, developing a crack in the interface carbide-material. Moreover, the presence of hard particles, such as TiC and NbC, can develop drag and smear [69]. Besides, surface cavities and plucking developed as a result of a high level of shear stresses, leading to carbide particles in the work material being removed from the machined surface [67].

4.2- Metallurgical aspects

Mechanical stress and thermal loads can alter carbide nucleation, grain orientation, and structure distribution during machining. Metallurgical aspects involve changes in the microstructure of the surface and sub-surface layers. Combination of mechanical stress and thermal loads can lead to thermal recrystallization and permanent grain deformation.

Metallurgical defects in machining can be classified into different zones. Zhou et al. [37] schematized metallurgical defects on Inconel 718 surface in three different zones as shown in Fig. 2:

- Zone 1 - Severely deformed region: nano-crystalline grains in a severely deformed layer.
- Zone 2 - Deformation area: Slip bands and elongated grains;
- Zone 3 - Unaffected area: bulk material unaffected by the machining process.

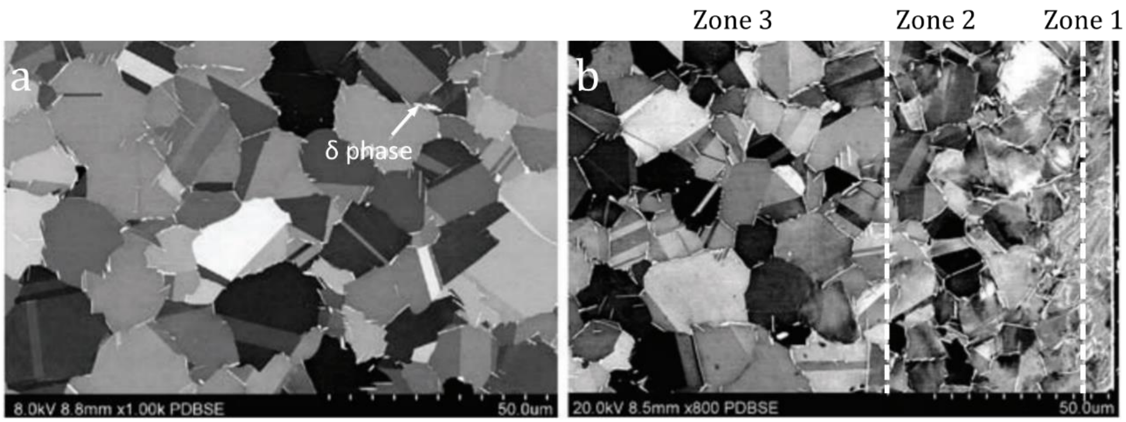


Fig. 2 - SEM pictures a) before and b) after machining with regard to zone 1, 2 and 3 [37]

Intending to have a repeatable measurement, they combined a Scanning Electron Microscope (SEM) with Electron Backscatter Diffraction and quantified both deformed and recrystallized areas. They reported that the extension of zone 1 and 2 was dependent on the cutting tool condition. It is evident in Fig. 3 that the depth of the recrystallized layer, as well as the severity of the deformed area, increases with the progression of tool wear. This confirms that tool wear has a significant impact on metallurgical properties of machined surfaces.

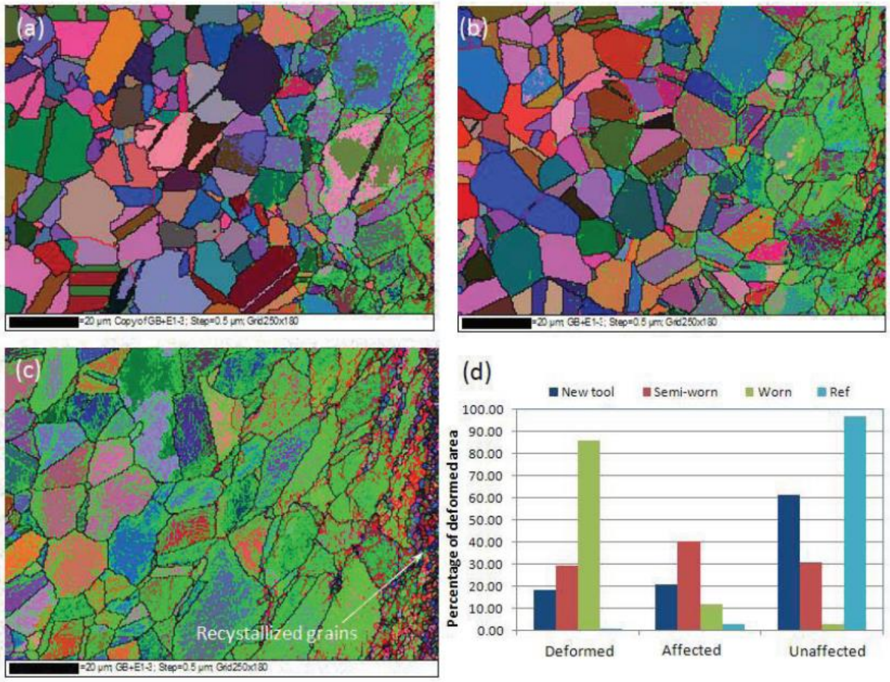


Fig. 3 - EBSD maps of Inconel 718 machined surface with new (a), semi-worn (b) and worn tool (c) [37]

It is commonly reported [7, 70] that Zone 2 represents the amplitude of plastic deformation with elongated grains and slip bands in the direction of machining. The extension of this area affects the mechanical proprieties of the workpiece material.

The severely deformed region with nanoscale recrystallization may appear white and featureless under some SEM and optical microscopes [71] and it is often referred to as the white layer in the literature [1, 70, 72].

Mechanical and thermal loads in machining can result in the recrystallization of the machined surface. Under extreme conditions, this can lead to the generation of nanocrystalized microstructures. Strain hardening and localized heat treatment result in a brittle and hardened layer distinct from the bulk material. It can be identified from its highly deformed microstructure beneath the machined surface, sometimes presenting δ fragmentation due to deformation breakage [36]. Chen et al. [36] reported that the white layer consists of nano-sized grains ranging from 20 nm to 50 nm.

Figure 4 shows (i) a white layer micrograph with δ fragmentation as well as (ii) the hardness and elastic modulus of the white layer in comparison with the bulk of the material. The white layer is 14% harder and 10% less elastic than the bulk. Whilst the hard and brittle condition may be desired for some applications, it is extremely detrimental to Inconel 718 fatigue resistance [70].

The severely deformed layer has been identified as one of the most critical parameters characterizing surface integrity [70].

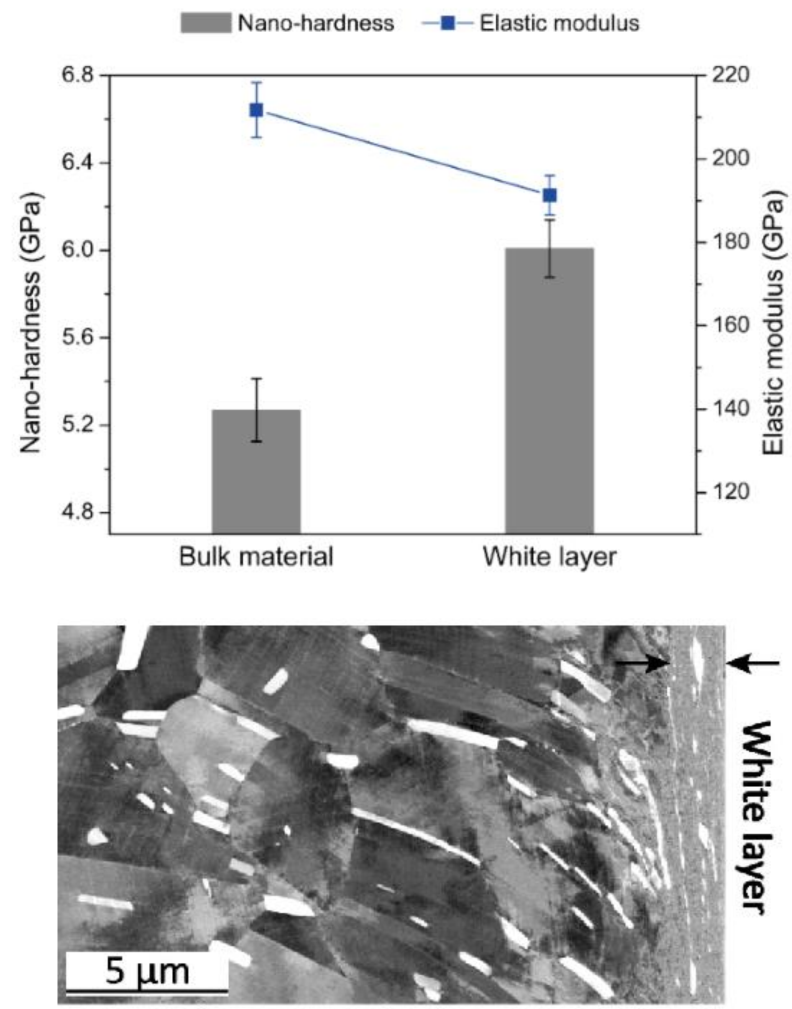


Fig. 4 - Comparison of nano-hardness and elastic modulus of the white layer from the undeformed bulk material (top). White layer micrograph showing the highly deformed microstructure beneath the machined surface with δ fragmentation due to deformation breakage (bottom) [36].

4.3 - Mechanical aspects

Machining alters surface mechanical properties. Among them, the increase in hardness and residual stress are the most detrimental alterations which can affect tool wear and fatigue properties [60]. The combination of different machining passes with the work hardening sensitivity of Inconel 718 produces significant strain on the surface and sub-surface layers. Several researchers reported increases in material surface and subsurface hardness as a result of machining. Increases in microhardness were also attributed to rapid heating-and-cooling cycles, which resulted in quenching and plasticization afterward [60, 73, 74]. In contrary, Sharman et al. [56, 75] reported lower surface hardness than the bulk material after machining Inconel 718. While some researchers [76, 77] attributed the general phenomena to thermal softening, Warren and Guo [78] attributed the effect to microhardness measurement error due to the lack of edge support. They demonstrated that this drop was observed only when measuring with microhardness but not when using nano-hardness tests.

Hardness and tool wear are correlated [75, 79]. The depth and endurance of the hardened layer were directly related to tool wear [60], and they influence each other. As the tool removes material in a pass, it hardens the surface, and thus subsequent tool passes would be influenced by the work-hardened material, which can lead to higher loads and result in increased tool wear. Moreover, as tool wear progresses, it leads to a more compressive work hardening. This can affect tool wear resulting in a detrimental vicious cycle.

Residual stress is defined as the stress distribution, which persisted after all external forces have been removed, due to inhomogeneous plastic deformation and equilibrium response of the material [80]. It is one of the most researched topics in the last decade regarding Inconel 718 due to its considerable impact during machining. It is always associated with dimensional instability, distortion, and a negative impact on fatigue life and corrosion. Whilst compressive residual stress can be beneficial for fatigue endurance and corrosion resistance, tensile residual stresses always have detrimental effects on these properties. General observations showed that machining induced residual stresses are primarily tensile near the machined surface and progressively change to compressive in sub-surface layers [75, 81, 82]. However, some researchers reported compressive residual stress throughout machined Inconel 718 samples [52, 82-85].

Residual stresses are the result of a combination of two components: (i) mechanical and (ii) thermally induced residual stresses. In mechanically induced residual stresses, the plastic deformation (i) occurs as the tool stretches the surface, developing a tensile status which locally exceeds the yield strength. After the force is removed, the top layer is longer, and, to achieve kinematic equilibrium, it becomes subjected to compression. In thermally induced residual stresses (ii), the top layer of the material expands due to heat generation during cutting. However, subsequent layers are not hot enough to follow the initial layer, and the material develops a compressive status on the top. Compression, in combination with high temperatures, results in the deformation of the top layer. When cooled, the top layer becomes shorter. Therefore, to achieve kinematic stability, it develops tensile stress.

Figure 5 shows the residual stress profiles in turning Inconel 718 using Al_2O_3-SiCw and PCBN cutting tools, at 200 m/min and 350 m/min cutting speed [82].

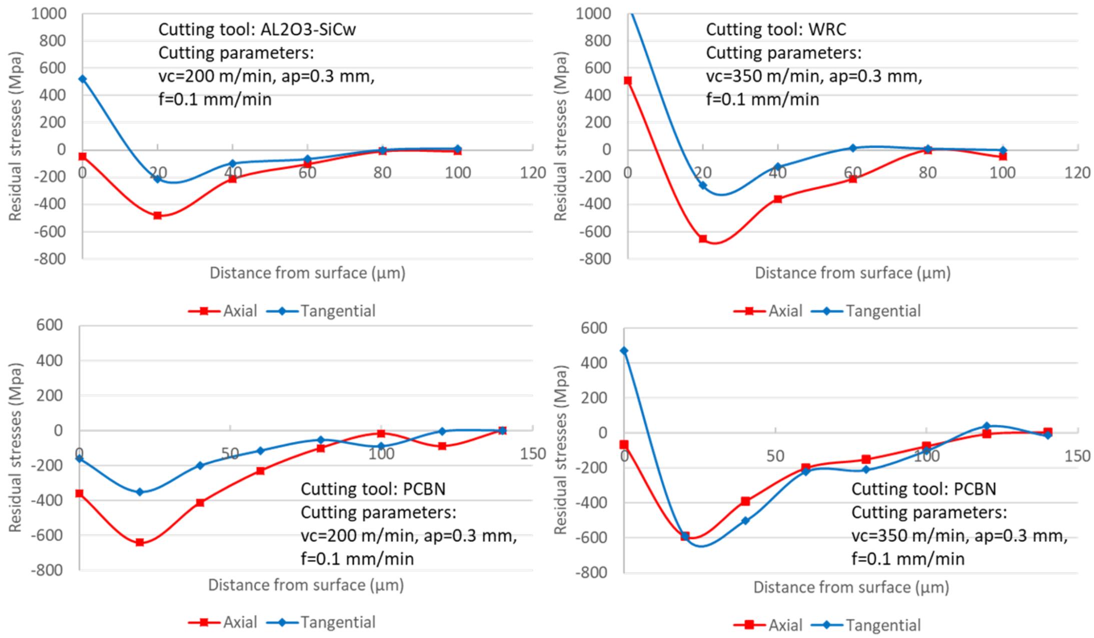


Fig. 5 - Residual stress profiles in depth produced by Al_2O_3-SiCw and PCBN cutting tools, at 200 m/min and 350 m/min cutting speeds [82]

As shown in Figure 5, cutting tools with a low thermal conductivity as well as increases in cutting speed can result in excessive heat generation and tensile residual stress development. Sharman et al. [75] also remarked that tools with Al_2O_3 thermal barrier layers prevent heat dissipation inside the bulk of the tool and develop higher tensile stress.

Furthermore, they observed that tool wear affects residual stresses negatively. Figure 6 shows in-depth residual stress profiles generated with a new and worn tool. The worn tool almost tripled the tensile component in both the feed and cutting direction [75].

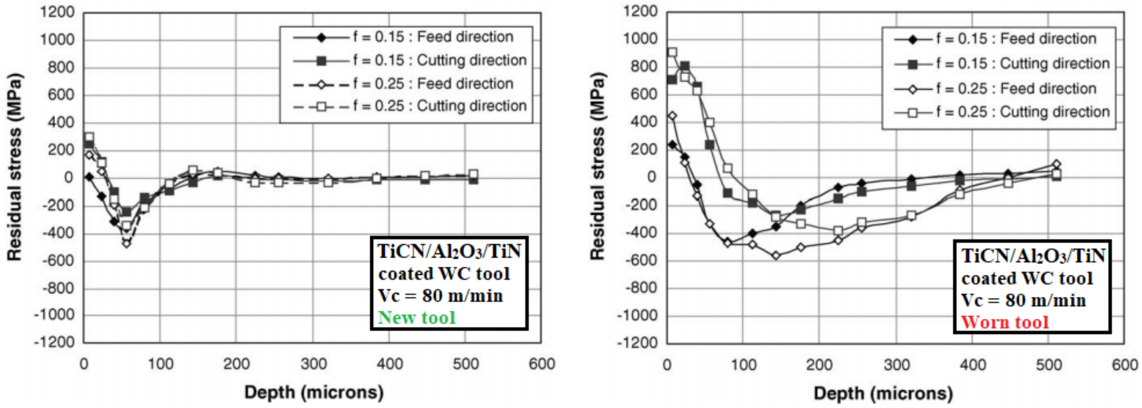


Fig. 6 - In-depth residual stress profiles generated with new and worn tools [75].

Madariaga et al. [86] pointed out that surface tensile residual stress tends to increase with increment in flank wear up to a critical value. Increases over this critical value reduce the surface residual stresses. This can be explained through the proportion of mechanical and thermal stresses. Huang et al. [87] reported that in dry turning, tools with small tool radius develop lower tensile residual stress than the ones with a large nose radius. Low cutting speeds result in low temperatures and high cutting forces; therefore, at low speeds, compressive stress is dominant. PVD tool coating was found to favorably reduce tensile residual stresses at 60 m/min cutting speed, 0.1 mm/rev federate, and 1 mm depth of cut. According to the model proposed by Jafarian [88], the hardness of Inconel 718 influences residual stress negatively. An Inconel 718 workpiece with 45 HRC is more prone to developing tensile residual stresses than a workpiece with 30 HRC. Therefore, machining strategies aimed at reducing Inconel 718 work hardening may also have a positive influence on residual stress. Chen et al. [89] found that surface tensile residual stress, produced by broaching Inconel 718, can be relaxed with 30 h exposure at 550 °C while subsurface compressive residual stress needs 3000 h at the same temperature.

Surface integrity is a concept that involves residual stress, roughness, and metallurgical aspects. Therefore, the simultaneous optimization of all these parameters can be challenging. With the use of artificial neural networks and genetic algorithms, multiple parameters can be modeled and simultaneously optimized. Jafarian et al. [15] trained two separate artificial neural networks for residual stresses and surface roughness and used a genetic algorithm for multi-objective optimization of residual stress and surface roughness varying the cutting speed, DoC, and feed rate when turning Inconel 718. Fan et al. [50] demonstrated that calculating the optimal cutting temperature using Archard's model for adhesion wear can result in improvements in surface integrity [90].

Tool wear has a negative influence on all aspects of surface integrity. The application of C&L can reduce tool wear growth rate. It can also have a direct effect on surface quality by changing material proprieties and tribological behavior of the tool-workpiece contact. Therefore, C&L systems for machining Inconel 718 have a vital role in improving its machinability and extend its sustainable industrial fields [7, 8].

5- COOLING AND LUBRICATION TECHNOLOGIES FOR MACHINING INCONEL 718

Heat generation is one of the crucial issues affecting machining performance [91], and it becomes pronounced with high cutting speeds. High material strength and hardness of Inconel 718 require high power input for machining which transforms into heat at the cutting zone. Poor thermal conductivity of Inconel 718 necessitates the use of coolant and lubricant to control cutting temperature and minimize heat generation at the cutting zone [9]. However, it has been argued that the vast quantity used when machining has a dramatic impact on operators' health and the environment. Dudzinski et al. [11] reported that the costs associated with flood cooling of difficult-to-machine materials counted up to 400% the cost of consumed tools. Pusavec et al. [92] pointed out that the expenses associated with those fluids form 16% of the total manufacturing cost.

Cooling and lubrication for machining of Inconel 718 have been classified under 5 major headings of (i) Dry machining, (ii) Flood cooling, (iii) High-Pressure Cooling (HPC), (iv) Minimum Quantity Lubrication (MQL), (v) Cryogenic machining.

5.1 - Dry machining

Dry machining is machining without coolant or lubricants [93] eliminating the economic and environmental issues associated with cutting fluids. However, over-heating, surface damage as well as limited cutting speeds and productivity are severe drawbacks of using this technique.

Inconel 718 can suffer over-heating at the cutting zone due to its low thermal conductivity [94]. Research in reducing over-heating has been carried out by varying the cutting speed, tool/coating material, and tool geometry [6, 47, 95-97]. Hao et al. [95] investigated the tool wear mechanism during dry machining of Inconel 718 with coated cemented carbide tools. They reported that at 20 m/min, increased adhesion led to chipping whilst at 45 m/min oxidation and diffusion accelerated debris formation. Devillez et al. [6] found that using 60 m/min cutting speed improved residual stresses, surface condition, and cutting forces. However, a tool life of less than 7 min was observed. Ramanujam et al. [96] reported that as cutting speed increased from 50 to 70 m/min, non-uniform wear occurred on the flank with cracks in the crater region as well as micro-chipping.

In dry machining of Inconel 718, tool wear was found as the major limiting factor. Therefore, innovative coatings and materials have been studied. Nalbant et al. [97] tested the effect of coatings on surface roughness and cutting forces during dry turning with cutting speeds between 15 and 75 m/min. They compared 3 different coatings on cemented carbide tools: a quadruple-layer coating with a TiN top layer, a triple-layer coating with Al_2O_3 on top, and a single-layer TiN coating. The latter provided the lowest average surface roughness at around 0.8 µm with 15 m/min cutting speed, while the triple-layer coating with Al_2O_3 on top resulted in the lowest cutting force of just over 500 N when machining at 75 m/min cutting speed. This was attributed to the adiabatic propriety of the tool, which forced the heat to remain in the workpiece resulting in material softening. Arunachalam et al. [83] reported that dry machining of Inconel 718 with ceramic tools resulted in high residual stress development. They suggested using carbide tools to reduce heat due to their high thermal conductivity in combination with tool geometry. They also observed that round tools resulted in low surface roughness and reduced tensile residual stress. Cutting tool geometry has shown to have a dominant influence on both tool wear and surface integrity. Huang et al. [87]

suggested using a PVD coated carbide tool with a smaller nose radius to avoid residual stress development. Furthermore, Li et al. [98] compared coated carbides and ceramic inserts during high-speed cutting of Inconel 718 in dry conditions. They reported that round-shaped ceramic tools outperformed the others in terms of tool wear endurance. Pawade et al. [99] investigated surface damage during high-speed, dry turning of Inconel 718. They observed metal debris, feed marks with smeared material, and secondary carbide particles caused by welding and adhesion. They also reported that the last two behaviors are intrinsically linked to dry machining.

The techniques aimed at reducing tool wear in dry machining damaged surface integrity and vice versa. Despite the progress in tool technology, the adoption of dry machining has been widely considered unsuitable for machining Inconel 718.

5.2 - Flood cooling

Flood machining, also known as wet or conventional, is the most common technique for machining Inconel 718. Cutting fluids, also known as metalworking fluids, are employed to flood the machining area and provided lubrication, heat dissipation, chip flushing as well as chemical protection.

Metalworking fluids are an engineered combination of oil, water, and chemical additives. The oil acts principally as a lubricant, with 95% of its manufacturing coming from mineral oil [100]. It is cheaper than alternative options despite being a potential pollutant. Oil is mixed with water using emulsifiers to enhance its cooling capability, making it a desirable habitat for bacterial and fungi growth. Chemical additives such as biocides and fungicides, as well as neutralization agents, corrosion inhibitors, lubricating additives, and foam inhibitors, are also added [100].

Cutting fluids are classified into (i) neat (straight) and (ii) water-soluble oils. The latter is further categorized into soluble oils, semi-synthetic, and synthetic fluids. These are commonly referred to as “water-based” since they require dilution with water before use [9]. The dilution percentage of water-based cutting fluids in water varies based on the application and manufacturers’ recommendation, and it is usually 2.5 – 5 % for machining and 1.6 – 4 % for grinding [101-103].

Zhou et al. [82] reported that flood machining of Inconel 718 produced less surface damage when compared with dry machining, while Devillez et al. [6] suggested adopting wet conditions as it lowered the tensile residual stress.

Sadat [104] observed that the positive effects of lubricant were negligible during high-speed-machining of Inconel 718 due to its low thermal conductivity. This inefficiency was explained by Kitagawa et al. [105], who noticed that high temperatures at the tool-workpiece interface resulted in the vaporization of water-based cutting fluid. They observed a “steam blanket” formation, which significantly hindered the reachability. Ezugwu et al. [22] also reported that conventional cutting fluids start boiling at about 350°C. At that temperature, they lose their cooling ability due to the Leiden frost effect. Kadam and Pawade [106] associated the Leiden frost effect with increases in surface roughness. This can be due to local high temperatures, which resulted in high-frequency BUE occurrence and detachment.

According to Alagan et Al. [107], the vapor blanket originates because of the Leiden frost effect when the surface temperature is higher than the coolant boiling point. They observed that the vapor layer traces on the cutting tool appear as a “dark region” rich in Calcium and Sulphur.

Cutting fluids require preparation, maintenance, and disposal. Just the disposal cost represents 200% and 400% of the original purchase cost in the USA and EU, respectively [108] as the cutting fluids are not naturally biodegradable and require treatment before disposal. Furthermore, cutting fluids require regular maintenance to prevent micro-organism colonization. Bacteria and yeasts negatively alter fluid proprieties whilst also being hazardous for workers on the shop floor.

5.3 - High-pressure cooling (HPC)

HPC supplies conventional water-based cutting fluids at high pressures, maximizing their effectiveness. HPC is associated with an exceptional boost in productivity and process optimization, especially when machining Inconel 718 [25]. The kinetic force developed through pressures up to 360 MPa [109] not only has the potential to eliminate the undesirable vapor blanked, but also acts as a “Hydraulic wedge”. The latter can improve chip segmentation and fluid penetrability at the friction area [110, 111]. Figure 7 depicts the effect of the hydraulic wedge on chip curling. Compared with conventional machining (left), the HPC jet (right) strongly deformed the chip; thus, developing the desirable C-shaped chips. However, it is categorized as an environmentally hostile process due to the use of high amount of hazardous cutting fluids as well as high energy requirements [9, 112].

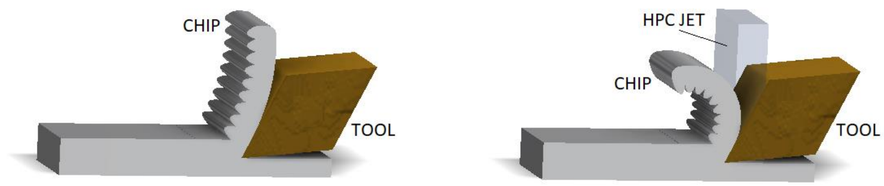


Fig. 7 - Effect of the hydraulic wedge on chip curling [110, 111]

Four major HPC parameters studied for machining of Inconel 718, were identified from the literature:

- Pressure and flow rate [109, 113];
- Nozzle orifice diameter and pressure/cutting speed ratio [113, 114];
- Jet distance, target point and inclination [115, 116];
- Configuration, stability, and delivery method [112, 117].

The choice of pressure and flow rate depends on the tool-workpiece combination and cutting speed. Öjmertz and Oskarson [109] used water as a medium with ultra-high pressures up to 360 MPa. They reported improvements in surface finish, burr formation, and chip segmentation due to deeper penetration of the fluid. However, accelerated notch wear was observed at cutting edge center as well as cracks on the jet target point. These detrimental effects were reduced with the right choice of pressure and flow rate. Ezugwu and Bonney [113] adopted significantly lower pressures up to 20.3 MPa at a higher flow rate of 3000 l/h when rough turning Inconel 718 with coated carbide tools at 50 m/min, 0.3 mm/rev and 3 mm DoC. They reported a 740% extension in tool life compared with conventional machining. They attributed the result to the ability of HPC jet to lift the chip and gain closer access to the critical area. Furthermore, they pointed out the existence of a critical pressure, above which, further increase led to a negligible effect on tool life. However, at the low cutting speed of 20 m/min, increasing the coolant pressure from 15 MPa to 20.3 MPa resulted in reduced tool life. Ezugwu et al. [118] repeated the experiment using ceramic tools, and the results showed that increasing pressure led to tool life extension just up to 15 MPa and not 20.3 MPa. At 20.3 MPa pressure, they observed increased notching and, consequently, dramatic decreases in tool life. Vagnorius and Sorby [119] investigated performances of SiAlON-based ceramic tools under 20 MPa fluid pressure in turning. They reported that tool life was not extended with HPC adoption as the thermal proprieties of ceramic tools made them vulnerable to thermal alterations caused by the jet. Furthermore, they pointed out that nozzle orientation, stability, and configuration are the critical factors for improving machining performance.

Courbon et al. [115] investigated the impact of various high-pressure jet coolant parameters as well as cutting parameters in turning Inconel 718. They applied response surface methodology by investigating nozzle diameter (0.25-0.4 mm), coolant jet pressure (50-130 MPa), the distance between nozzle and cutting zone (0.25-0.4 mm), cutting speed (46-74 m/min) and feed rate (0.2-0.25 mm/rev).

They noted that increasing coolant pressure results in a reduction in cutting forces. This effect is more profound at the lower cutting speed of 46 m/min, and the impact becomes negligible at 74 m/min.

Hoier et al. [116] studied the flank wear behavior of WC-Co tools in machining using traditional water-based coolants at 16 MPa pressure on the rake face and 8 MPa pressure on the flank. After 70 m machining, below the flank wear land, it appeared a bright Co-free surface. Since this area was not in contact with the workpiece, they attributed the cause of Co-binder removal to the impact of the HPC. This demonstrates the drawback of HPC damaging the cutting tool. The impact of the cooling media can remove debris from the tool surface, which can be controlled through direction, target point, and inclination of the jet.

In terms of configuration, Busch et al. [112] observed 4 supplying modes shown in Fig. 8:

- A- Tool-chip interface on the rake face;
- B- Tool-workpiece on the flank face;
- C- Both rake and flank faces;
- D- Direct injection through-the-tool;

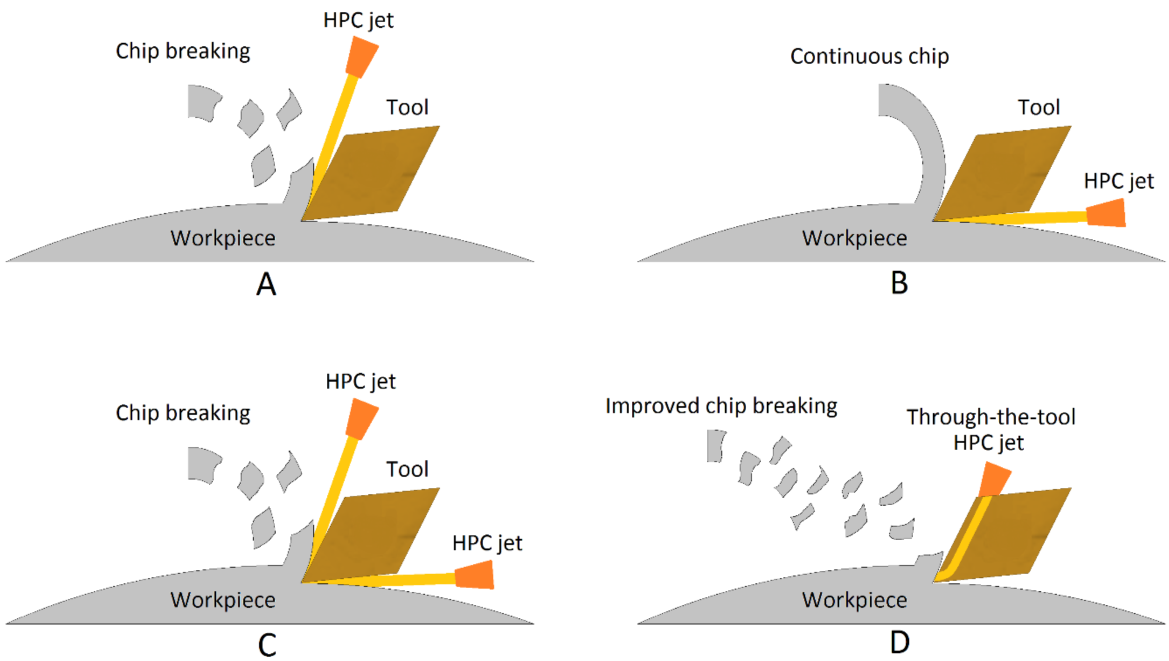


Fig. 8 – Four modes of high-pressure coolant supply, revisited from [112]

They reported that the jet directed on the rake face (A) provided chip breakability and good surface roughness due to hydraulic wedge and BUE suppression, respectively. On the other hand, the jet on the flank (B) reduces workpiece temperature, and therefore, it was considered beneficial for residual stresses. The combination of both methods (C) provided these benefits simultaneously, but it increased the stress on the tool.

Sharman et al. [117] developed a through-the-holder system that supplied coolant on both flank and rake face. They reported microstructural deformation levels similar to flood cooling with no significant improvement in tool life with an ultra-high pressure of 45 MPa.

Another approach to maximize the benefits of HPC is a through-the-tool jet (D). This method enlarged the pressure range as the wedge was more directed on the chip avoiding the direct impact of HPC on the tool [112]. The impact of the wedge can also be altered by changing tool geometry. Fang and Obikawa [111] proposed a new concept of inserts with cooling channels on the flank aimed at generating turbulence in the coolant flow. Their special inserts doubled tool life when compared with conventional high-pressure machining. In another work [120], they also realized a micro-texture on the flank face of the tool, which imposed turbulence in the high-pressure flow enhancing thermal exchange and consequently reducing flank wear. The surface metallurgy of the workpiece also influences the efficiency of HPC. In particular, Polvorosa et al. [110] studied both flank and notch wear, pointing out that the Inconel 718 grain dimension had a significant effect on wear behavior. Figure 9 shows the comparison between two grain sizes (3 - 8 ASTM) of Inconel 718 when machining at 30 m/min with uncoated cemented carbide inserts under HPC.

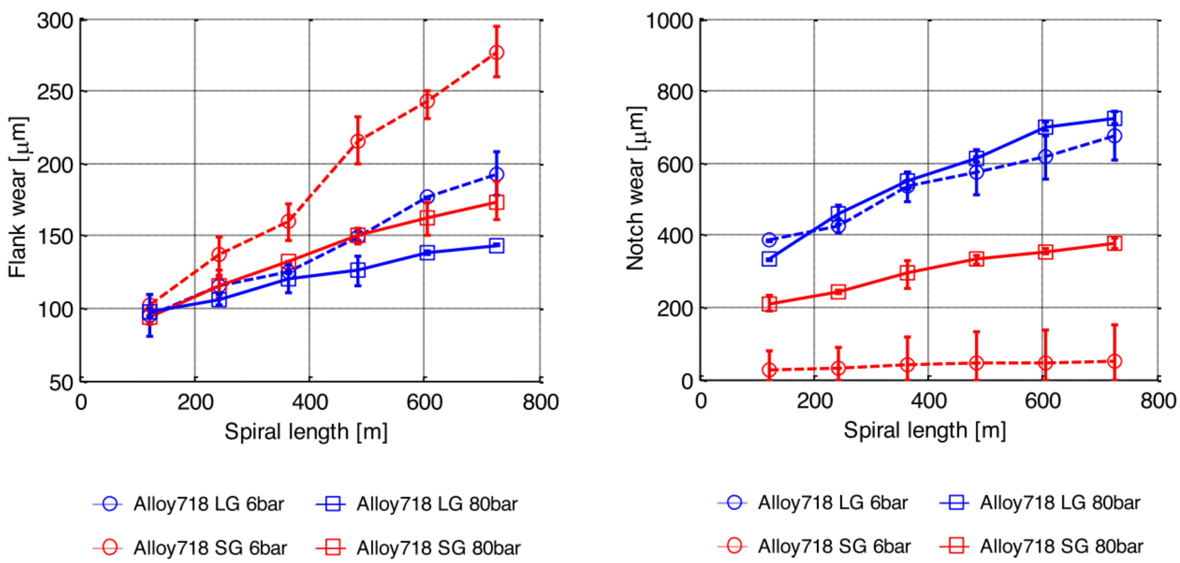


Fig. 9 - Effect of grain size when machining Inconel 718 with high-pressure coolants [110]

As illustrated in Fig. 9, the 3 ASTM grain Inconel 718 showed lower flank wear [110]. Furthermore, increases in liquid pressure from 0.6 to 8 MPa resulted in a beneficial reduction of average flank wear but also in a detrimental increment of notch wear. The latter was found negligible for large grain but significant in case of small grain size. This suggests that the large grain anisotropy affected the interaction between interface and jet, causing significant fluctuation of C/L conditions.

Raykar and Dabade [114] applied grey relational analysis to optimize cutting force, feed force, radial force, surface roughness, and tool wear for HPC turning of Inconel 718. They found that optimized process parameters were 8 MPa coolant pressure, 60 m/min cutting speed, 0.1 mm/rev feed, and 1 mm DoC.

For more details on the usage of HPC and their effect on Inconel 718 surface integrity, readers are referred to Mohsan et al. [25].

5.4 - Minimum quantity lubrication (MQL)

MQL is a near-dry technique within a minuscule amount of oil (10-200 ml/h) is mixed together with compressed air. The result is a thin mist that penetrates effectively in the tool-chip interface and lubricates the cutting zone. The massive reduction of lubricant consumption over conventional and high-pressure machining systems is the key feature of this technology. Furthermore, adequate lubrication, as well as improvement in cutting performances, has been observed by its adoption [121-128].

Recent investigations in MQL are concentrated on:

- Lubricant viscosity, composition, and droplet size;
- Flow rate;
- Air pressure and oxygen content;
- Spray direction and nozzle-tool distance;
- Addition of solid lubricants.

Viscosity has a critical impact on the lubrication and penetrability of lubricants used in MQL. Whilst low viscosity can potentially increase penetrability [129], in general, more viscous fluids provide enhanced lubrication [73]. This suggests that there is an optimal level of viscosity, which is a trade-off between lubrication and penetrability, depending on machining conditions.

It is worth to mention that the existence of the optimum has not proven yet as it is difficult to observe the wetting behavior of MQL when wetting the tool-chip interface.

Penetrability tests are usually simulated, ejecting the MQL mist towards the clearance of two acrylic plates [129].

Furthermore, MQL machining performances can be increased by shifting the optimum level towards higher viscosity by reducing the size of the oil micro-droplets. Reduced droplet mean diameter has been associated with increased penetrability of fluid into the tool-chip interface [121, 130].

MQL flow rate also impacts machining performance. Yazid et al. [122] compared dry machining with MQL at flow rates of 50 ml/h and 100 ml/h when finish turning Inconel 718 with PVD-coated carbide tools. The best surface roughness was obtained with 50 ml/h oil flow of MQL at 90 and 120 m/min cutting speed. The high flow rate of 100 ml/h could have increased droplet dimension and reduced penetrability. Similarly, Thamizhmanii [123] tested 3 levels of MQL oil flow: 12.5, 25 and 37.5 ml/h. However, they observed no optimum when milling Inconel 718. The flow rate of 37.5 ml/h reduced surface roughness and tool wear by 32.65% and 29.2%, respectively, when compared with the lower level of MQL supply. When milling Inconel 718, the speed of the impacting droplet can potentially have a more significant effect rather than its size as the tool is intermittently exposed to the flow. The nozzle-tool distance and optimal oil flow rate have been identified to be correlated [124, 131]. Obikawa et al. [124] reported that oil consumption can be decreased to less than 1 ml/h without affecting machining performances by reducing the nozzle-tool distance to 15 mm. Furthermore, they designed and tested a special cover-type nozzle by varying spray direction and oil flow. They found that when machining at 78m/min, an oblique oil flow of 0.5 ml/h extended tool life to 47 min, which was 1 min less than tool life when machining with flood conditions.

Air pressure is another critical parameter influencing machining performance in MQL. Increases in pressure lead to higher penetrability but reduce the lubricant mass accumulated at the cutting zone. Kamata and Obikawa [125] noted that there was an optimum pressure value when finish turning of Inconel 718 with MQL systems. In their study, the pressure of 0.4 MPa maximized tool life and surface finish. Moreover, they tested the use of argon as a carrier gas by comparing it to oxygen. Their result showed that there is no benefit in using argon, while oxygen increased performance by affecting the tribological behavior at the interface. In particular, oxygen developed a protective oxide layer, which helped lubrication.

The performance of MQL can be improved with the addition of solid lubricants to the oil [126-128]. Paturi et al. [127] compared tungsten disulfide (WS_2) assisted MQL with conventional MQL when turning Inconel 718 between 60 and 100 m/min cutting speeds. They reported that WS_2 assisted MQL resulted in a 35% reduction in surface roughness Ra over conventional MQL. On the other hand, Marques et al. [126] stated that the inclusion of MoS_2 or graphite in MQL resulted in minor changes in surface integrity. They recommended using solid lubricants with good thermal proprieties.

5.5 - Cryogenic machining

Cryogenic machining is an alternative cooling technique using a super-cold liquefied gas such as nitrogen (LN_2) or carbon dioxide (CO_2) for cooling workpiece material or cutting tools during machining. Furthermore, evaporation of the delivered fluid eradicates the need for filtration and disposal of coolants resulting in the dry and clean workpiece and chips.

Three methods of supplying cryogen are commonly adopted, namely: i) workpiece cooling, ii) indirect cooling, and iii) cutting zone cooling [132]. In workpiece cooling, the workpiece is submerged or flooded by a cryogenic fluid. This will alter the material properties of the workpiece and increases its hardness and strength. Depending on the material, it can also favorably reduce material toughness. It is mostly used for machining soft materials and polymers. Indirect cooling is aimed at freezing cutting tools without having direct contact between cryogen and cutting zone. In this way, heat is absorbed internally and a brief description of this technique, commonly known as “heat pipe”, was provided by Shokrani et al. [132]. Based on this idea, a unique tool holder with a cryogenic cooling chamber was adopted by Wang et al. [133], which helped the tool material to keep its hardness and strength when machining Inconel 718. In contrast, cutting zone cooling consisted of spraying the coolant directly into the cutting zone. The heat is dissipated by direct cooling of the critical zone with improvement in cutting tool proprieties. Cutting zone cooling is the most widely researched method, in particular when machining difficult-to-machine materials such as Inconel 718 [132]. Three major parameters have been identified, which affect cryogenic machining performances when cutting zone cooling:

- Type of cryogen fluid, air/cryogen pressure, and flow rate;
- Number of nozzles and delivery method (flank, rake or both);
- Spraying directions.

There are several types of cryogens used for machining. Among them, LN_2 and CO_2 are the most common. It is noteworthy to mention that health and safety requirements in using cold and pressurized gases should be taken into account for cryogenic machining processes. Specifically, the need for ventilation and oxygen monitoring systems when using CO_2 should be considered. Table 3 provides a brief comparison between LN_2 and CO_2 [5, 10, 134, 135].

Cryogen fluid:	**Liquid nitrogen (LN_2)**	**Carbon dioxide (CO_2)**
Evaporation temperature:	-195.8 °C	-78.5 °C
Delivery temperature:	-195.8 °C	Ambient temperature
Thermal insulation:	Requires vacuum jacket insulation	No need for thermal insulation
Storage tank:	Vacuum insulated Dewar vessel	7-MPa pressurized gas bottle
Supplying:	Air compressor/Self pressurized Dewar	No need for a compressor
Pressure drop interaction when spraying:	Design considerations should be taken into account to ensure delivery of liquid phase	It is delivered at ambient temperature in gas phase which deposits from gas to solid
Impact on the environment:	78% of the atmosphere is made of N_2. Significant energy requirement for generating LN_2.	CO_2 is considered a greenhouse gas. Significant energy requirement for generating high-pressure CO_2.
Smell:	Odorless	Irritating odor
Effect on operators' health:	Oxygen monitoring is recommended.	Oxygen monitoring and ventilation is required. There is a risk of asphyxiation.
Ambient gas density	1.1606 kg/m^3. (lighter than air)	1.98 kg/m^3 (heavier than air)
OSHA's exposure limit in breathing atmosphere:	2%	0.5%
Latent heat of vaporization:	200 kJ/kg at -196 °C	280 kJ/kg at -78 °C
Absorbed heat from vaporization to room temperature:	228 kJ/kg	67 kJ/kg
Total absorbed heat:	428 kJ/kg	347 kJ/kg

Table 3 - Comparison between LN_2 and CO_2 for cryogenic machining applications [5, 10, 134, 135]

When machining Inconel 718, the delivery pressure and flow rate were found to be significant parameters. Experiments were usually conducted with LN_2 at 1.5 MPa pressure with around ~44 l/h [0.6 Kg/min] LN_2 flow rate [10, 136] but the optimal machining condition may vary based on tool geometry, material and cutting parameters.

Pusavec et al. [5] pointed out that information about cryogenic fluids are not enough to characterize the machining interaction as it is imperative to know how, at what phase, and where it was delivered. Hribersek et al. [137] proposed a FEM model to analyze heat transfer between LN_2 and Inconel 718. They remarked that the heat transfer coefficient decreased with increasing cutting temperature. Furthermore, Tebaldo et al. [138] underlined the importance of supplying the coolant internally or coaxially. Intending to increase efficiency, they adopted a through-the-holder equipment which focused the cryogen flow on the cutting zone.

Three standard spray directions were reported in Fig. 10 [5]:

A. Far from the cutting zone, directed on the workpiece;

B. Near the cutting zone, directed on the rake face;

C. Near the cutting zone, directed on the flank face.

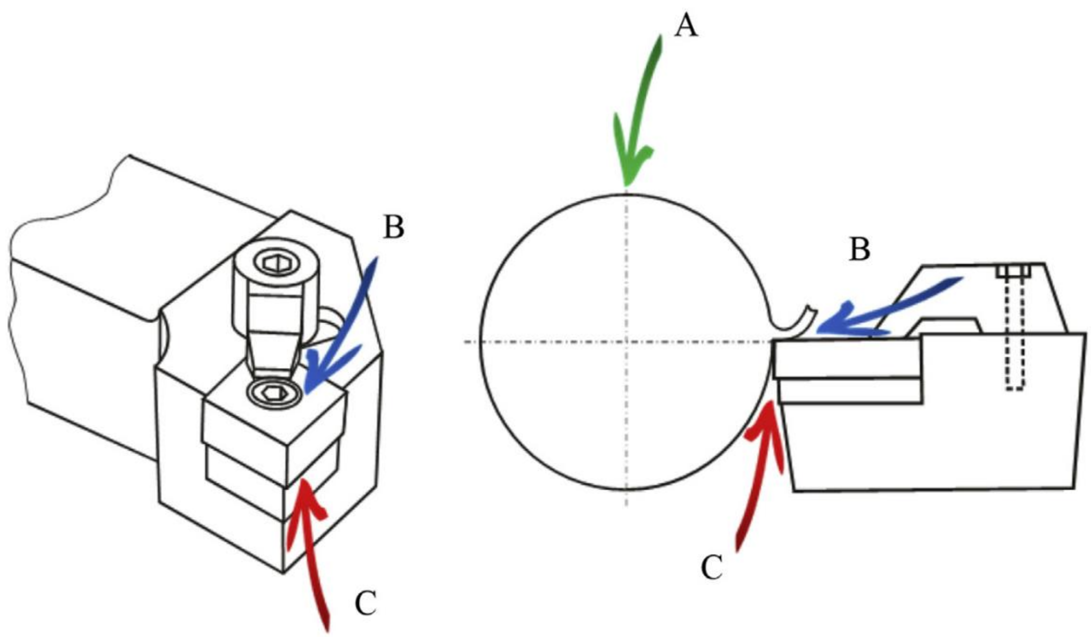


Fig. 10 - Delivery directions in cryogenic machining: workpiece cooling (A), rake face cooling (B) and flank face cooling (C) [5]

"B + C" configuration was analyzed by Kaynak [139], who investigated its influence on cutting forces and power consumption. They pointed out that spraying cryogen simultaneously on both flank and rake face increased cutting forces. The result was integrated by Hribersek et al. [140], who analyzed the effect of "B" and "C" singularly. They registered a 6% increase in cutting forces when fluid was supplied just on the rake face (B). Furthermore, LN_2 delivery just on the flank face (C) resulted in a more compressive residual stress.

Generally, spraying just on the flank face has been reported as the best configuration as it improves residual stresses and reduces cutting forces when machining Inconel 718.

6 - DISCUSSION

This section discusses the impact of various advanced C&L techniques in relation to:

- Wear behavior and tool life
- Surface integrity
- Machining forces and energy consumption
- Comparison of C&L techniques

6.1 - Wear behavior and tool life in relation to C&L

Controlling tool wear behavior has a significant impact on machining performance. Dudzinski et al. [11] reported that dry machining Inconel 718 led to abrasion, adhesion, and welding of chips. While abrasion is well-known to be an uncontrollable characteristic of carbide particles in Inconel 718, Devillez et al. [141] noted that welding and adhesion were related to dry cutting and resulted in the formation of a built-up-layer (BUL) as well as BUE. Furthermore, Xavior et al. [41] remarked that improper lubricant application can result in BUE and even chipping. Both the BUE and BUL can be effectively reduced with cryogenic applications. According to Courbon et al. [142], enhanced BUE delamination was achieved due to the ductile-brittle transition temperature. However, premature chipping tends to occur in this case [59, 143].

Shokrani et al. [59] observed premature chipping in combination with a fracture at the nose of the PVD-TiAlN solid carbide tool in cryogenic milling. Similar results were reported by Uçak & Çiçek [143], who noticed excessive chipping when cryogenically drilling Inconel 718. The high amplitude of thermal fluctuation and embrittlement of tool material can develop significant cyclic loads resulting in crack nucleation. Cracks were observed not only on the tool but also on the workpiece [144].

Lubrication has been shown to be an effective solution to control BUE and premature chipping. Ucun et al. [145] tested 5 different coatings when micro-milling of Inconel 718 under dry, flood, and MQL conditions. They observed that MQL reduced chip adherence in all cases. Moreover, Xavior et al. [41] noticed higher flank wear in flood cooling than MQL and attributed tool wear reduction to the increased penetrability of MQL in the critical area.

Tool-chip penetrability is also a critical factor in controlling tool wear [146]. One of the most effective strategies to avoid BUE and chipping is HPC. Through the use of HPC, a pressurized jet can effectively penetrate the friction area and prevent BUE formation. Investigations conducted as Hoier et al. [116] revealed that the coolant impact at 8 MPa eroded the Co-capping layer of WC-Co tools, causing a local alteration of the surface.

Tables 4 and 5 have been developed to show the tool life achieved with different machining parameters and cooling scenario combinations, based on a number of references, when turning and milling, respectively. The authors calculated tool life in terms of machining length and material removal rate to enhance comparison. Dry and cryogenic machining of Inconel 718 generally showed short tool life. Furthermore, Shokrani et al. [147] indicated that cryogenic cooling on its own is not beneficial for machining Inconel 718 as it results in increased material hardness and rapid tool wear. Kumar et al. [148] reported that flood and MQL provided a prolongation in tool life; however, Ucun et al. [145] observed that MQL increased tool life by reducing chip adherence. Ezugwu & Bonney [113] reported a 740% extension in tool life with HPC over conventional machining, while Busch et al. [112] achieved a tool life of 30 min with 8 MPa pressure.

The review of the literature indicates that HPC has the highest potential for improving tool life in machining Inconel 718. Research should focus on improving hydrodynamic lubrication during machining, which can concentrate on new cutting fluids developments, alternative delivery systems, and modifying cutting tool geometry and surface characteristics to enhance hydrodynamic lubrication.

Table 4 - Tool life based on turning parameters and cooling scenarios. Tool wear criterion followed ISO 3685

Reference	Cooling scenario	Tool life	Cutting speed	Feed rate	Axial DOC	Edge MRR	Removed material per edge
[12]	Dry	~250 sec	60 m/min	0.075 mm/rev	0.8 mm	60 mm^3/s	15000 mm^3
[138]	Dry	29 min	20 m/min	0.1 mm/rev	1 mm	33.3 mm^3/s	58000 mm^3
[138]	Dry	6.5 min	40 m/min	0.1 mm/rev	1 mm	66.7 mm^3/s	26000 mm^3
[138]	Dry	3 min	45 m/min	0.1 mm/rev	1 mm	75 mm^3/s	13500 mm^3
[39]	Flood	57 min	40 m/min	0.15 mm/rev	0.25 mm	25 mm^3/s	85500 mm^3
[39]	Flood	22 min	80 m/min	0.15 mm/rev	0.25 mm	50 mm^3/s	66000 mm^3
[39]	Flood	17 min	120 m/min	0.15 mm/rev	0.25 mm	75 mm^3/s	76500 mm^3
[39]	Flood	34 min	40 m/min	0.15 mm/rev	0.25 mm	25 mm^3/s	51000 mm^3
[139]	Flood	~ 3 min	420 m/min	0.1 mm/rev	0.3 mm	210 mm^3/s	37800 mm^3
[139]	Flood	~ 2 min	480 m/min	0.1 mm/rev	0.3 mm	240 mm^3/s	28800 mm^3
[139]	Flood	~ 2.5 min	540 m/min	0.1 mm/rev	0.3 mm	270 mm^3/s	40500 mm^3
[139]	Flood	~ 1.6 min	600 m/min	0.1 mm/rev	0.3 mm	300 mm^3/s	28800 mm^3
[139]	Flood	~ 1.1 min	660 m/min	0.1 mm/rev	0.3 mm	330 mm^3/s	21780 mm^3
[123]	Flood	104 sec	300 m/min	0.2 mm/rev	1 mm	1000 mm^3/s	104000 mm^3
[119]	HPC 8 MPa	30 min	50 m/min	0.1 mm/rev	1.5 mm	125 mm^3/s	225000 mm^3
[119]	HPC 8 MPa	12 min	75 m/min	0.1 mm/rev	1.5 mm	187.5 mm^3/s	135000 mm^3
[123]	HPC at 20 MPa	129 sec	300 m/min	0.2 mm/rev	1 mm	1000 mm^3/s	129000 mm^3
[12]	MQL	~250 sec	60 m/min	0.075 mm/rev	0.8 mm	60 mm^3/s	15000 mm^3
[12]	Cryo	~250 sec	60 m/min	0.075 mm/rev	0.8 mm	60 mm^3/s	15000 mm^3
[119]	CO_2 Cryo	10 min	50 m/min	0.1 mm/rev	1.5 mm	125 mm^3/s	75000 mm^3
[119]	CO_2 Cryo	6 min	75 m/min	0.1 mm/rev	1.5 mm	187.5 mm^3/s	67500 mm^3
[119]	ADL + CO_2	12 min	50 m/min	0.1 mm/rev	1.5 mm	125 mm^3/s	90000 mm^3
[119]	ADL + CO_2	8 min	75 m/min	0.1 mm/rev	1.5 mm	187.5 mm^3/s	90000 mm^3

Table 5 - Tool life based on milling parameters and cooling scenarios. Tool wear criterion followed ISO-8688

Reference	Cooling scenario	Tool life	Cutting speed	Feed rate	Axial DOC	Radial DOC	Tool Diameter	Edge MRR	Removed material per edge
[137]	Dry	42.9 min	55 m/min	0.1 mm/tooth	0.5 mm	1 mm	20 mm	4.6 mm^3/s	11797.5 mm^3
[133]	Dry	15 min	160 m/min	0.15 mm/tooth	0.3 mm	0.2 mm	16 mm	3 mm^3/s	2700 mm^3
[135]	Cryo	198 sec	60 m/min	0.05 mm/tooth	20 mm	1 mm	12 mm	166.7 mm^3/s	33000 mm^3
[133]	Cryo	29 min	160 m/min	0.15 mm/tooth	0.3 mm	0.2 mm	16 mm	3 mm^3/s	5220 mm^3
[135]	MQL	283 sec	60 m/min	0.05 mm/tooth	20 mm	1 mm	12 mm	166.7 mm^3/s	47166.67 mm^3
[135]	Cryo+MQL	523 s	60 m/min	0.05 mm/tooth	20 mm	1 mm	12 mm	166.7 mm^3/s	87166.67 mm^3
[137]	MQCL	67.2 min	55 m/min	0.1 mm/tooth	0.5 mm	1 mm	20 mm	4.6 mm^3/s	18480 mm^3

6.2 - Surface integrity in relation to C&L

The condition of the workpiece surface is a primary concern for engineering applications, and C&L has a significant role in preserving surface integrity. High temperatures, in combination with high mechanical stresses, can lead to poor workpiece quality [149]. Inappropriate cutting conditions can even develop new metallurgical compounds such as severely deformed microstructure (white layer) [1]. As expected, this is usually the case in dry machining [55], which can develop a white layer as thick as 30 µm [70].

Cryogenic cooling, instead, leads to improved surface quality [143] and significantly low surface roughness [59]. According to Musfirah et al. [144], surface roughness as low as 0.2 µm Ra can be achieved by cryogenic machining. This can provide an alternative for expensive and time-consuming grinding operations.

Lubrication techniques, such as MQL and HPC, also showed benefits in terms of surface roughness [150]. With MQL, Deshpande et al. [151] observed 51% enhancement in the surface finish over dry machining while Kumar et al. [148] observed a 17% improvement over the wet scenario. Electrostatic application of MQL can further increase the benefits [152]. Furthermore, Mohsan et al. [25] concluded that HPC can improve surface integrity over flood concerning surface roughness and residual stress.

Dry machining, though, is associated with the development of high tensile stresses, while the use of coolant has been shown to result in residual stress reduction. In some instances, the residual stress reduction was so high so as to go from tensile to compressive status [52]. However, the impact of coolants reduces with increased cutting speed. Devillez et al. [6] emphasized that the tensile component of residual stress parallel to the cutting direction was 700 MPa at 80 m/min for both dry and wet machining. Furthermore, parallel and perpendicular components of residual stress in dry machining slightly decreased with increasing in cutting speed from 40 to 80 m/min. Nonetheless, they observed that tensile residual stresses in dry machining were always higher than flood cooling conditions. Pusavec et al. [10] analyzed residual stresses when turning Inconel 718 under dry, MQL, and cryogenic conditions. They reported that cryogenic machining positively influenced surface integrity, increasing the final product quality level with extensions of the compressive zone up to 185%. HPC also provided greater subsurface compressive residual stress when compared with flood cooling [51]. Mechanical plasticization of the surface coupled with cryogenic cooling can lead to increased surface hardness. Kenda et al. [136] observed increases in hardness from 500 HV to 800 HV with the use of cryogenic cooling.

The majority of studies for alternative C&L have been undertaken in comparison with dry machining. This work indicates that dry machining of Inconel 718 with existing technologies is neither economical nor technologically viable. As such, future studies, including dry machining with new cutting tools and coatings, must be benchmarked against viable processes adopted in industry, such as flood cooling.

6.3 - Machining forces and energy consumption in relation to C&L

Machining forces are directly related to machine power requirements as well as energy consumption in cutting applications [139]. Increments over 400% in machining loads were observed when dry cutting Inconel 718 compared with MQL [130] and even more was recognized when using LN_2 due to material embrittlement [140]. However, Kaynak [139] argued that, at 120 m/min cutting speed, LN_2 reduced 18%, 23%, and 13% the radial, feed, and main cutting force, respectively, when compared with dry. This is because LN_2 provided a slight lubrication effect called ‘vapor cushion’ [153] though this contact mechanism is not fully explained [142].

Lubrication techniques such as MQL also offered a cutting force reduction [151]. In contrast to cryogenic cooling, the benefits of MQL on decreasing cutting forces were reduced with increases in cutting speed. Çolak [154] showed that cutting forces can be reduced through high-pressure when adopting HPC conditions. The cutting forces are directly related to the lubrication at the cutting zone and the thermomechanical properties of the workpiece material. Inconel 718 is known to maintain its hardness at temperatures as high as 700 °C [9]. If the cutting temperature reaches above this temperature, the material undergoes thermal softening, which can potentially reduce the cutting forces. These high temperatures, however, have a detrimental impact on the majority of known cutting tool materials and can also result in the development of heat affected zone on the workpiece. Recent developments in impact-resistant ceramic tools have demonstrated that higher cutting temperatures can be achieved where surface integrity is not of significant importance, such as in roughing operations [23, 119, 155].

Liu et al. [156] reported a 15% increase in specific energy consumption of flood milling over dry due to the auxiliary pump, and even more was observed when running HPC [112]. Figure 11 presents the specific energy consumption when turning Inconel 718 at 50 and 75 m/min cutting speed with 3 different strategies: Aerosol dry lubrication (ADL) with CO_2, HPC, and CO_2 alone [112].

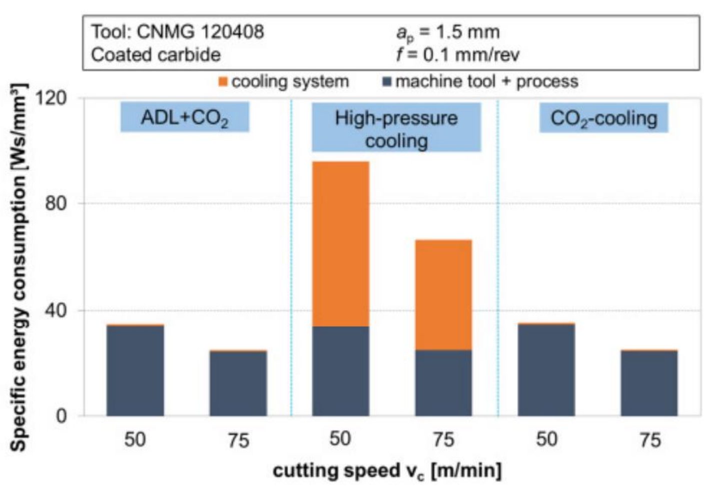


Fig. 11 - Specific energy consumption in turning Inconel 718 (v_c = 75 m/min, f = 0.1 mm/rev, a_p = 1.5 mm) [112]

The graph in Fig. 11 shows that the increase in energy spent when using HPC is around 150% of the energy spent on machine tool and process. This means that the global energy consumption for machining Inconel 718 almost tripled with HPC adoption while the cryogenic scenario showed negligible increases. In these comparisons, the energy required for producing CO_2 at high pressure and with pressurized air in the case of MQL are preferentially not considered, and measurements are limited to the machine tools' power consumption. In addition, the energy requirements and carbon footprint of manufacturing lubricants as well as maintenance and disposal for HPC and flood cooling are not considered. The authors believe that more comprehensive life cycle assessment (LCA) studies are required taking the manufacturing and delivery of different C&Ls into account.

6.4 - Qualitative comparison of C&L

Table 6 qualitatively compares dry, HPC, MQL, and cryogenic machining environments with conventional flood techniques against various performance metrics based on a number of references [6-9, 100, 157].

Table 6 - Qualitative comparison of dry, MQL, HPC, and cryogenic (CRYO) machining of Inconel 718 with conventional flood techniques.

	FLOOD	DRY	HPC	MQL	CRYO
Lubrication	Base standard	Inferior	Superior	Superior	Inferior
Cooling		Inferior	Superior	Inferior	Superior
Tool life extension		Inferior	Superior	Similar	Inferior
Machining forces decrement		Inferior	Superior	Similar	Inferior
Energy consumption reduction		Superior	Inferior	Superior	Superior
Installation costs reduction		Superior	Inferior	Superior	Similar
Running costs reduction		Superior	Inferior	Superior	Similar
Productivity		Inferior	Superior	Similar	Inferior
Workpiece surface integrity		Inferior	Superior	Similar	Superior
Space requirement amelioration		Superior	Inferior	Superior	Similar
Residue on chips reduction		Superior	Similar	Similar	Superior
Turning suitability		Inferior	Superior	Similar	Superior
Milling suitability		Inferior	Similar	Superior	Inferior
Drilling suitability		Inferior	Similar	Superior	Similar
High-speed machining aptness		Inferior	Superior	Similar	Superior
Environmentally friendliness		Superior	Inferior	Superior	Superior
Safety – Healthiness		Superior	Inferior	Superior	Similar
Evaporation of dangerous particles		Superior	Similar	Inferior	Superior
Chip breakability		Inferior	Superior	Inferior	Superior
Operators know-how		Superior	Similar	Superior	Inferior
Waste disposal cost amelioration		Superior	Inferior	Superior	Superior
Surface roughness reduction		Inferior	Superior	Superior	Superior
Tensile residual stress suppression		Inferior	Superior	Similar	Superior
Hardness increment prevention		Inferior	Superior	Superior	Inferior
White layer suppression		Inferior	Superior	Superior	Superior
Compatibility with different cutting tool materials		Superior	Similar	Superior	Inferior
Maintenance reduction		Superior	Inferior	Superior	Superior
Machining stoppages and operator supervision reduction		Inferior	Superior	Similar	Similar

(Flood has been used as the base standard for comparing the 4 C&L technologies)

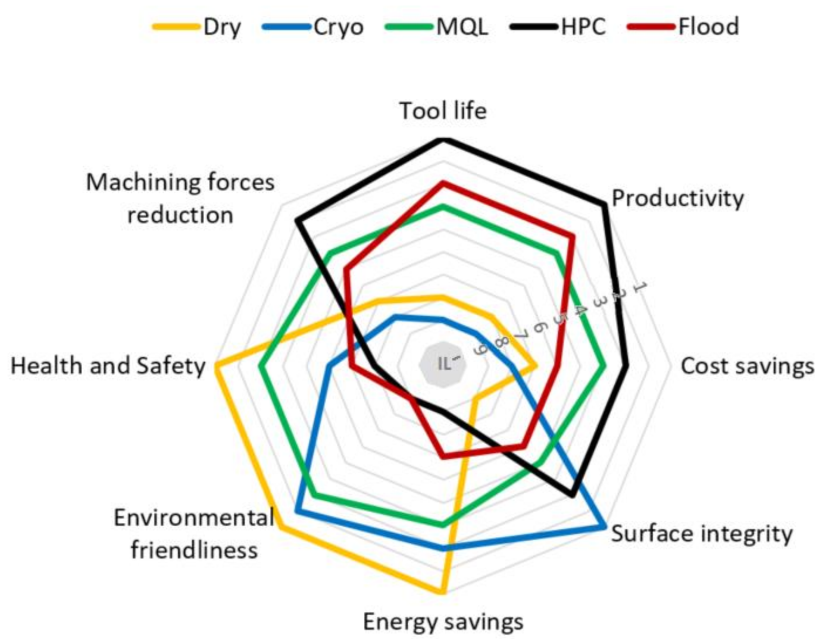
Table 6 show that the technologies which adopt oil generally provide better lubrication while those which involve water or cryogens improve the heat removal effect. The tool life extension is high with HPC adoption due to the combination of water-based cutting fluids and high pressures. In most cases, the decrease in machining forces was primarily given by the lubricating oil, which reduced friction, while strong coolants provided the opposite effect due to the workpiece hardness at low temperatures. Despite the reduction in machining power given by the reduction in machining forces, the energy consumption can be seen to be high due to the cutting fluid pumps in HPC, flood, and to a lesser extent, in MQL.

Installation and running costs are relative to the fixed and variable costs of each technology, respectively. They involve cutting fluid waste disposal, space requirements, energy consumption, and maintenance. On the other hand, the benefit achieved in productivity, high-speed aptness, and surface integrity can pay back these costs. Again, HPC has the highest cost-benefits combination followed by flood, MQL, cryogenic, and, finally, dry machining.

Furthermore, the suitability of different C&L technologies largely depends on the machining operation, specifically due to the differences in kinematics and cutting tool loads. For example, the relatively higher thermal loads developed when turning require more cooling [111]. On the other hand, the impact of alternated mechanical loads of milling is reduced though lubrication [155], while high penetrability of C&L has to be preferred when drilling [158].

None of the alternatives to flood cooling meets the ideal sustainability and productivity in machining Inconel 718, whose combination can be represented by the largest octagon in Fig. 12. Fig. 12 summarizes a qualitative comparison between various C&L technologies based on the general observations from the literature. However, it is worth to mention that the figure is general and does not consider different machining applications, cutting tool geometries as well as materials that may vary the classification. Figure 12 shows that flood cooling technologies improve surface integrity and tool life, but they rely on environmentally hostile and hazardous cutting fluids. HPC provided superior benefits in productivity as well as in surface integrity, but, again, HPC based its performance on cutting fluids usage and almost tripled the specific energy required by the machining process. On the other hand, environmentally conscious alternatives such as dry, MQL, and cryogenic machining showed lower performances. Cryogenic machining generally provided exceptional surface integrity, but short tool lives. MQL showed the potential to extend tool life, preserve surface integrity, but it lacked efficiency at high machining speeds.

Furthermore, general observations reported that dry machining Inconel 718 rarely showed good productivity. This was only possible with adverse consequences such as high tensile residual stress with new detrimental metallurgical compounds on the machined surface.



Impact Level (IL)	Description of the Impact Level range	Detrimental impact of the C&L technology	Scoring criteria, sine-qua-non conditions:
1 (best)	The technology meets the industrial and/or ecological standards required with excellence in this aspect. The latter is one of the key strengths of the technology. Eventual drawbacks may be ignored with small consequences	Zero	At least 5 researchers have reported the technology to be advantageous.
2		Negligible	At least 4 researchers have reported the technology to be advantageous.
3		Very low	At least 3 researchers have reported the technology to be advantageous.
4	The technology presents a balance between advantages and disadvantages in this field. Its impact is usually dependent on the investigated machining conditions. The drawbacks associated are not negligible and require minor procedures/equipment.	Low	At least 2 researchers have reported the technology to be advantageous.
5		Tolerable	At least 1 researcher has reported the technology to be advantageous and another as an issue.
6		Medium	At least 2 researchers have reported the technology as an issue.
7	The technology has a significant detrimental impact on this aspect. It can require financed costs and/or investments in research. It can also result in permanent damage to the organization reputation or extended production delays.	High	At least 3 researchers have reported the technology as an issue.
8		Very high	At least 4 researchers have reported the technology as an issue.
9 (worst)		Extreme	At least 4 researchers have reported the technology as an issue.

Fig. 12 - Radar chart describing the comparison between different C&L technologies in machining Inconel 718 together with weighting matrix.

7 – Research Gaps & Future Research Directions

The devolpement of new technologies which are able to guarantee sustainability and productivity at the same time is imperative. This is currently the biggest challenge of

C&L technologies for machining Inconel 718, and the state of the art of each reviewed system can be considered a trade-off between two aspects. High-speed inefficiency, in combination with the unsuitability of cutting fluids, highlights the need for a new technology able to guarantee sustainability and productivity at the same time. The surface integrity achieved through machining processes has been found to be of random nature with cutting parameters and machining environment selected to meet a minimum requirement. It is clear that manufacturing of prescribed surfaces is still far from reality. The use of artificial intelligence and multi-objective optimization may facilitate manufacturing of prescribed surfaces in future. Currently, there is no evidence of this technology, and the state-of-the-art of each reviewed system can be considered a trade-off between these two directions.

This study found that the current reported research is oriented towards:

- Increasing productivity in machining Inconel 718 through the adoption of higher cutting speeds and feed rates. This has been realized through new developments in cutting tool materials and coatings as well as enhanced cooling technologies [13, 155].
- Enhancing hydrodynamic lubrication at the cutting edge through developing new cooling media such as through the addition of solid lubricants [159, 160].
- Improving the heat removal at the cutting edge through turbulence-aimed cutting tool designs, geometries, and surface proprieties [111, 120].

- Introducing novel delivery methods such as through-the-tool and through-the-holder approaches to supply C&L closer to the machining area and improve reachability [158, 161].

Furthermore, the authors propose a number of research gaps and possible future research directions in Table 7 that may be explored, categorized under dry machining, HPC, cryogenic machining, and MQL.

Table 7 - Research gaps & future research directions.

	Potential research directions for machining Inconel 718
Dry machining	• Tools with enhanced thermal conductivity to preserve surface integrity and reduce residual stress in finishing conditions. • Tools shielded with low thermal conductivity coatings to increase machinability for roughing, when surface integrity is not a concern. • Composite tools to combine enhanced heat removal with high hot hardness where strength is needed. • Self-lubricating tools where the erosion of the coating releases solid lubricant preventing BUE formation. • Self-oxidizing lubricating coatings under enriched oxygen content which can improve lubrication at the cutting edge. • Internal cooling channels inside cutting tools to combine dry conditions with an enhanced cooling effect.
HPC	• Though-the-tool approaches and turbulence-aimed designs to increase reachability and cooling, respectively. • 3D-printing of integrated nozzles in toolholders and tool geometries aimed at improving the targeting of HPC jets in specific areas. • Cryogenically cooled emulsions.
Cryogenic machining	• Combination of cryogenic machining with MQL. • Micropatterning on cutting tools aimed at focalizing the cryogen on the cutting area through the Leiden frost effect. • Cooling both workpiece and cutting tool simultaneously to reduce thermal shocks at the cutting edge. • Adoption of high thermal conductivity tools to reduce the impact of thermal fluctuation on the cutting edge. • Studies on the thermal component of the fatigue cycle on the cutting edge.
MQL	• Combination of cryogenic machining with MQL. • Electrostatic application of MQL. • Oxygen control in the machining area aimed at improving tribological proprieties. • Numerical and experimental work based on the optimal positioning of the nozzles. • Bleeding tools where a porous surface close to the cutting edge releases lubricant from inside the tool without compromising the tool strength.

8 - CONCLUSIONS

In this paper, the machining induced surface integrity of Inconel 718 is investigated and categorized into 3 areas, namely, topological, metallurgical, and mechanical aspects. Novel cooling and lubricating technologies for machining of Inconel 718 are also presented and compared.

Generally, the technologies which present the following characteristics provide essential improvements in machining induced surface integrity of Inconel 718:

- Enhanced cooling;
- Tool wear reduction;
- Optimal configuration and positioning of the nozzles;
- Turbulence developed near the cutting edge;
- Reachability of the critical machining area.

The underlying cause for failure of cooling technologies in machining Inconel 718 was found to be related to the evaporation of the cutting fluid at the cutting zone. Whilst suppressing coolant evaporation is imperative to extend cooling efficiency, the state-of-the-art C&L highlighted that only the technologies based on high-pressure coolant have been explored.

This study identified that today, there is no technology capable of guaranteeing sustainability and productivity at the same time whilst meeting the surface integrity requirements of safety-critical components, with further work is required to develop sustainable alternatives.

Future research directions should focus on enhancing hydrodynamic lubrication at the cutting zone through developing new cooling-lubricating media, new delivery methods as well as cutting tool geometry and surface properties. In addition, the authors believe there is a significant need for increasing productivity in machining Inconel 718 through the adoption of higher cutting speeds and feed rates. This being realized through new developments in cutting tool materials and coatings as well as enhanced cooling technologies.

ACKNOWLEDGMENT

This paper is based on a collaboration between the University of Bath and Technische Universität Dortmund. The authors would like to acknowledge Elsevier for the permission of using Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 9, Fig. 10, and Fig. 11.

FUNDING

The research was supported by the University of Bath, United Kingdom. No conflict of interest exists for all participating authors.

NOMENCLATURE

BUE	Built-Up Edge
C&L	Cooling and Lubrication
DoC	Depth of Cut
FCC	Face-Centered Cubic
HPC	High-Pressure Cooling
MQL	Minimum Quantity Lubrication
PVD	Physical Vapor Deposition
SEM	Scanning Electron Microscope

REFERENCES

[1] D. Ulutan and T. Ozel, “Machining induced surface integrity in titanium and nickel alloys: A review,” Int. J. Mach. Tools Manuf., vol. 51, no. 3, pp. 250–280, 2011.

[2] D. Furrer and H. Fecht, “Ni-based superalloys for turbine discs,” JOM, vol. 51, no. 1, pp. 14–17, 1999.

[3] C. Slama and M. Abdellaoui, “Structural characterization of the aged Inconel 718,” J. Alloys Compd., vol. 306, no. 1–2, pp. 277–284, 2000.

[4] T. M. Pollock and S. Tin, “Nickel-Based Superalloys for Advanced Turbine Engines: Chemistry, Microstructure and Properties,” J. Propuls. Power, vol. 22, no. 2, pp. 361–374, 2006.

[5] F. Pusavec et al., “Sustainable machining of high temperature Nickel alloy - Inconel 718: Part 1 - Predictive performance models,” J. Clean. Prod., vol. 81, pp. 255–269, 2014.

[6] A. Devillez, G. Le Coz, S. Dominiak, and D. Dudzinski, “Dry machining of Inconel 718, workpiece surface integrity,” J. Mater. Process. Technol., vol. 211, no. 10, pp. 1590–1598, 2011.

[7] A. Thakur and S. Gangopadhyay, “State-of-the-art in surface integrity in machining of nickel-based super alloys,” Int. J. Mach. Tools Manuf., vol. 100, pp. 25–54, 2016.

[8] X. Liang, Z. Liu, and B. Wang, “State-of-the-art of surface integrity induced by tool wear effects in machining process of titanium and nickel alloys: A review,” Measurement, vol. 132, pp. 150–181, Jan. 2019.

[9] A. Shokrani, V. Dhokia, and S. T. Newman, “Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids,” Int. J. Mach. Tools Manuf., vol. 57, pp. 83–101, 2012.

[10] F. Pusavec, H. Hamdi, J. Kopac, and I. S. Jawahir, “Surface integrity in cryogenic machining of nickel based alloy - Inconel 718,” J. Mater. Process. Technol., vol. 211, no. 4, pp. 773–783, 2011.

[11] D. Dudzinski, A. Devillez, A. Moufki, D. Larrouquère, V. Zerrouki, and J. Vigneau, A review of developments towards dry and high speed machining of Inconel 718 alloy, vol. 44, no. 4. Pergamon, 2004, pp. 439–456.

[12] T. Kitagawa, A. Kubo, and K. Maekawa, “Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti-6Al-6V-2Sn,” Wear, vol. 202, no. 2, pp. 142–148, 1997.

[13] B. C. Behera, H. Alemayehu, S. Ghosh, and P. V. Rao, “A comparative study of recent lubri-coolant strategies for turning of Ni-based superalloy,” J. Manuf. Process., vol. 30, pp. 541–552, 2017.

[14] F. Akhavan Niaki and L. Mears, “A comprehensive study on the effects of tool wear on surface roughness, dimensional integrity and residual stress in turning IN718 hard-to-machine alloy,” J. Manuf. Process., vol. 30, pp. 268–280, 2017.

[15] F. Jafarian, H. Amirabadi, J. Sadri, and H. R. Banooie, “Simultaneous optimizing residual stress and surface roughness in turning of inconel718 superalloy,” Mater. Manuf. Process., vol. 29, no. 3, pp. 337–343, 2014.

[16] J. C. Outeiro, J. C. Pina, R. M’Saoubi, F. Pusavec, and I. S. Jawahir, “Analysis of residual stresses induced by dry turning of difficult-to-machine materials,” CIRP Ann. - Manuf. Technol., vol. 57, no. 1, pp. 77–80, 2008.

[17] I. O. for Standardization, International Standard ISO 3685: Tool-life Testing with Single-point Turning Tools. ISO, 1993.

[18] I. S. ISO, International Standard ISO 8688: Tool-life Testing in milling. 1989.

[19] I. A. Choudhury and M. A. El-Baradie, “Machinability of nickel-base super alloys: A general review,” J. Mater. Process. Technol., vol. 300, no. 3–4, pp. 278–284, 1998.

[20] E. O. Ezugwu, Z. M. Wang, and A. R. Machado, “The machinability of nickel-based alloys: a review,” J. Mater. Process. Technol., vol. 86, no. 1–3, pp. 1–16, 1999.

[21] R. Arunachalam and M. A. Mannan, “Machinability of Nickel-based high temperature alloys,” Mach. Sci. Technol., vol. 4, no. 1, pp. 127–168, 2000.

[22] E. O. Ezugwu, J. Bonney, and Y. Yamane, “An overview of the machinability of aeroengine alloys,” J. Mater. Process. Technol., vol. 134, no. 2, pp. 233–253, 2003.

[23] D. Zhu, X. Zhang, and H. Ding, “Tool wear characteristics in machining of nickel-based superalloys,” Int. J. Mach. Tools Manuf., vol. 64, pp. 60–77, 2013.

[24] T. Singh, P. Singh, J. S. Dureja, M. Dogra, H. Singh, and M. S. Bhatti, “A review of near dry machining/minimum quantity lubrication machining of difficult to machine alloys,” Int. J. Mach. Mach. Mater., vol. 18, no. 3, pp. 213–251, 2016.

[25] A. U. H. Mohsan, Z. Liu, and G. K. Padhy, “A review on the progress towards improvement in surface integrity of Inconel 718 under high pressure and flood cooling conditions,” Int. J. Adv. Manuf. Technol., vol. 91, no. 1–4, pp. 107–125, 2017.

[26] G. R. Thellaputta, P. S. Chandra, and C. S. P. Rao, “Machinability of Nickel Based Superalloys: A Review,” Mater. Today Proc., vol. 4, no. 2, pp. 3712–3721, 2017.

[27] B. Wang and Z. Liu, “Influences of tool structure , tool material and tool wear on machined surface integrity during turning and milling of titanium and nickel alloys : a review,” pp. 1925–1975, 2018.

[28] Special Metals, “Inconel alloy 718.” [Online]. Available: http://www.specialmetals.com/assets/smc/documents/inconel_alloy_718.pdf. [Accessed: 19-Mar-2018].

[29] H. K. D. H. Bhadeshia, “Nickel Based Superalloys,” Cambridge website, 2003. [Online]. Available: http://www.phase-trans.msm.cam.ac.uk/2003/Superalloys/superalloys.html. [Accessed: 19-Mar-2018].

[30] J. R. Davis and A. S. M. I. H. Committee, “ASM Specialty Handbook: Heat-Resistant Materials,” in ASM Specialty Handbook: Heat-Resistant Materials, 1997, p. 36.

[31] Sean Gribbin, Saeede Ghorbanpour, Nicholas C. Ferreri, Jonathan Bicknell, Igor Tsukrov, Marko Knezevic, “Role of grain structure, grain boundaries, crystallographic texture, precipitates, and porosity on fatigue behavior of Inconel 718 at room and elevated temperatures,” Mater. Charact., vol. 149, p. Pages 184-197, 2019.

[32] R. C. Reed, The Superalloys fundamentals and applications, vol. 9780521859. 2006.

[33] M. Sundararaman, P. Mukhopadhyay, and S. Banerjee, “Carbide Precipitation in Nickel Base Superalloys 718 and 625 and Their Effect on Mechanical Properties,” in Superalloys 718, 625, 706 and Various Derivatives (1997), 1997, pp. 367–378.

[34] J. Zhou, V. Bushlya, P. Avdovic, and J. E. Ståhl, “Study of surface quality in high speed turning of Inconel 718 with uncoated and coated CBN tools,” Int. J. Adv. Manuf. Technol., vol. 58, no. 1–4, pp. 141–151, 2012.

[35] S. Sui et al., “The influence of Laves phases on the room temperature tensile properties of Inconel 718 fabricated by powder feeding laser additive manufacturing,” Acta Mater., vol. 164, pp. 413–427, 2019.

[36] Z. Chen et al., “Nano-scale characterization of white layer in broached Inconel 718,” Mater. Sci. Eng. A, vol. 684, pp. 373–384, 2017.

[37] J. M. Zhou, V. Bushlya, R. L. Peng, S. Johansson, P. Avdovic, and J. E. Stahl, “Effects of tool wear on subsurface deformation of nickelbased superalloy,” Procedia Eng., vol. 19, pp. 407–413, 2011.

[38] J. L. Cantero, J. Díaz-Álvarez, M. H. Miguélez, and N. C. Marín, “Analysis of tool wear patterns in finishing turning of Inconel 718,” Wear, vol. 297, no. 1–2, pp. 885–894, 2013.

[39] P. Hoier, “Microstructural characteristics of Alloy 718 and Waspaloy and their influence on flank wear during turning,” To be Publ. Wear, vol. 400–401, no. September 2017, pp. 184–193, 2018.

[40] D. G. Thakur, B. Ramamoorthy, and L. Vijayaraghavan, “Machinability investigation of Inconel 718 in high-speed turning,” Int. J. Adv. Manuf. Technol., vol. 45, no. 5–6, pp. 421–429, 2009.

[41] M. A. Xavior, M. Manohar, P. Jeyapandiarajan, and P. M. Madhukar, “Tool Wear Assessment during Machining of Inconel 718,” Procedia Eng., vol. 174, pp. 1000–1008, 2017.

[42] S. A. Khan et al., “Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling,” Procedia CIRP, vol. 1, no. 1, pp. 283–288, 2012.

[43] W. Grzesik, P. Niesłony, W. Habrat, J. Sieniawski, and P. Laskowski, “Investigation of tool wear in the turning of Inconel 718 superalloy in terms of process performance and productivity enhancement,” Tribol. Int., vol. 118, no. September 2017, pp. 337–346, 2018.

[44] D. G. Thakur, B. Ramamoorthy, and L. Vijayaraghavan, “Study on the machinability characteristics of superalloy Inconel 718 during high speed turning,” Mater. Des., vol. 30, no. 5, pp. 1718–1725, 2009.

[45] A. Bhatt, H. Attia, R. Vargas, and V. Thomson, “Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718,” Tribol. Int., vol. 43, no. 5–6, pp. 1113–1121, 2010.

[46] J. P. P. Costes, Y. Guillet, G. Poulachon, and M. Dessoly, “Tool-life and wear mechanisms of CBN tools in machining of Inconel 718,” Int. J. Mach. Tools Manuf., vol. 47, no. 7–8, pp. 1081–1087, Jun. 2007.

[47] A. Altin, M. Nalbant, and A. Taskesen, “The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools,” Mater. Des., vol. 28, no. 9, pp. 2518–2522, 2007.

[48] M. Field and J. F. Kahles, “The Surface Integrity of Machined and Ground High Strength Steels.,” DMIC Rep., vol. 210, pp. 54–77, 1964.

[49] J. P. Davim, Surface integrity in machining. 2010.

[50] Y. H. Fan, Z. P. Hao, M. L. Zheng, F. L. Sun, and S. C. Yang, “Study of surface quality in machining nickel-based alloy Inconel 718,” Int. J. Adv. Manuf. Technol., vol. 69, no. 9–12, pp. 2659–2667, 2013.

[51] S. L. Soo et al., “High speed turning of Inconel 718 using PVD-coated PCBN tools,” CIRP Ann. - Manuf. Technol., vol. 65, no. 1, pp. 89–92, Jan. 2016.

[52] R. M. Arunachalam, M. A. Mannan, and A. C. Spowage, “Residual stress and surface roughness when facing age hardened Inconel 718 with CBN and ceramic cutting tools,” Int. J. Mach. Tools Manuf., vol. 44, no. 9, pp. 879–887, 2004.

[53] A. Madariaga, J. A. Esnaola, E. Fernandez, P. J. Arrazola, A. Garay, and F. Morel, “Analysis of residual stress and work-hardened profiles on Inconel 718 when face turning with large-nose radius tools,” Int. J. Adv. Manuf. Technol., vol. 71, no. 9–12, pp. 1587–1598, 2014.

[54] A. R. C. Sharman, J. I. Hughes, and K. Ridgway, “The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718???,” J. Mater. Process. Technol., vol. 216, pp. 123–132, 2015.

[55] D. Umbrello, “Investigation of surface integrity in dry machining of Inconel 718,” Int. J. Adv. Manuf. Technol., vol. 69, no. 9–12, pp. 2183–2190, 2013.

[56] a. R. C. C. Sharman, J. I. Hughes, and K. Ridgway, “Workpiece surface integrity and tool life issues when turning inconel 718TM nickel based superalloy,” Mach. Sci. Technol., vol. 8, no. 3, pp. 399–414, 2004.

[57] S. L. Soo, D. K. Aspinwall, and R. C. Dewes, “Three-dimensional finite element modelling of high-speed milling of Inconel 718,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 218, no. 11, pp. 1555–1561, 2004.

[58] D. M. D’Addona, S. J. Raykar, and M. M. Narke, “High Speed Machining of Inconel 718: Tool Wear and Surface Roughness Analysis,” Procedia CIRP, vol. 62, pp. 269–274, 2017.

[59] A. Shokrani, V. Dhokia, S. T. Newman, and R. Imani-Asrai, “An initial study of the effect of using liquid nitrogen coolant on the surface roughness of inconel 718 nickel-based alloy in CNC milling,” Procedia CIRP, vol. 3, no. 1, pp. 121–125, 2012.

[60] A. Iturbe, E. Hormaetxe, A. Garay, and P. J. Arrazola, “Surface Integrity Analysis when Machining Inconel 718 with Conventional and Cryogenic Cooling,” Procedia CIRP, vol. 45, no. Table 1, pp. 67–70, 2016.

[61] M. Nataraj, M. Ramamoorthy, and M. Pradeep Kumar, “Study on surface integrity of high speed turning of inconel 718 using taguchi DOE approach,” Int. J. Appl. Eng. Res., vol. 10, no. 2, pp. 4191–4200, 2015.

[62] P. C. Priarone, M. Robiglio, L. Settineri, and V. Tebaldo, “Modelling of specific energy requirements in machining as a function of tool and lubricoolant usage,” CIRP Ann. - Manuf. Technol., vol. 65, no. 1, pp. 25–28, 2016.

[63] I. Marinescu and D. Axinte, “A time-frequency acoustic emission-based monitoring technique to identify workpiece surface malfunctions in milling with multiple teeth cutting simultaneously,” Int. J. Mach. Tools Manuf., vol. 49, no. 1, pp. 53–65, 2009.

[64] I. Marinescu and D. A. Axinte, “A critical analysis of effectiveness of acoustic emission signals to detect tool and workpiece malfunctions in milling operations,” Int. J. Mach. Tools Manuf., vol. 48, no. 10, pp. 1148–1160, 2008.

[65] R. S. Pawade and S. S. Joshi, “Analysis of acoustic emission signals and surface integrity in the high-speed turning of Inconel 718,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 226, no. 1, pp. 3–27, 2012.

[66] C. Liu, C. Ren, G. Wang, Y. Yang, and L. Zhang, “Study on surface defects in milling Inconel 718 super alloy,” J. Mech. Sci. Technol., vol. 29, no. 4, pp. 1723–1730, 2015.

[67] J. M. Zhou, V. Bushlya, and J. E. Stahl, “An investigation of surface damage in the high speed turning of Inconel 718 with use of whisker reinforced ceramic tools,” J. Mater. Process. Technol., vol. 212, no. 2, pp. 372–384, 2012.

[68] R. M’Saoubi et al., “Surface integrity analysis of machined Inconel 718 over multiple length scales,” CIRP Ann. - Manuf. Technol., vol. 61, no. 1, pp. 99–102, Jan. 2012.

[69] H. S. Ranganath S, Guo C, “Experimental investigations into the carbide cracking phenomenon on Inconel 718 superalloy material,” Int. Manuf. Sci. Eng. Conf., vol. 2, pp. 33–39, 2009.

[70] V. Bushlya, J. M. Zhou, F. Lenrick, P. Avdovic, and J. E. Ståhlan, “Characterization of white layer generated when turning aged inconel 718,” Procedia Eng., vol. 19, pp. 60–66, 2011.

[71] R. M’Saoubi, D. Axinte, C. Herbert, M. Hardy, and P. Salmon, “Surface integrity of nickel-based alloys subjected to severe plastic deformation by abusive drilling,” CIRP Ann. - Manuf. Technol., vol. 63, no. 1, pp. 61–64, 2014.

[72] W. Li, Y. B. B. Guo, M. E. E. Barkey, and J. B. B. Jordon, “Effect tool wear during end milling on the surface integrity and fatigue life of inconel 718,” Procedia CIRP, vol. 14, pp. 546–551, 2014.

[73] E. A. Rahim and H. Sasahara, “An analysis of surface integrity when drilling inconel 718 using palm oil and synthetic ester under MQL condition,” Mach. Sci. Technol., vol. 15, no. 1, pp. 76–90, 2011.

[74] J. A. Sanchez et al., “Machining evaluation of a hybrid MQL-CO2grinding technology,” J. Clean. Prod., vol. 18, no. 18, pp. 1840–1849, 2010.

[75] A. R. C. R. C. C. Sharman, J. I. I. Hughes, and K. Ridgway, “An analysis of the residual stresses generated in Inconel 718 when turning,” J. Mater. Process. Technol., vol. 173, no. 3, pp. 359–367, Apr. 2006.

[76] C. H. Che-Haron and A. Jawaid, “The effect of machining on surface integrity of titanium alloy Ti-6% Al-4% v,” J. Mater. Process. Technol., vol. 166, no. 2, pp. 188–192, 2005.

[77] A. Ginting and M. Nouari, “Surface integrity of dry machined titanium alloys,” Int. J. Mach. Tools Manuf., vol. 49, no. 3–4, pp. 325–332, 2009.

[78] A. W. Warren and Y. B. Guo, “On the clarification of surface hardening by hard turning and grinding,” Trans North Am Manuf Res Inst SME, vol. 34, no. April, pp. 309–316, 2006.

[79] A. A. Farid et al., “Effect of Machining Parameters and Cutting Edge Geometry on Surface Integrity when Drilling and Hole Making in Inconel 718,” SAE Int. J. Mater. Manuf., vol. 2, no. 1, pp. 564–569, 2008.

[80] P. J. Withers and H. K. D. H. Bhadeshia, “Residual stress. Part 1–measurement techniques,” Mater. Sci. Technol., vol. 17, no. April, pp. 355–365, 2001.

[81] R. L. Peng, J. Zhou, S. Johansson, A. Billenius, V. Bushlya, and J.-E. Stahl, “Surface Integrity and the Influence of Tool Wear in High Speed Machining of Inconel 718,” 13th Int. Conf. Fract., pp. 1–10, 2013.

[82] J. Zhou, V. Bushlya, R. L. Peng, Z. Chen, S. Johansson, and J. E. Stahl, “Analysis of subsurface microstructure and residual stresses in machined Inconel 718 with PCBN and Al2O3-SiCwtools,” Procedia CIRP, vol. 13, pp. 150–155, Jan. 2014.

[83] R. M. M. Arunachalam, M. A. A. Mannan, and A. C. C. Spowage, “Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools,” Int. J. Mach. Tools Manuf., vol. 44, no. 14, pp. 1481–1491, Nov. 2004.

[84] V. Bushlya, J. Zhou, and J. E. Ståhl, “Effect of cutting conditions on machinability of superalloy inconel 718 during high speed turning with coated and uncoated PCBN tools,” Procedia CIRP, vol. 3, no. 1, pp. 370–375, 2012.

[85] R. T. Coelho, L. R. Silva, A. Braghini, and A. A. Bezerra, “Some effects of cutting edge preparation and geometric modifications when turning INCONEL 718TM at high cutting speeds,” J. Mater. Process. Technol., vol. 148, no. 1, pp. 147–153, 2004.

[86] A. Madariaga, A. Kortabarria, E. Hormaetxe, A. Garay, and P. J. Arrazola, “Influence of Tool Wear on Residual Stresses When Turning Inconel 718,” Procedia CIRP, vol. 45, pp. 267–270, 2016.

[87] Z. Huang, S. He, Z. Kejia, X. Zhang, and H. Ding, “An Analysis of Cutting Parameters, Coated Materials and Nose Radii on Residual Stresses When Turning Inconel 718,” Procedia CIRP, vol. 46, pp. 368–371, 2016.

[88] F. Jafarian, “3D modeling of recrystallized layer depth and residual stress in dry machining of nickel - based alloy,” J. Brazilian Soc. Mech. Sci. Eng., vol. 41, no. 4, pp. 1–10, 2019.

[89] Z. Chen et al., “Analysis of thermal effect on residual stresses of broached Inconel 718,” Adv. Mater. Res., vol. 996, pp. 574–579, 2014.

[90] J. F. Archard, W. Hirst, and T. E. Allibone, “The wear of metals under unlubricated conditions,” Proc. R. Soc. London. Ser. A. Math. Phys. Sci., vol. 236, no. 1206, pp. 397–410, 1956.

[91] M. C. Shaw, Metal cutting principles: Chapter 3, no. 5. 2005.

[92] F. Pusavec, P. Krajnik, and J. Kopac, “Transitioning to sustainable production - Part I: application on machining technologies,” J. Clean. Prod., vol. 18, no. 2, pp. 174–184, 2010.

[93] F. Klocke and G. Eisenblätter, “Dry Cutting,” CIRP Ann., vol. 46, no. 2, pp. 519–526, Jan. 1997.

[94] A. Kortabarria, A. Madariaga, E. Fernandez, J.a. Esnaola, and P. J. Arrazola, “A comparative study of residual stress profiles on inconel 718 induced by dry face turning,” Procedia Eng., vol. 19, pp. 228–234, 2011.

[95] Y. Fan, Z. Hao, J. Lin, and Z. Yu, “New observations on tool wear mechanism in machining Inconel 718 under water vapor + air cooling lubrication cutting conditions,” J. Clean. Prod., vol. 90, pp. 381–387, 2015.

[96] R. Ramanujam, K. Venkatesan, V. Saxena, and P. Joseph, “Modeling and Optimization of Cutting Parameters in Dry Turning of Inconel 718 Using Coated Carbide Inserts,” Procedia Mater. Sci., vol. 5, pp. 2550–2559, 2014.

[97] M. Nalbant, A. Altin, and H. Gökkaya, “The effect of coating material and geometry of cutting tool and cutting speed on machinability properties of Inconel 718 super alloys,” Mater. Des., vol. 28, no. 5, pp. 1719–1724, 2007.

[98] L. Li, N. He, M. Wang, and Z. . G. Wang, “High speed cutting of Inconel 718 with coated carbide and ceramic inserts,” J. Mater. Process. Technol., vol. 129, no. 1–3, pp. 127–130, Oct. 2002.

[99] R. S. S. Pawade, S. S. Joshi, P. K. K. Brahmankar, and M. Rahman, “An investigation of cutting forces and surface damage in high-speed turning of Inconel 718,” J. Mater. Process. Technol., vol. 192–193, pp. 139–146, Oct. 2007.

[100] U. S. Dixit, D. K. Sarma, and J. P. Davim, Green manufacturing, no. 9781461423072. 2012.

[101] Rocol, “Cutting fluids - ULTRACUT® 320 technical data.” [Online]. Available: https://www.rocol.com/products/ultracut320-ep-cutting-grinding-fluid. [Accessed: 28-May-2020].

[102] Morris Lubricants, “SUPERCUT 1000 product information.” [Online]. Available: https://www.morrislubricants.co.uk/products/237_5dcbd32fb8f33.pdf. [Accessed: 28-May-2020].

[103] Milacron, “Waterbased Metalworking Fluids: Proper Mixing Practices.” [Online]. Available: https://www.milacron.com/proper-mixing-practices/. [Accessed: 28-May-2020].

[104] A. B. Sadat, “Surface region damage of machined inconel-718 nickel-base superalloy using natural and controlled contact length tools,” vol. 119, pp. 225–235, 1987.

[105] T. Kitagawa, A. Kubo, K. Maekawa, T. Kitagawa, A. Kubo, and K. Maekawa, “Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti-6A1-6V-2Sn,” Wear, vol. 202, no. 2, pp. 142–148, 1997.

[106] G. Kadam and R. Pawade, “Influence of Machining Environment on Surface Integrity in HSM of Inconel 718 with Productivity Perspective,” vol. 137, pp. 89–93, 2017.

[107] N. Tamil Alagan, P. Hoier, P. Zeman, U. Klement, T. Beno, and A. Wretland, “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, vol. 434–435, p. 102922, 2019.

[108] S. Y. Hong and Z. Zhao, “Thermal aspects, material considerations and cooling strategies in cryogenic machining,” Clean Technol. Environ. Policy, vol. 1, no. 2, pp. 107–116, 1999.

[109] K. M. C. Öjmertz and H. B. Oskarson, “Wear on sic-whiskers reinforced ceramic inserts when cutting inconel with waterjet assistance,” Tribol. Trans., vol. 42, no. 3, pp. 471–478, 1999.

[110] R. Polvorosa, A. Suárez, L. N. L. de Lacalle, I. Cerrillo, A. Wretland, and F. Veiga, “Tool wear on nickel alloys with different coolant pressures: Comparison of Alloy 718 and Waspaloy,” J. Manuf. Process., vol. 26, pp. 44–56, 2017.

[111] Z. Fang and T. Obikawa, “Turning of Inconel 718 using inserts with cooling channels under high pressure jet coolant assistance,” J. Mater. Process. Technol., vol. 247, no. March, pp. 19–28, 2017.

[112] K. Busch, C. Hochmuth, B. Pause, A. Stoll, and R. Wertheim, “Investigation of Cooling and Lubrication Strategies for Machining High-temperature Alloys,” Procedia CIRP, vol. 41, pp. 835–840, 2016.

[113] E. O. O. Ezugwu and J. Bonney, “Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools,” J. Mater. Process. Technol., vol. 153–154, no. 1–3, pp. 1045–1050, Nov. 2004.

[114] S. Raykar and U. Dabade, “Optimization of High Pressure Coolant Assisted Turning of Inconel 718 using TOPSIS,” vol. 137, no. 1, pp. 113–120, 2017.

[115] C. Courbon, D. Kramar, P. Krajnik, F. Pusavec, J. Rech, and J. Kopac, “Investigation of machining performance in high-pressure jet assisted turning of Inconel 718: An experimental study,” Int. J. Mach. Tools Manuf., vol. 49, no. 14, pp. 1114–1125, 2009.

[116] P. Hoier, U. Klement, N. Tamil Alagan, T. Beno, and A. Wretland, “Flank wear characteristics of WC-Co tools when turning Alloy 718 with high-pressure coolant supply,” J. Manuf. Process., vol. 30, pp. 116–123, 2017.

[117] A. R. C. Sharman, J. I. Hughes, and K. Ridgway, “Surface integrity and tool life when turning Inconel 718 using ultra-high pressure and flood coolant systems,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 222, no. 6, pp. 653–664, 2008.

[118] E. O. Ezugwu, J. Bonney, D. A. Fadare, and 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., vol. 162–163, no. SPEC. ISS., pp. 609–614, 2005.

[119] Z. Vagnorius and K. Sørby, “Effect of high-pressure cooling on life of SiAlON tools in machining of Inconel 718,” Int. J. Adv. Manuf. Technol., vol. 54, no. 1–4, pp. 83–92, 2011.

[120] Z. Fang and T. Obikawa, “Cooling performance of micro-texture at the tool flank face under high pressure jet coolant assistance,” Precis. Eng., vol. 49, pp. 41–51, 2017.

[121] T. Lv, S. Huang, X. Hu, Y. Ma, and X. Xu, “Tribological and machining characteristics of a minimum quantity lubrication (MQL) technology using GO/SiO2hybrid nanoparticle water-based lubricants as cutting fluids,” Int. J. Adv. Manuf. Technol., vol. 96, no. 5–8, pp. 2931–2942, 2018.

[122] M. Z. A. Yazid, G. A. Ibrahim, A. Y. M. Said, C. H. CheHaron, and J. A. Ghani, “Surface integrity of Inconel 718 when finish turning with PVD coated carbide tool under MQL,” Procedia Eng., vol. 19, pp. 396–401, 2011.

[123] S. Thamizhmanii, S. Hasan, and R. S. Hasan, “A study of minimum quantity lubrication on Inconel 718 steel,” Arch. Mater. Sci. Eng., vol. 39, no. 1, pp. 38–44, 2009.

[124] T. Obikawa, Y. Kamata, Y. Asano, K. Nakayama, and A. W. Otieno, “Micro-liter lubrication machining of Inconel 718,” Int. J. Mach. Tools Manuf., vol. 48, no. 15, pp. 1605–1612, 2008.

[125] Y. Kamata and T. Obikawa, “High speed MQL finish-turning of Inconel 718 with different coated tools,” J. Mater. Process. Technol., vol. 192–193, pp. 281–286, 2007.

[126] A. Marques, C. Guimaraes, R. B. da Silva, M. da Penha Cindra Fonseca, W. F. Sales, and Alisson Rocha Machado, “Surface Integrity Analysis of Inconel 718 after Turning with Different Solid Lubricants Dispersed in Neat Oil Delivered by MQL,” Procedia Manuf., vol. 5, pp. 609–620, 2016.

[127] U. M. R. Paturi, Y. R. Maddu, R. R. Maruri, and S. K. R. Narala, “Measurement and Analysis of Surface Roughness in WS2 Solid Lubricant Assisted Minimum Quantity Lubrication (MQL) Turning of Inconel 718,” Procedia CIRP, vol. 40, pp. 138–143, 2016.

[128] M. A. M. Ali, A. N. M. Khalil, A. I. Azmi, and H. M. Salleh, “Optimization of Cutting Parameters for Surface Roughness under MQL, using Al 2 O 3 Nanolubricant, during Turning of Inconel 718,” IOP Conf. Ser. Mater. Sci. Eng., vol. 226, p. 012067, 2017.

[129] Y. S. Liao, C. H. Liao, and H. M. Lin, “Study of oil-water ratio and flow rate of MQL fluid in high speed milling of Inconel 718,” Int. J. Precis. Eng. Manuf., vol. 18, no. 2, pp. 257–262, 2017.

[130] S. Zhang, J. F. Li, and Y. W. Wang, “Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions,” J. Clean. Prod., vol. 32, pp. 81–87, 2012.

[131] K. H. Park, J. Olortegui-Yume, M. C. Yoon, and P. Kwon, “A study on droplets and their distribution for minimum quantity lubrication (MQL),” Int. J. Mach. Tools Manuf., vol. 50, no. 9, pp. 824–833, 2010.

[132] A. Shokrani, V. Dhokia, P. Muñoz-Escalona, and S. T. Newman, “State-of-the-art cryogenic machining and processing,” Int. J. Comput. Integr. Manuf., vol. 26, no. 7, pp. 616–648, 2013.

[133] Z. Y. Wang, K. P. Rajurkar, J. Fan, S. Lei, Y. C. Shin, and G. Petrescu, “Hybrid machining of Inconel 718,” Int. J. Mach. Tools Manuf., vol. 43, no. 13, pp. 1391–1396, 2003.

[134] F. Pusavec et al., “Sustainable machining of high temperature Nickel alloy - Inconel 718: Part 2 - Chip breakability and optimization,” J. Clean. Prod., vol. 87, no. 1, pp. 941–952, 2015.

[135] A. Bagherzadeh and E. Budak, “Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach,” Tribol. Int., vol. 119, pp. 510–520, 2018.

[136] J. Kenda, F. Pusavec, and J. Kopac, “Analysis of Residual Stresses in Sustainable Cryogenic Machining of Nickel Based Alloy—Inconel 718,” J. Manuf. Sci. Eng., vol. 133, no. 4, p. 041009, 2011.

[137] M. Hribersek, V. Sajn, F. Pusavec, J. Rech, and J. Kopac, “The Procedure of Solving the Inverse Problem for Determining Surface Heat Transfer Coefficient between Liquefied Nitrogen and Inconel 718 Workpiece in Cryogenic Machining,” Procedia CIRP, vol. 58, pp. 617–622, 2017.

[138] V. Tebaldo, G. G. di Confiengo, and M. G. Faga, “Sustainability in machining: ‘Eco-friendly’ turning of Inconel 718. Surface characterisation and economic analysis,” J. Clean. Prod., vol. 140, pp. 1567–1577, 2017.

[139] Y. Kaynak, “Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining,” Int. J. Adv. Manuf. Technol., vol. 72, no. 5–8, pp. 919–933, 2014.

[140] M. Hribersek, F. Pusavec, J. Rech, and J. Kopac, “Modeling of machined surface characteristics in cryogenic orthogonal turning of Inconel 718,” Mach. Sci. Technol., vol. 0, no. 0, pp. 1–22, 2018.

[141] A. Devillez, F. Schneider, S. Dominiak, D. Dudzinski, and D. Larrouquere, “Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools,” Wear, vol. 262, no. 7–8, pp. 931–942, Mar. 2007.

[142] C. Courbon, F. Pusavec, F. Dumont, J. Rech, and J. Kopac, “Tribological behaviour of Ti6Al4V and Inconel718 under dry and cryogenic conditions - Application to the context of machining with carbide tools,” Tribol. Int., vol. 66, pp. 72–82, 2013.

[143] N. Uçak and A. Çiçek, “The effects of cutting conditions on cutting temperature and hole quality in drilling of Inconel 718 using solid carbide drills,” J. Manuf. Process., vol. 31, pp. 662–673, 2018.

[144] A. H. Musfirah, J. A. Ghani, and C. H. C. Haron, “Tool wear and surface integrity of inconel 718 in dry and cryogenic coolant at high cutting speed,” Wear, vol. 376–377, pp. 125–133, 2017.

[145] Irfan Ucun, K. Aslantas, and F. Bedir, “An experimental investigation of the effect of coating material on tool wear in micro milling of Inconel 718 super alloy,” Wear, vol. 300, no. 1–2, pp. 8–19, 2013.

[146] A. Thakur and S. Gangopadhyay, “Dry machining of nickel-based super alloy as a sustainable alternative using TiN/TiAlN coated tool,” J. Clean. Prod., vol. 129, pp. 256–268, 2016.

[147] A. Shokrani, V. Dhokia, and S. T. Newman, “Hybrid Cooling and Lubricating Technology for CNC Milling of Inconel 718 Nickel Alloy,” Procedia Manuf., vol. 11, pp. 625–632, 2017.

[148] S. Kumar, D. Singh, and N. S. Kalsi, “Experimental Investigations of Surface Roughness of Inconel 718 under different Machining Conditions,” Mater. Today Proc., vol. 4, no. 2, pp. 1179–1185, 2017.

[149] N. Khanna, C. Agrawal, M. K. Gupta, and Q. Song, “Tool wear and hole quality evaluation in cryogenic drilling of Inconel 718 superalloy,” Tribol. Int., vol. 143, no. October 2019, 2020.

[150] G. de Paula Oliveira, M. Cindra Fonseca, and A. C. Araujo, “Analysis of residual stress and cutting force in end milling of Inconel 718 using conventional flood cooling and minimum quantity lubrication,” Int. J. Adv. Manuf. Technol., vol. 92, no. 9–12, pp. 3265–3272, 2017.

[151] Y. V. Deshpande, A. B. Andhare, and P. M. Padole, “Experimental results on the performance of cryogenic treatment of tool and minimum quantity lubrication for machinability improvement in the turning of Inconel 718,” J. Brazilian Soc. Mech. Sci. Eng., vol. 40, no. 1, p. 6, 2018.

[152] A. De Bartolomeis, S. T. Newman, and A. Shokrani, “Initial investigation on Surface Integrity when Machining Inconel 718 with Conventional and Electrostatic Lubrication,” Procedia CIRP, vol. 87, pp. 65–70, 2020.

[153] V. S. Sharma, M. Dogra, and N. M. Suri, “Cooling techniques for improved productivity in turning,” Int. J. Mach. Tools Manuf., vol. 49, no. 6, pp. 435–453, 2009.

[154] O. Çolak, “Investigation on machining performance of Inconel 718 under high pressure cooling conditions,” Stroj. Vestnik/Journal Mech. Eng., vol. 58, no. 11, pp. 683–690, 2012.

[155] A. Çelik, M. Sert Alağaç, S. Turan, A. Kara, and F. Kara, “Wear behavior of solid SiAlON milling tools during high speed milling of Inconel 718,” Wear, vol. 378–379, pp. 58–67, May 2017.

[156] Z. Y. Liu, C. Li, X. Y. Fang, and Y. B. Guo, “Cumulative Energy Demand and Environmental Impact in Sustainable Machining of Inconel Superalloy,” J. Clean. Prod., 2018.

[157] I. S. Jawahir et al., “Cryogenic manufacturing processes,” CIRP Ann., vol. 65, no. 2, pp. 713–736, Jan. 2016.

[158] E. Oezkaya, N. Beer, and D. Biermann, “Experimental studies and CFD simulation of the internal cooling conditions when drilling Inconel 718,” Int. J. Mach. Tools Manuf., vol. 108, no. June, pp. 52–65, 2016.

[159] C. Darshan, S. Jain, M. Dogra, M. K. Gupta, M. Mia, and R. Haque, “Influence of dry and solid lubricant-assisted MQL cooling conditions on the machinability of Inconel 718 alloy with textured tool,” Int. J. Adv. Manuf. Technol., vol. 105, no. 5–6, p. 1851, 2019.

[160] A. Marques, M. Paipa Suarez, W. Falco Sales, and Á. Rocha Machado, “Turning of Inconel 718 with whisker-reinforced ceramic tools applying vegetable-based cutting fluid mixed with solid lubricants by MQL,” J. Mater. Process. Technol., vol. 266, no. August 2018, pp. 530–543, 2019.

[161] O. Pereira et al., “Internal cryolubrication approach for Inconel 718 milling,” Procedia Manuf., vol. 13, pp. 89–93, Jan. 2017.

Figure Captions List

Fig. 10 Delivery directions in cryogenic machining: workpiece cooling (A), rake face cooling (B) and flank face cooling (C) [5]

Fig. 11 Specific energy consumption in turning Inconel 718 (v_c = 75 m/min, f = 0.1 mm/rev, a_p = 1.5 mm) [112]

Fig. 12 Radar chart describing the comparison between different C&L technologies in machining Inconel 718 together with weighting matrix.

Table Caption List