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Future research directions in the machining of Inconel 718

Andrea De Bartolomeis[a], Stephen T Newman[a], I S Jawahir[b],
Dirk Biermann[c] , Alborz Shokrani[a,*]

[a]*Department of Mechanical Engineering, University of Bath, Convocation Avenue, Bath BA2 7AY, United Kingdom*
[b]*Department of Mechanical Engineering, and Institute for Sustainable Manufacturing, University of Kentucky, Lexington, KY, USA*
[c]*Institute of Machining Technology (ISF), Baroper Strasse 303, Technische Universität Dortmund, 44227 Dortmund, Germany*

* Corresponding author. Tel.: +44 1225 386588. E-mail address: A.Shokrani@bath.ac.uk

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Abstract

Inconel 718 is the most popular nickel-based superalloy, extensively used in aerospace, automotive and energy industries owing to its extraordinary thermomechanical properties. It is also notoriously a difficult-to-cut material, due to its short tool life and low productivity in machining operations. Despite significant progress in cutting tool technologies, the machining of Inconel 718 is still considered a grand challenge.

This paper provides a comprehensive review of recent advances in machining Inconel 718. The progress in cutting tools' materials, coatings, geometries and surface texturing for machining Inconel 718 is reviewed. The investigation is focused on the most adopted tool materials for machining of Inconel 718, namely Cubic Boron Nitrides (CBNs), ceramics and coated carbides. The thermal conductivity of cutting tool materials has been identified as a major parameter of interest. Process control, based on sensor data for monitoring the machining of Inconel 718 alloy and detecting surface anomalies and tool wear are reviewed and discussed. This has been identified as the major step towards realising real-time control for machining safety critical Inconel 718 components. Recent advances in various processes, e.g. turning, milling and drilling for machining Inconel 718 are investigated and discussed. Recent studies related to machining additively manufactured Inconel 718 are also discussed and compared with the wrought alloy. Finally, the state of current research is established, and future research directions proposed.

Keywords: Machining, Inconel 718, cutting tools, sensors, tool geometries, tool materials.

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1 - Introduction

The global market for commercial aircraft engines has been estimated by Mazareanu (2021) at over $80 billion in 2021. Inconel 718 forms over 50% by weight of aircraft engines as reported by Ulutan and Ozel (2011). Pulidindi and Prakash (2020) found that Inconel 718 has over 54% of the nickel superalloy market share equivalent to over $4 billion in 2019, making it by far the largest nickel superalloy used globally.

Inconel 718 is a precipitation strengthened alloy of nickel that can maintain a large portion of its mechanical properties at elevated temperatures up to 650 °C. It also contains chromium and iron as well as traces of niobium, molybdenum, titanium and aluminium. These alloying elements are dispersed through the nickel γ matrix with a face centred cubic (FCC) lattice structure as explained by Davis and Committee (1997). They develop the main strengthening phases γ′ and γ″ with FCC and body centred tetragonal (BCT) lattice structures, respectively. The reinforcement by the BCT structure of Ni_3Nb γ″ precipitate in Inconel distinguishes this alloy from other nickel alloys (Hong et al., 2001). Zhang et al. (2020) explained that the large lattice misfit between the γ″ and γ enables the strain hardening properties of Inconel 718. The final metallurgical structure also presents a significant amount of hard carbides such as TiC and NbC, which inhibit dislocations and are also responsible for the high abrasive behaviour during machining, as observed by Zhou et al. (2012). Such carbides in combination with low thermal conductivity make the machining of Inconel 718 arduous.

Inconel 718 have exceptional fatigue endurance up to 650 °C, high hot hardness and the ability to maintain a large portion of its mechanical properties at elevated temperatures (Thakur and Gangopadhyay, 2016). The superalloy is extensively used where high mechanical performance at high-temperatures are required. Example applications are inside gas turbines, jet engines, manifolds in aerospace industries and rotor shafts, as well as holders in the oil and gas industries. It has also found applications in the automotive industry due to its desirable thermomechanical proprieties.

Inconel 718 is also known as one of the most difficult-to-cut materials. The major issues in machining Inconel 718 are the generation of high cutting forces and temperatures, as extensively discussed by Liang et al. (2019). Agmell et al. (2020) estimated mechanical stresses on the cutting tool can peak at 450 MPa and cutting temperatures reaching over 1100 °C. These issues result in short tool life and high manufacturing costs. In order to minimise cutting forces and temperatures, low cutting speeds and feed rates are generally used, leading to low productivity (De Bartolomeis et al., 2021). Inconel 718 is used for producing safety-critical components where the condition of the machined surface is of particular importance. Poor surface integrity can result in part rejection or failure in service (Thakur and Gangopadhyay, 2016). Therefore, the machining of Inconel 718 is not only associated with low cutting speeds but cutting tools are discarded much before reaching the end of tool life to prevent tool wear induced surface and subsurface damage.

Inconel 718 has similar alloying elements of different percentages to other nickel-based alloys such as Waspaloy, Udimet, Astroloy, Haynes and Hastelloy which are also considered difficult-to-cut materials. The common behaviour in terms of short tool life and high cutting forces stems from their high material strength and low thermal conductivity. However, Mignanelli et al. (2017) identified that Inconel 718 consists of different percentage of constituent phases (≈ 3% γ′ and ≈ 20% γ″) and has different thermomechanical properties. Specifically, Inconel 718 has lower thermal conductivity and higher tensile strength than majority of these alloys which can lead to higher tool wear in machining. Given the importance of Inconel 718 and its wide use, significant work has been dedicated to reviewing different aspects of machining this alloy. Dudzinski et al. (2004) reviewed the impact of machining on the surface integrity of

Inconel 718. Pusavec et al. (2011) and De Bartolomeis et al. (2021) reviewed the recent advances in various cooling/lubrication technologies such as flood, minimum quantity lubrication (MQL), dry, cryogenic and high-pressure coolant (HPC) in machining Inconel 718. Moshan et al. (2017) reviewed water-based cutting fluids application with regard to their effect on Inconel 718 surface integrity and machinability. Yin et al. (2020) reviewed the machinability of Inconel 718 in terms of cutting force, specific energy and tool wear, discussing how the chemical composition and microstructure of Inconel 718 affect surface integrity.

Despite these, the differences between various processes when machining Inconel 718 have been overlooked. The majority of papers are concentrated on turning Inconel 718, with lack of emphasis on milling and drilling. There is also a very limited number of investigations on the advances in cutting tool materials, geometries and surface texturing and their impact on machining Inconel 718.

This paper investigates the recent advances in cutting tool technologies for machining Inconel 718 focusing on cutting tool materials, geometries and surface texturing. In addition, the application of sensor based data collection for monitoring machining and detecting tool wear and surface anomalies in machining Inconel 718 is reviewed. The machining behaviour of Inconel 718 alloy is also investigated for different machining processes, namely, turning, milling and drilling. The work is extended to investigate the behaviour of additively manufactured Inconel 718 and its comparison with the wrought alloy. Finally, a comprehensive discussion related to the machining of Inconel 718 is provided together with proposed future research directions. The structure of this paper is illustrated in Fig.1.

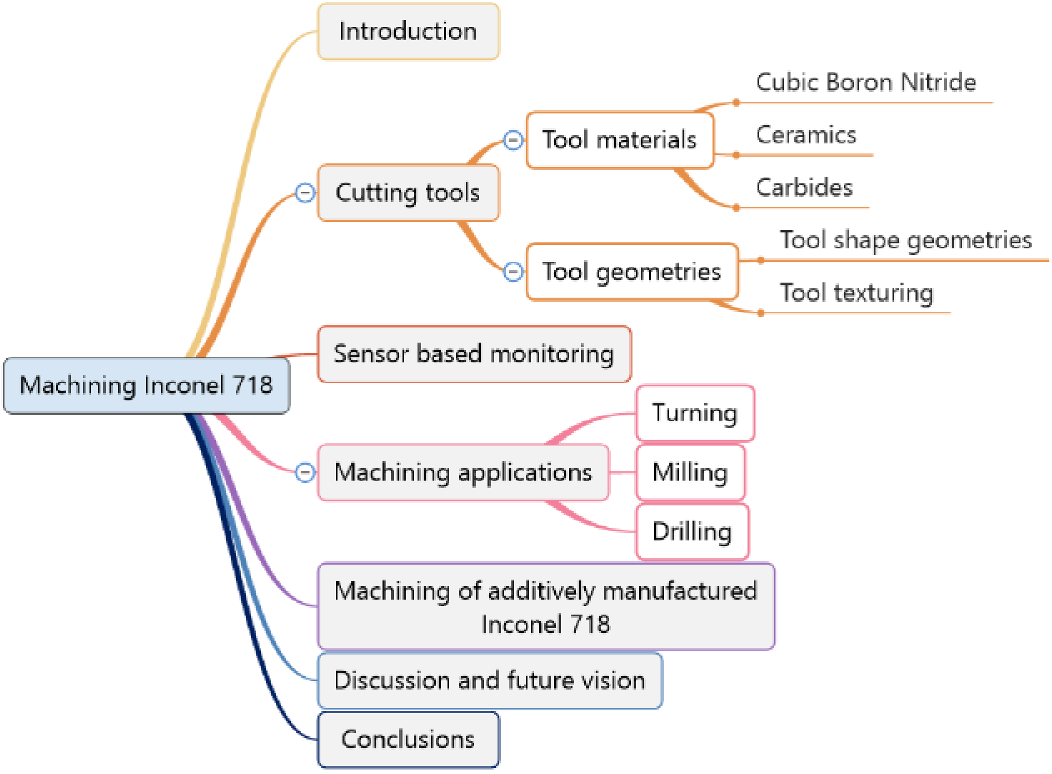

Fig. 1 - Paper structure

2 - Cutting tools for machining Inconel 718

Klocke and Kuchle (2011) stated that the ideal cutting tool for machining is expected to have high hardness, toughness, material strength and is chemically inert. It needs to withstand cyclic mechanical and thermal loads and maintain edge sharpness. In practice, such a cutting tool does not exist. Material and geometries of the cutting tools have been found to have a significant effect on the machining performance of Inconel 718. The optimum combination of geometry and thermo-mechanical properties can guarantee the performance of machining. In this section, recent advances in cutting tool materials and geometries for machining Inconel 718 are presented.

2.1 Materials for cutting tools

The interaction between cutting tool material and workpiece has been considered a primary concern during machining applications. The choice of cutting tool material can significantly influence the machining performance and surface integrity, increase productivity and optimal cutting speed.

According to Dudzinski et al. (2004), the five major tool material proprieties desired for cutting Inconel 718 that has been widely recognised are: (i) high hot hardness; (ii) high strength and toughness; (iii) high thermo-chemical stability; (iv) high wear resistance; and (v) high thermal shock resistance. Shokrani et al. (2012a) also stated that the majority of these material properties are affected by temperature. In machining, a large portion of the external work transforms into thermal energy at the cutting zone, whihech can result in workpiece softening and thus enhancing machinability. However, according to Astakhov (2013), most of the thermal energy is transported by the chip, and just a small amount is conducted to the workpiece, making thermal softening difficult to achieve. Inconel 718 has been designed to resist thermal softening up to 750 °C, as reported by Leshock et al. (2001). Therefore, thermally-sensitive materials such as ceramic metals (cermets), diamond and high-speed steel are unable to meet these requirements. According to Wang and Liu (2018), diamond is not recommended due to the chemical compatibility with Nickel, whilst HSS has low hot hardness. Therefore, the materials adopted for machining Inconel 718 are limited to three families of (i) CBNs, (ii) ceramics and (iii) carbides.

As shown in Fig. 2, Sreejith and Ngoi (2000) reported that CBN tools present the highest value of hardness, followed by ceramics and carbides. Whilst the hardness for the cutting tools reduces by increasing temperature; Liao et al. (2008) noted that the hardness of the γ′ structure of Inconel 718 increases with increasing temperature from ambient to about 700 °C. In the literature, the hot hardness of the γ′ structure is usually referred to as the hot hardness of the Inconel 718 without considering the other metallurgical structures. However, Bruker Nano Surfaces (2016, 2021) confirmed that hot hardness of Inconel 718 follows a similar behaviour.

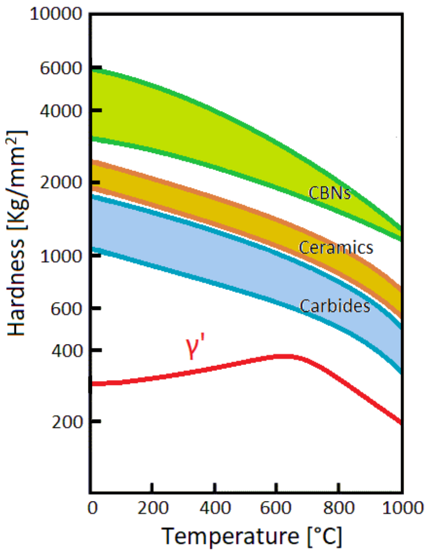

Fig. 2 - Hot hardness characteristic curve of CBN, Ceramic and Carbide tool materials (Sreejith and Ngoi, 2000) *compared with the γ′ structure of Inconel 718* (Liao et al., 2008)

Material hardness ensures that cutting tools can withstand abrasion during the cutting process. High toughness is required to prevent tool fracture, specifically in milling and drilling processes. Materials with enhanced hot hardness are usually associated with low toughness and vice versa. Similar to other difficult-to-cut materials, finish machining Inconel 718 requires cutting tools with high hardness. Therefore, whilst CBNs are more appropriate at high cutting speeds and finishing applications using stable and low vibration machine tools, straight carbides with high cobalt content are more suitable for heavy interrupted and roughing applications. On the other hand, Ezugwu et al. (2003) reported that mixed carbides can be used for finishing conditions as they contain metal carbides such as TiC and Ta(NbC) to increase their hardness replacing the softer cobalt binder.

Majority of the external work in machining transforms into thermal energy at the cutting zone. Tools with high thermal conductivity allow for effective heat transfer from the cutting zone preventing the generation of high-temperature gradients at the tool tip. The thermal conductivity of various tool materials is reported in Table 1. Ceramics have lower values than carbides, with the lowest thermal conductivity of 9W/mK reported for Alumina-based tools. Carbides and CBNs are found to have a superior thermal conductivity of up to 140 W/mK.

Whilst the majority of the heat generated during cutting is transported by the chips (Astakhov, 2013), the heat conducted through the tool, workpiece, and coolant should also be considered in machining Inconel 718. Adiabatic tool materials with low thermal conductivity can act as a weir. Yan et al. (2014) remarked that when machining using tools with low thermal conductivity, more heat is conducted through the workpiece. Balaji et al. (1999) reported that high interface temperatures are developed when tools with low thermal conductivity are used. Inconel 718 has a poor thermal conductivity of 8 W/mK. Therefore, conductive heat transfer is limited through the workpiece and chips, and high temperatures are generated in the cutting zone. It is also worth mentioning that thermal conductivity is a temperature dependant parameter. According to Grzesik et al. (2005), this can affect the machining efficiency and cutting performance. This effect is not specific to Inconel 718.

Table 1 - Thermal conductivity of commonly-known cutting tool material

Material	Thermal conductivity [W/mK]	Reference
PCBN (Low content CBN + TiN binder)	35 -55	Tanaka et al. (2016)
PCBN (50% CBN + TiC binder)	38	Soo et al. (2016a)
PCBN (65% CBN + TiCN binder + SiC whisker)	53	Soo et al. (2016b)
PCBN (High content CBN + Co binder)	75 – 85	Tanaka et al. (2016)
PCBN (100% CBN)	100	Coelho et al. (2004)
Ceramic (Alumina based)	9	Coelho et al. (2004)
Ceramic (TiN)	12	Koseki et al. (2016)
Ceramic (TiC added Alumina)	21	Kitagawa et al. (1997)
Ceramic (Si3N4)	54.4	Kitagawa et al. (1997)
Carbides (WC)	44.6 – 46	Parida et al. (2017)
Carbides (sintered)	79.5	Kitagawa et al. (1997)
Carbides (WC-Co)	120 – 140	Koseki et al. (2016)

2.1.1 Cubic boron nitride

Polycrystalline CBN (PCBN) is commonly adopted for machining Inconel 718. Costes et al. (2007) reported adhesion and diffusion as dominant wear mechanisms in turning Inconel 718 with CBN tools at 250 m/min, 350 m/min and 450 m/min cutting speed. Cantero et al. (2018) observed chipping, flank, notch and crater wear as the tool wear modes in turning with PCBN tools. They investigated the viability of dry cutting Inconel 718 using PCBN tools of different makes in comparison with tungsten carbide tools. They concluded that turning Inconel 718 with PCBN tools in dry conditions is not viable at 300 m/min cutting speed due to the tool life shorter than 2 min. In a follow up work, Diaz-Alaverz et al. (2018) noted that tool wear mode was not affected by flood cooling. However, tool life was significantly increased to more than 10 and 8 min for 250 and 300 m/min cutting speed, respectively. Sugihara and Enomoto (2015) reported that when turning Inconel 718 at 100 m/min and 300 m/min with PCBN tools, grinding marks appeared on the rake face just before crater wear. They polished the rake face of the cutting tools before machining which delayed the crater wear initiation by 40% when compared with unpolished tools.

Grain size, percentage of CBN, as well as the type of binder have been identified to have significant effect in machining Inconel 718. Low CBN content was suggested by Bushlya et al. (2013a) and Diaz-Alaverz et al. (2018). They reported that low content (50%) CBN tools presented both surface finish and tool life more than three times better than binderless PCBN tools in the whole range of 300-480 m/min cutting speed. This is potentially due to the increased toughness of the tool, which reduces the chipping and notch wear and wear induced surface damage.

Zhou et al. (2012) reported that applying a TiN coating on CBN tools extends the tool life by 20% in finish turning Inconel 718 at 350 m/min cutting speed. Nevertheless, TiN insulation resulted in more tensile residual stress compared to uncoated tools. Soo et al. (2016b) tested 5 different coatings (TiSiN, TiSiN/TiAlN, AlCrN, CrNAl 1, CrNAl 2) and 2 PCBN grades (DCC500 and CBN170). Their monolayer TiSiN was the only successful coating, with 40% increased tool life when compared to uncoated PCBN. All other coatings lasted less than 1 min due to poor coating integrity.

Coating integrity could have been affected by high thermomechanical loads the can reach extreme values on the tool surface. Agmell et al. (2020) estimated a temperature of over 1100 °C at the centre of the cutting interface when turning Inconel 718 with PCBN tools at 250 m/min cutting speed with a feed of 0.15 mm/rev. They also reported principal mechanical stresses at the rake up to 300 MPa while stresses on the notch region of the tool can peak 450 MPa.

Laser surface processing of PCBN has shown to develop a local transformation from cubic to hexagonal phase at the cutting edge. Breidenstein et al. (2019) reported that the hexagonal phase acts as a solid lubricant, reducing cutting forces to the detriment of tool hardness, with reduction of more than 1700 HV1. Denkena et al. (2018) reported that laser preparation of cutting edges is beneficial for frictional behaviour and reducing adhesive wear. They reported a 40% reduction in flank wear compared with untreated tools in turning Inconel 718 at 48 m/min cutting speed.

2.1.2 Ceramics

Specific ceramic tools have the potential to revolutionise the productivity of machining of Inconel 718 (M'Saoubi et al., 2012) with cutting speeds up to 10 times higher than carbides (Arunachalam and Mannan, 2000). According to Arunachalam and Mannan (2000), long tool life and superior thermo-chemical stability are the major characteristics of ceramic tools. However, ceramic tools have poor resistance to thermal shock caused by cyclic heating and cooling during machining when coolant/lubricants are used. Grguraš et al. (2018) noted that MQL can potentially be used to reduce the impact of thermal shock and enhance tool life by 75% when compared with dry cutting. Çelik et al. (2017) confirmed that SiAlON tools can last over 30 min in milling Inconel 718 at 585 m/min cutting speed while Zhuang et al. (2014) reported that alumina-based tools show oxidation resistance up to 1000°C. Arunachalam and Mannan (2000) recognised low toughness as the major weakness of ceramic tools, making them particularly sensitive to thermal and mechanical dynamic stresses. Ezugwu and Tang (1995) observed that the addition of dispersed SiC and TiC whiskers into the ceramic matrix can help increase the hot hardness and wear resistance. However, Avdovic (2011), as cited by Bushlya et al. (2013b), suggested that persistent toughness deficiency can result in unpredictable tool life.

Akhtar et al. (2016) compared SiC whisker-reinforced coated tools with PVD TiAlN coated carbide tools in machining Inconel 718 at 5 levels of cutting speed, feed rate and depth of cut. They showed that ceramic tools developed worse surface roughness than coated carbides in each experiment and suggested using ceramic tools just for roughing and semi-roughing applications.

The low thermal conductivity of ceramics has been shown as a prime concern (Arunachalam et al., 2004a). As the thermal barrier shields the bulk of the tool from heat flow, the same barrier also develops a weir effect resulting in increased temperatures at the tool-workpiece interface due to the friction between workpiece and tool. Zhou et al. (2014) reported that this might lead to tensile residual stress development as well as profound metallurgical damage on the machined surface. However, further investigation is required to establish this effect. Zhou et al. (2014) investigated the subsurface microstructure and residual stresses development with PCBN and Al_2O_3-SiC_W tools. They reported that Al_2O_3-SiC_W tools developed much higher residual stresses than PCBN tools at 200 and 350 m/min cutting speed.

2.1.3 Carbides

Tungsten carbide with cobalt binder (WC-Co), also known as cemented carbide, is the most used cutting tool material in the industry. This is also reflected in the research as majority of the published literature is concentrated on machining with carbide tools. The worldwide production of more than 90,000 tonnes of cemented carbide with about 65% specifically for metal cutting purposes underlines their importance (García et al., 2019). Besides, low cost, high toughness and high thermal conductivity make cemented carbides well suited for machining Inconel 718.

Cantero et al. (2013) reported that the most significant tool wear modes in finish turning Inconel 718 are notch wear, chipping and flank wear. However, they did not report crater wear within the studied cutting speed range of 50-70 m/min despite noticing the formation of built up edge. Liao and Shiue (1996) observed that the wear behaviour in turning Inconel 718 consisted of synergism between abrasion and diffusion wear mechanisms. Kaynak (2014) showed that controlling the cutting temperature when turning can reduce tool wear, especially with uncoated carbides.

The high temperature which facilitates the diffusion of Nickel and Iron into the Cobalt matrix of WC-Co tools is a significant limitation for high-speed machining with uncoated carbides. As a result, coatings have been introduced to protect carbides tools from diffusion and improve machining performance. Grzesik et al. (2018) suggested a 2 to 15 µm thick layer of coatings such as AlTiN, TiAlN to be applied as a thermal and chemical barrier.

In some cases, multiple layers of different coatings are applied to enhance hardness and reduce thermal conductivity. Nalbant et al. (2007) investigated the effect of multi-layered coating material on the surface finish as well as cutting forces when turning Inconel 718 at 15 to 75 m/min cutting speed. They compared a quadruple layered coating with TiN on the top, a triple-layer with Al_2O_3 on top and a single-layer TiN coating. The triple-layer coating with Al_2O_3 on top provided the lowest cutting force at the highest level of cutting speed but presented the highest surface roughness. However, the single-layer TiN coating improved surface finish to about 50% of the roughness achieved with the triple-layer coated tool. This is because some coatings provide thermochemical protection of carbide substrate in exchange for thermal barrier resulting in residual stress development. For instance, coatings such as Al_2O_3 are associated with minimising adhesion as well as tear-free surfaces (Ezugwu et al., 1999). In contrast, they are also associated with the development of tensile residual stresses, as observed by Sharman et al. (2006). Grzesik et al. (2020) also reported that protective Al_2O_3 films can form between the TiAlN PVD-coating and Inconel 718 during turning.

The variation of the thermal conductivity of several coatings for carbide tools, WC and Inconel 718 with temperatures is presented in Fig. 3. Fig. 3 was realised by combining the results reported by Derflinger et al. (2006) for TiAlN, AlTiN and AlCrN materials with the values reported by Grzesik and Nieslony (2008) in addition to the thermal conductivity variation of Inconel 718 observed by Kim and Lee (2014). It demonstrates that the AlCrN coating layer has the lowest thermal conductivity of about 4 W/mK at 25 °C, while TiC presented around 8 times higher value. Furthermore, Inconel 718 and WC depicted an increase in thermal conductivity with increasing temperature, whereas Al_2O_3 showed an opposite trend.

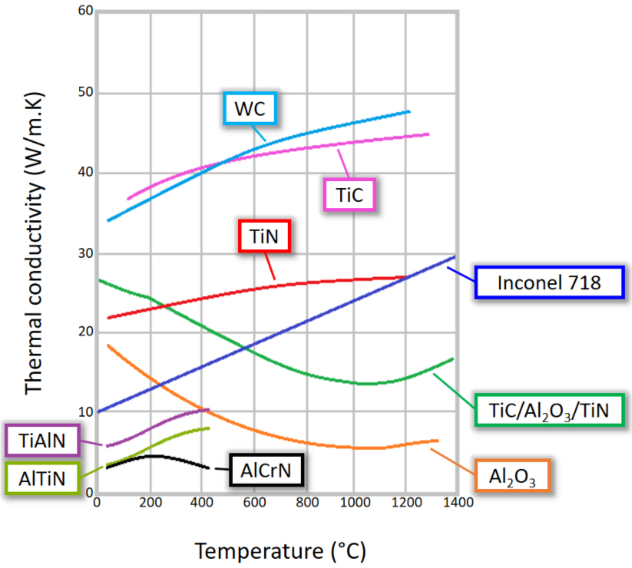

Fig. 3 – Thermal conductivity of WC, Inconel 718 and different coatings for carbide tools against temperature. Note: the figure was realised by combining the results reported by Derflinger et al. (2006) with the values reported by Grzesik and Nieslony (2008) in addition to the thermal conductivity variation of Inconel 718 observed by Kim and Lee (2014).

2.2 Cutting tool geometries and their influence on machining Inconel 718

Investigations on cutting tool geometries are one of the most common areas of improving metal cutting performance for difficult-to-machine materials. The right choice of tool features based on the workpiece material has the potential to affect tool life significantly (Fang and Obikawa, 2017a) and effectively prevent chipping at the cutting edge (Arunachalam et al., 2004b). Tool features such as insert shape, edge characteristics, surface texture and their specific effect on the machinability of Inconel 718 are investigated.

2.2.1 Tool shape geometries

It is well known that tool angles and shapes have a direct effect on cutting forces and tool strength. Whilst sharp cutting edges reduce the cutting forces, they also weaken the cutting edge. In machining Inconel 718, high cutting forces require strength at the cutting edge to avoid chipping and notch wear. Celaya et al. (2019) suggested using tools with rounded cutting edge profiles with low relief and rake angles.

Negative rake angles are generally chosen for machining Inconel 718. This is specifically used in turning applications. When turning Inconel 718, Thakur et al. (2012) and Altin et al. (2007)

adopted -6° and -7°, respectively. Negative values improved surface integrity to the detriment of cutting forces. For example, Behera et al. (2017) observed an increase of more than 20% in cutting force when changing the rake angle from 14° to -10° in turning Inconel 718 under MQL conditions at 80 m/min cutting speed and 0.2 mm/rev feed rate. Milling studies presented more orthogonal rake values than turning. Kasim (2018) used an end mill cutter with a rake angle of -3° while Çelik et al. (2017) employed SiAlON tools -2° rake angle.

Arunachalam et al. (2004a) reported that round inserts develop compressive residual stress when turning Inconel 718 at low cutting speeds, and this suggests a better control of temperature development over the square and rhomboid inserts. They recommended using round CBN inserts at 150 m/min cutting speed with a small depth of cut of 0.05 mm under the wet cutting conditions to minimise residual stresses and realise a surface finish Ra of 0.4 µm.

Some investigations have shown that the influence of tool shape is confined to low cutting speeds. Khan et al. (2012) reported that PCBN round tools outperformed rhomboid PCBN tools just at cutting speeds lower than 300 m/min while between the 300 and 450 m/min, there was no considerable difference when turning Inconel 718. Generally, a large nose radius offered reduced chipping and surface roughness. However, drawbacks such as subsurface grain deformation, more profound residual stresses with large surface tensile components were also observed. For example, Sharman et al. (2015) observed high tensile residual stress close to the surface when increasing the nose radius. For this reason, they did not recommend a large nose radius for the finish machining of Inconel 718. In contrast to conventional metal cutting, the machining of Inconel 718 with a large nose radius is associated with high tensile residual stresses, notwithstanding the increase in cutting forces in accordance with Thakur and Gangopadhyay (2016). Besides, Parida and Maity (2017) observed that chip thickness decreases and chip-tool contact increases with increases in nose radius.

According to Madariaga et al. (2014), the adoption of tools with a large nose radius allows using higher feed rates without compromising surface roughness. They reported that a higher nose radius leads to a larger difference between the maximum surface tensile stress and minimum subsurface compressive stress. The higher peak surface tensile stress was attributed to higher heat generation, whilst larger compressive stress was due to the increased subsurface deformation as a result of higher cutting forces. Madariaga et al. (2014) reported that the passive force was higher than the main cutting force in their experiment and attributed that to the geometry of the tool. However, Sharman et al. (2015) found that the main cutting forces were always larger than the radial and thrust forces when using a tool with a nose radius ranging from 2 to 6 mm. They observed a similar behaviour for surface tensile and subsurface compressive residual stresses in turning Inconel 718. However, it was only dominant when a tool with a nose radius of 6 mm was used at 0.5 mm/rev feed rate. This effect was not observed when a slower feed rate of 0.25 mm/rev or smaller nose radius (<6 mm) were used. Whilst Madariaga et al. (2014) noted a deformation depth as high as 100 µm, it was less than 30 µm in the study by Sharman et al. (2015). Sharman et al. (2015) found that increasing the tool nose radius results in increased subsurface plastic deformation. They observed that increases from 2 to 6 mm radius resulted in a gradual increase in radial force, microstructural deformation depth, compressive residual stress distribution and higher near-surface tensile stress.

Chamfers, hones, and wiper geometries on the cutting edge are found to be beneficial for tool strength (Thakur and Gangopadhyay, 2016) as sharp edges tend to develop rapid chipping (Wang and Liu, 2018). While larger nose radius reduced surface roughness, it resulted in severe plastic deformation on the machined surface. Jafarian et al. (2016) reported that mechanical load, as well as metallurgical damage, increased with increasing edge radius. Thus, the thickness of the layer affected by severe grain refinement was found to be 150 and 250 µm for chamfered and modified (honed) edges, respectively.

The underlying reason for this effect is explained by Pawade et al. (2008). As illustrated in Fig. 4, the sharpness reduction of the cutting edge is associated with an extended area of workpiece deformation, which delocalised the tensional state. In low depth of cut, increasing the cutting edge radius can act as a negative rake angle. Therefore, the ratio between the uncut chip thickness and the cutting edge radius should be taken into account when a large cutting edge radius is used. Increased edge radius that acts as a negative rake angle can result in severe plastic deformation, as observed by Jafarian et al. (2016). Tool wear can also result in edge roundness and modification of the rake angle during machining, potentially leading to increased plastic deformation, as reported by Sharman et al. (2015).

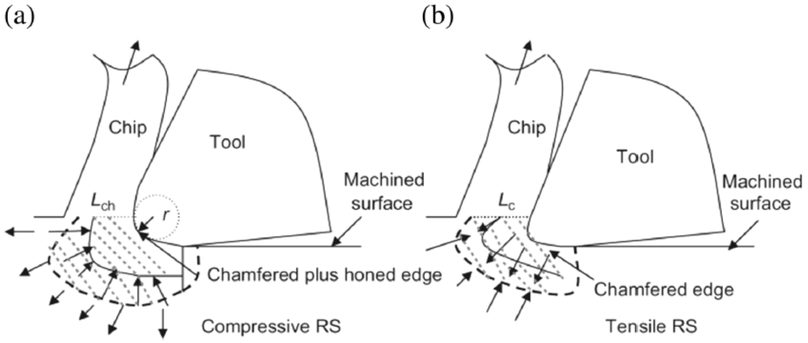

Fig. 4 - Effect of cutting edge geometry on residual stress when machining Inconel 718 with a) chamfered and honed edge and b) only chamfered edge (Pawade et al., 2008)

Jafarian et al. (2016) developed a method for identifying Johnson-Cook model parameters for finite element modelling of cutting Inconel 718 and investigated the impact of chamfer angle and edge radius on surface hardness and grain size. They reported that increasing chamfer angle and edge radius both leads to increased surface hardness and microstructure refinement. This trend was observed to be more intensive when chamfered tools were used compared to honed tools. However, they did not provide the cutting forces and temperatures observed in the simulations to explain the underlying reason for these effects. Further investigation using digital image correlation and orthogonal cutting experiments can provide valuable information on the impact of edge radius and wear on subsurface microstructure.

2.2.2 Tool texturing

Tool texturing can improve tribological proprieties as well as reducing cutting forces and tool wear (Alagan et al., 2019). The micro textures on tools' rake and flank faces developed by

Sugihara et al. (2017b) have been found to be effective in improving tool life by reducing friction between the tool and Inconel 718 workpiece/chips. In another work, Sugihara et al. (2017a) used a femtosecond laser to generate micro patterns on the flank face of a CBN cutting tool, as shown in Fig. 5. They demonstrated that the patterned flank suppressed chipping and extended tool life during the high-speed turning of Inconel 718. The designed micro-grooves stopped the adhesion formed on the flank face from flaking off due to the superior resistance offered by the interlock mechanisms, also known as the anchoring effect (Kim et al., 2010).

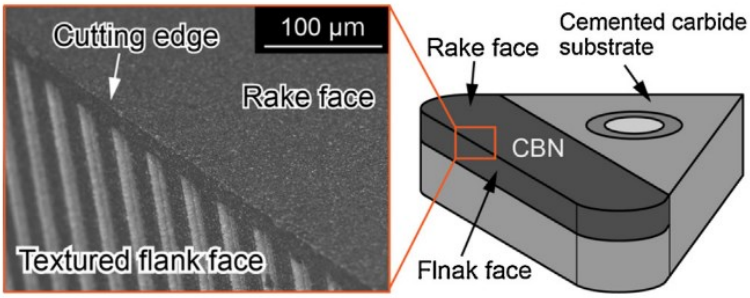

Fig. 5 – Example of textured flank face aimed at reducing adhesion (Sugihara et al., 2017a)

In another work, Sugihara et al. (2017b) proposed a tool with a grooved flank face for turning Inconel 718 under wet conditions. The grooves acted as micro-channels promoting coolant reachability at the friction area and suppressed flank wear effectively. Fang and Obikawa (2017b) investigated five types of micro-textures aimed at increasing thermal exchange when turning Inconel 718 under high-pressure cooling, as shown in Fig. 6. Pin fins, plate fins, and pits fabricated 0.3 mm away from the cutting edge increased cooling performance. Among them, the tool with 10 μm deep pit array outperformed the others with a maximum width of flank wear reduction of about 50% and 80% cutting edge recession over non-textured tools.

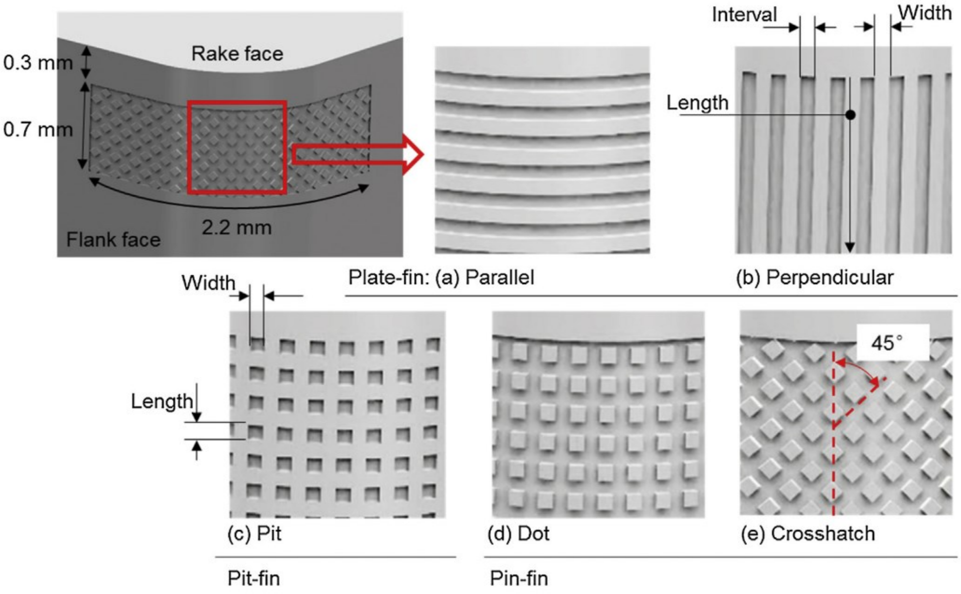

Fig. 6 - Example of different fin arrays and shapes used by Fang and Obikawa (2017b) *on the flank face*

Alagan et al. (2016a) introduced geometrical cooling features on both flank and rake faces of a cutting insert for machining Inconel 718 under forced coolant application. The pattern on the cutting tool increased the surface area of thermal exchange by 12% and resulted in improved heat dissipation. Fig. 7a shows the patterned insert proposed by Alagan et al. (2016a) and the topology of an additional channel proposed in a subsequent work (Fig. 7b) (Alagan et al., 2016b). Alagan et al. (2016b) noticed that introducing the additional channel near the cutting edge extended coolant reachability to the cutting zone with a reduction in tool wear of about 30%. Jäger et al. (2016) analysed the two inserts proposed by Alagan et al. (2016a, 2016b) against an unmodified insert by using ESD analysis. They concluded that the temperature gradient changed between regular and modified inserts. However, they did not perform a thermal analysis, and this conclusion was based on identifying traces of calcium potentially from the water-based coolant on the cutting insert.

Sivaiah et al. (2020) compared the performance of a hybrid textured tool that combined circular pit holes and linear grooves against a textured tool with just the circular pit holes in MQL turning Inconel 718 using cutting speeds ranging from 17 m/min to 66 m/min. They noticed that the addition of the linear grooves decreased the flank wear (Vb) and surface roughness (Ra) up to 48% and 30%, respectively. This highlights the importance of the topology of the surface features.

The micro-geometry of the flank face can also be modified to increase cooling efficiency using a Computational Fluid Dynamics (CFD) approach. Fang and Obikawa (2017a) proposed turning inserts for machining Inconel 718 with blind and through channels on the flank face (Fig. 8). Both features aimed at developing turbulent flow in the flank clearance, which increased the thermal exchange of the high-pressure cooling near the cutting edge. As a result, flank wear and adhesion decreased. They observed that through channels led to increased machining time of about 100% over regular tools, whereas the beneficial effect of blind holes was confined to a small depth of cut.

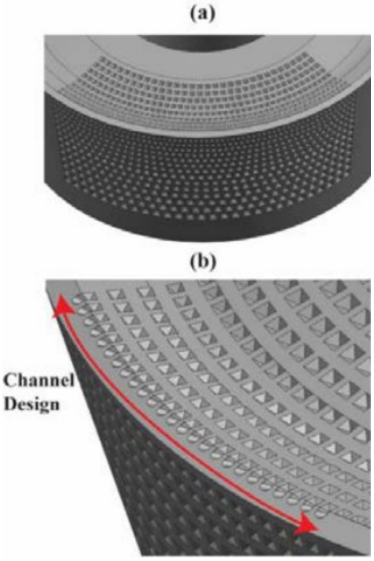

Fig. 7 – (a) Insert proposed by Alagan et al. (2016a)*; and (b) additional channel design proposed by the same author in a further work* (Alagan et al., 2016b).

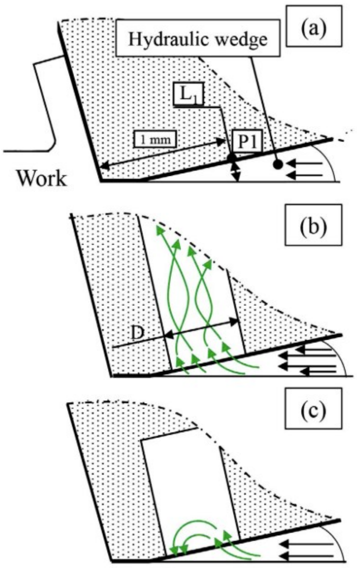

Fig. 8 - Schematic diagrams of the turning using an ordinary tool and tools with a through or blind cooling channel. (a) Ordinary tool. (b) Tool with a through channel. (c) Tool with a blind channel (Fang and Obikawa, 2017a).

Beer et al. (2014) proposed new geometrical features on drills based on the CFD simulations of Oezkaya et al. (2016). The novelty was a 50 µm deep groove on the flank face backspace parallel to the cutting edge, as shown in Fig. 9.

The additional feature improved the cooling, where high thermo-mechanical loads developed. They reported that the modified twist drills extended tool life by about 50% and improved the hole roundness deviation and average surface roughness when compared with a standard twist drill.

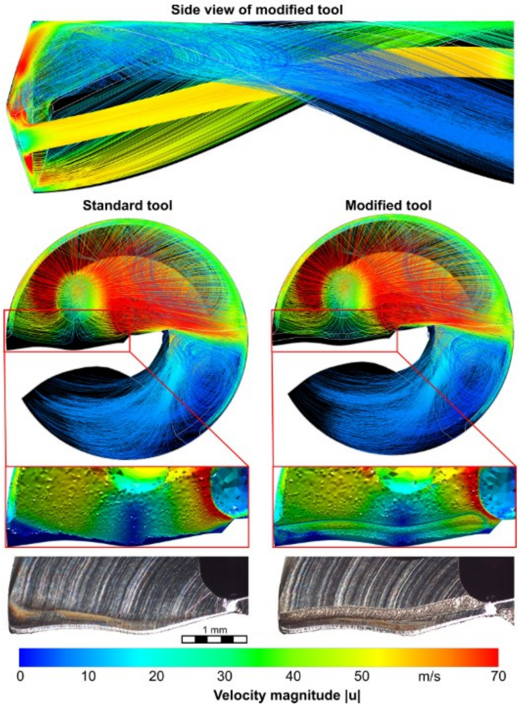

Fig. 9 - Coolant velocity and flank faces of the worn drills (Beer et al., 2014)

Design methodologies for tool geometries on a macro, micro and nanoscale can potentially further improve the machining performance of Inconel 718. Three functions have been identified for textures on the tool: (i) modifying friction behaviour, (ii) coolant reachability and (iii) increased surface area for heat dissipation. Initially, surface texturing was intended for modifying surface friction behaviour at the cutting zone. This was extended to enable coolants to reach the workpiece-tool and chip-tool contact zones. More recently, it has been found that they can also increase the surface area to enhance conductive and convective heat transfer. Despite the improvements, Leidenfrost effect has been reported as a limiting factor in enhancing heat transfer and coolant reachability into the cutting zone. Further surface modification methods can potentially change the surface behaviour of the cutting tool surfaces to minimise the adverse impacts of Leidenfrost effect. Surface texturing is currently generated by postprocessing with ultra short pulse lasers. This method may not be suitable for mass production of cutting tools, and new innovative solutions should be considered.

3 – Sensors based monitoring of machining Inconel 718

Sensors have been used for decades for process condition monitoring during machining (Dimla, 2000) and combined with signal processing and artificial intelligence, they can ultimately provide real-time control and optimisation of the machining processes (Serin et al., 2020). However, majority of these applications have been limited to scientific and academic research. The tool life in Inconel 718 is short, not leaving much time for off-line adjustment of cutting parameters. Therefore, adapting cutting parameters needs to take place based on real-time data within the lifespan of the cutting tool. Sensor-based monitoring and control systems enable early detection of tool wear and adapting cutting parameters within the short lifespan of cutting tools in machining Inconel 718. Tool wear and machining induced surface damage, and surface integrity anomalies can be prevented or detected for safety-critical components made from Inconel 718. Subhas et al. (2004) reported that Inconel 718 suffers from dimensional instability over time after machining and noted that this behaviour is not observed in other nickel based alloys. They attributed this behaviour to the presence of γ″ in Inconel 718 and the residual stresses developed during machining. Since cutting parameters and tool wear affects the state of the residual stresses, this indicates the importance of sensor based monitoring of machining Inconel 718.

The most common types of sensors adopted in machining Inconel 718 are dynamometers with piezoelectric sensors such as Kistler's dynamometer for cutting force monitoring (Amrita and Kamesh, 2020) and thermocouples or infrared sensors for cutting temperature measurements, as utilised by Díaz-Álvarez et al. (2017). Dynamometers are expensive and require a specific setup for measuring and monitoring cutting forces which can be difficult for production line applications. Power consumption monitoring can provide an alternative for monitoring tool wear. Khanna et al. (2020b) also reported that power monitoring provides a simpler setup than a dynamometer, and it can be wired permanently into the machine tools.

Segreto et al. (2012) used a combination of cutting force measurement using a tool dynamometer, acoustic emission and vibration sensors mounted on the cutting tool holder to monitor tool wear in turning Inconel 718. They used signal feature extraction with principal component analysis and neural networks to correlate the data from the sensors to tool wear.

A similar setup was used by Mali et al. (2017) using a tool dynamometer for force measurement and vibration sensors. They used ANOVA and regression analysis to correlate the sensor data with tool wear. They noted that the vibration signal had a nonlinear correlation with tool wear making it difficult to be correlated with tool wear. The combination of cutting forces and vibration signal improved the capability of the system. Balsamo et al. (2016) used a combination of a Kistler 3-axis force sensor and an acoustic emissions sensor to detect catastrophic tool failure in turning. Wang et al. (2020a) reported that acoustic emission signals can also be applied to monitor cutting energy consumption.

Shi and Gindy (2007) used a combination of a Kistler tool dynamometer and force, acceleration, power and surface strain sensors mounted on a platform for tool holder and used statistical process monitoring (SPM) to monitor tool wear in turning Inconel 718. They reported that the system was capable of detecting small changes in tool wear as well as chipping of the tool during machining.

Kaya et al. (2011) used a rotating tool dynamometer integrated with a milling tool holder for measuring cutting forces and torque in milling Inconel 718. They correlated the tool flank wear with cutting forces and torque using artificial neural network regression. Kaya et al. (2012) added a 3-axis accelerometer and an acoustic emission sensor mounted on the workpiece to the previous setup for tool condition monitoring. They only used the time-domain and statistical features of the signals for tool wear monitoring. The statistical features extracted from each signal were minimum, maximum, standard deviation, median, root mean square, kurtosis, mean and skewness. In addition, they used a tenth-order linear regression model to fit the data and used the coefficients of the model as statistical features for analysis. Kaya et al. (2012) used a genetic algorithm to identify the best subset of input variables with significant relationships between input tool wear and employed support vector machines (SVM) algorithm for making decisions regarding the tool condition.

Eckstein et al. (2015) developed a setup to extract the spindle torque, spindle power and feed drive power from the machine tool's Siemens 840D controller for drilling Inconel 718. They noted the advantage of this system is using the machine tool's internal components instead of requiring costly additional sensors. They found that power and torque increases as the tool wear progress which can be used for tool wear monitoring. A similar observation has been reported by Shokrani et al. (2017) in milling Inconel 718. They used a Hioki power analyser wired into the machine tool to monitor power consumption and reported that the tool wear is directly related to the machine tool's power consumption.

Axinte et al. (2004) correlated the signals from a combination of acoustic and vibration sensors as well as Kistler tool dynamometer with the surface quality of Inconel 718 workpiece generated by broaching. They reported that the proposed method is capable of detecting chatter marks and anomalies on the machined surface based on the sensor signals. Axinte et al. (2004) noted that different sensors are capable of detecting different surface features, as shown in Table 2. Therefore, a combination of multiple sensors is required to be able to detect all these features.

Table 2 - Overview of the sensors effectiveness to detect defects of the machined surfaces (Axinte et al., 2004)

Overview of the sensor effectiveness to detect defects of the machined surfaces

Output signals used for detection	Workpiece surface defects						
	Profile deviation	Burr	Chatter	Plucking	Smearing	Laps	Flaking
Acoustic emission				★/✦	★/✧	★/✦	★/✧
Cutting forces	★	★	☆/✦				
Vibration			☆/✦				

Time domain: (★), High effectiveness; (☆), reduced effectiveness.

Frequency domain: (✦), High effectiveness; (✧), reduced effectiveness.

Simone et al. (2013) used cutting forces, vibrations and acoustic emissions to monitor residual stresses generated in turning Inconel 718 using principal component analysis and neural network pattern recognition. Wang and Liu (2017) reported that the workpiece-chip separation mechanism can be monitored using acoustic emission sensors. In addition, they found that there is a correlation between the acoustic emission and power consumption signals in turning Inconel 718. The investigations show that the chip serration frequency is almost equal to the frequency of the dominant acoustic emission signal. This can be used for monitoring the cutting mechanism during machining Inconel 718.

Temperature sensors such as pyrometers and thermocouples are also widely adopted for measuring the cutting temperature in certain regions/locations of the cutting tool. Through the deployment of such sensors, the temperature profile inside and outside the cutting tool or workpiece can be extracted by implementing the Fourier equation as shown by Augspurger et al. (2019). Monitoring cutting temperature can provide an opportunity to control residual stresses in Machining Inconel 718.

Augspurger et al. (2020) also explored using a thermal infrared camera that can provide the temperature distribution on the external surface of the cutting tool and/or workpiece in dry machining. Pyrometers are adopted for measuring tool and workpiece temperature in dry cutting as they have high sampling rates. For example, Diaz-Alvarez et al. (2017) used a two-colour pyrometer at a sampling rate of 1 kHz to measure the cutting temperature. Different from many other materials, the calibration of the Inconel 718 emissivity with variation in temperature as well as in oxidation should be taken into account. According to Keller et al. (2015), the total hemispherical emissivity of Inconel 718 linearly increases from about 0.21 to more than 0.275 in a range of temperature between 475 °C and 1000 °C. However, they also reported Inconel 718, when oxidised in air, can vary its hemispherical emissivity by more than 130% in a range of temperatures between 350 °C and 900 °C with a non-linear behaviour. Therefore, special attention should be paid when determining the chip temperature using optical methods.

Furthermore, the application of infrared thermal cameras and pyrometers is limited when coolants/lubricants are used in flood cooling conditions. These methods require a line of sight access to the target, which can be obscured by coolants and mist. As a result, thermocouples have been used extensively for non-dry machining conditions. In this case, thermocouples are embedded inside the cutting tool with the bulb close to the cutting edge and fastened with highly conductive thermopastes, as explained by Narutaki et al. (1993). Jafarian et al. (2014) also demonstrated that the machining temperature on the cutting edge can then be estimated with reverse numerical models. However, a small change in the position of the thermocouple inside the embedding hole can result in a large measurement error. Typically, K-type thermocouples are adopted for turning applications (Jafarian et al., 2014). One of the main disadvantages of using thermocouples is their limited response time. In addition, embedding the thermocouples inside the cutting tool/insert requires drilling holes close to the cutting edge which can weaken the cutting edge resulting in chipping. Moreover, there is a limitation on how close the thermocouple can be positioned to the cutting edge without sacrificing the tool's integrity.

The application of sensors in machining Inconel has been largely limited to the use of dynamometers for measuring cutting forces, vibration measurement with vibration sensors, various acoustic emission sensors with a wide range of frequencies and temperature measurement using thermocouples and pyrometers. Signal processing has been very basic, and, in most cases, it has been limited to correlation development and regression analysis. Further developments in signal processing can potentially unlock new capabilities in monitoring and controlling machining processes which are not limited to Inconel 718. Specifically, most studies are concentrated on tool wear monitoring, and very limited investigations are available for surface integrity parameters such as surface roughness and residual stresses. Developments in this area can lead to manufacturing and machining of surfaces with prescribed properties with applications beyond Inconel 718.

4 - Machining applications for Inconel 718

It has been identified that there is an intrinsic difference in the behaviour of Inconel 718 in various machining processes. In this section, major machining applications, namely turning, milling and drilling, are presented for machining Inconel 718.

4.1 Turning

Turning is a single point cutting application in which the cutting tool is in constant contact with the workpiece and the chip. According to Wang and Liu (2018), this results in heat accumulation on the tool friction area. Kitagawa et al. (1997) reported that the cutting temperatures can reach over 1200 °C in machining Inconel 718 due to its poor thermal conductivity.

Fang and Obikawa (2017a) stated that heat generation and accumulation of heat at the cutting zone is one of the most significant limitations when turning Inconel 718. The major consequences of this issue primarily relate to workpiece surface integrity, tool wear and productivity (Chaabani et al., 2019). Bushlya et al. (2011) observed white layer formation, while Sharman et al. (2004) reported elongated grains, carbide cracking, as well as cavities on the machined surface. They observed that temperature rose with increasing tool wear and vice versa, leading to a dramatic tool consumption. Fig. 10 presents an example of the white layer and subsurface deformation observed by Bushlya et al. (2011) in the speed direction (a) and feed direction (b) formed as a result of high-temperature development.

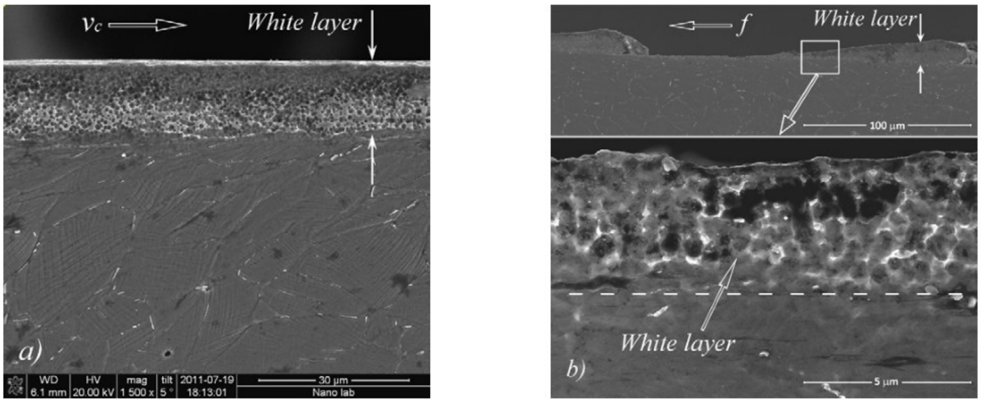

Fig. 10 - White layer and subsurface deformation in the speed direction (a) and feed direction (b) formed as a result of high-temperature development (Bushlya et al., 2011)

Marques et al. (2019) reported significant damage at the cutting edge of whisker-reinforced Al_2O_3+SiC ceramic tools when dry turning Inconel 718 at 250 m/min cutting speed, 0.5 mm depth of cut and 0.1 mm/rev feed rate. Fig. 11 (a) and Fig. 11 (b) present the SEM images of the wear on flank and rake face, respectively. They reported that notch, flank and crater wear adjacent to the cutting edge were the dominant wear modes with abrasion, adhesion and diffusion as the main wear mechanisms. Although ceramic tools are considered inert, chemical reaction between nickel and ceramics such as SiC and Al_2O_3 has been reported by Mehan and Bolon (1979) at high temperatures.

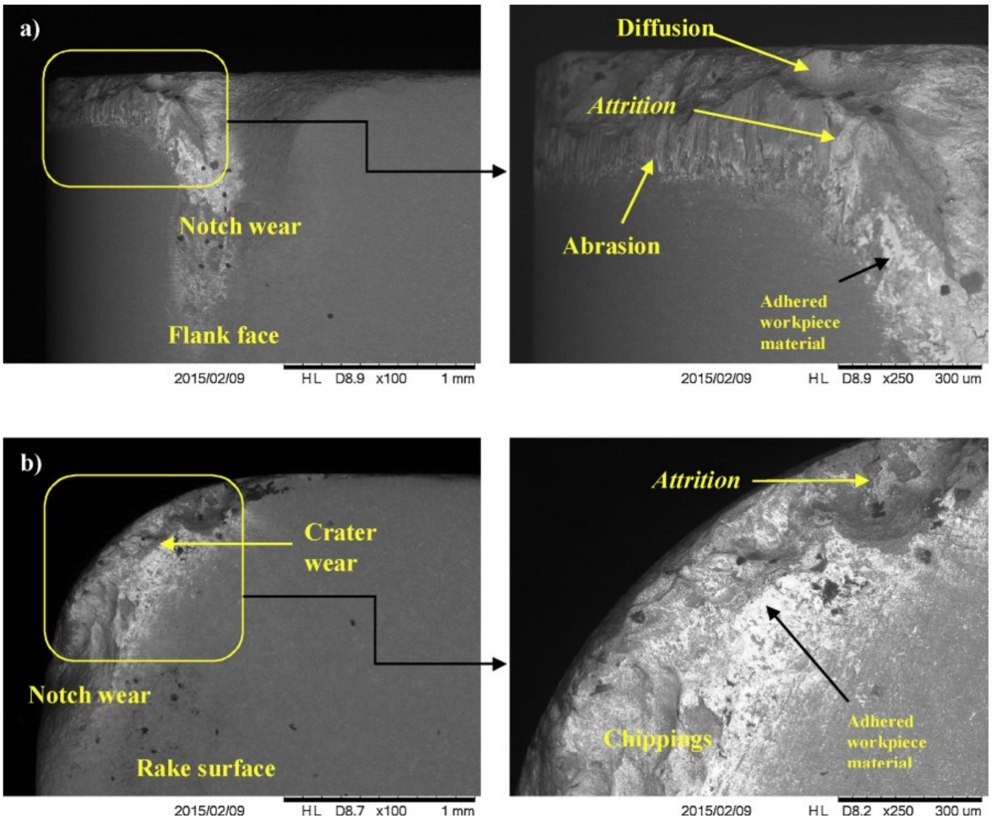

Fig. 11 - Pictures of the flank view (a) and rake view (b) of the damage experienced by a whisker-reinforced ceramic tool after machining Inconel 718 in dry machining (Marques et al., 2019).

Hoier (2018) compared the influence of Inconel 718 and Waspaloy on flank wear when turning at 45 m/min cutting speed, 0.05 - 0.1 mm/rev feed rate and 1 mm depth of cut. They observed that flank wear developed nearly 3 times faster with Inconel 718 than Waspaloy. They suggested this was due to high pressures and temperatures at the tool interface in combination with the presence of abrasive phases such as MC carbides and TiN inclusions.

Cutting fluids are commonly used to remove heat from the cutting zone (Bevara et al., 2020). The constant and intense contact between the tool, workpiece and chips hinder the reachability of cutting fluids into the cutting zone. Mehta et al. (2018) reported that inefficient cooling resulted in undesirable diffusion wear and notching of cutting tools, while Niaki and Mears (2017) observed abrasion, adhesion and chipping under conventional cooling.

In order to improve the cutting fluid penetrability in turning, the delivery of cutting fluids through the cutting tool and tool holder and application of high-pressure coolant (HPC) was found advantageous. In HPC, the high-pressure coolant develops a "hydraulic wedge" which lifts up and curls/breaks the Inconel 718 chips, as stated by De Bartolomeis et al. (2020a). However, cutting fluid cannot fully penetrate the tool-chip interface even when using HPC as the pressure of the HPC technology is lower than the stress over the tool chip interface. Ezugwu and Bonney (2004) reported a 740% tool life extension by implementing HPC. Delivering the cutting fluids through special nozzles generated on the rake/flank faces of the cutting tools or tool holders to impinge cutting fluids between the tool and workpiece and tool and the chip can enhance turning performance. However, Hoier et al. (2017) highlighted that the Co-binder of uncoated carbide tools can be eroded by the impact of HPC jet. Although, no wear performance alteration due to erosion damage was noted. When machining Inconel 718, cutting tool temperature fields also presents a higher gradient with increasing in pressure, as observed by Suarez et al. (2017).

As shown in Fig. 12, Alagan et al. (2020) identified an uncommon wear behaviour due to cavitation on uncoated carbide tools when turning Inconel 718 under HPC conditions. The high temperatures developed in turning Inconel 718 evaporates the cutting fluid leading to Leidenfrost effect at the cutting zone. The implosion of high pressure vapour bubbles near the tool surface resulted in cavitation wear. The erosion previously observed by Hoier et al. (2017) could relate to this mechanism. Further investigation is necessary to establish the mechanism and existence of cavitation wear in machining.

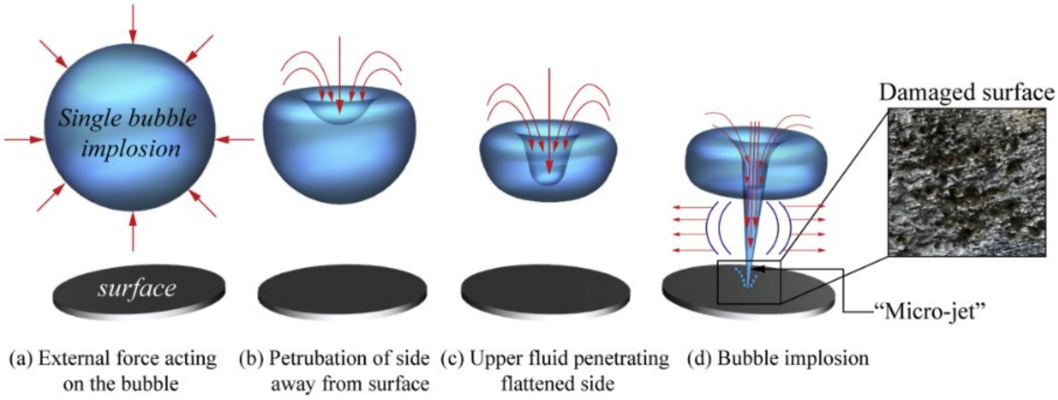

Fig. 12 - Cavitation wear mechanism (Alagan et al., 2020)

According to Bücker et al. (2020), HPC performance can also be improved by cooling the HPC cutting fluid prior to supply to -10 °C temperature. This was made possible by the addition of monoethylene glycol (MEG), which reduced the fluid's melting point.

Enhanced cooling has also been achieved through tool geometries and patterns on the cutting edge. As discussed in Section 2.2, Fang and Obikawa (2017b) realised micro-textures as well as blind channels on the flank face in another work (Fang and Obikawa, 2017a). They observed that geometrical alterations induced localised turbulence which increased thermal exchange. Alagan et al. (2016b) proposed a Nusselt-channel tool consisting of a round insert with textures on both rake and flank faces. They reported that Nusselt-channel inserts led to reduced tool wear and increased tool life due to the improved reachability of the forced coolant into the tool-chip interface. Pusavec et al. (2014) show that hybrid (Cryo + MQL) turning of Inconel 718 generated lower surface roughness and cutting forces and reduced tool-wear rates compared with dry, MQL and cryogenic machining. Their subsequent work (Pusavec et al., 2015) also show that hybrid machining produced improved chip breakability and led to improved machining optimization also by considering the machining productivity in terms of the material removal rate. Peng et al. (2021) investigated ultrasonic vibration assisted machining at ~21 kHz frequency coupled with high-pressure coolant in finish turning Inconel 718. They reported that this method reduced cutting forces in comparison with conventional turning and increased tool life. The maximum improvement of 250% increased tool life was achieved at 80 m/min cutting speed.

The majority of finite element analysis (FEA) and simulation of cutting Inconel 718 is concentrated on turning and orthogonal cutting. Lorentzon and Järvstråt (2008) predicted the worn geometry of cemented carbide inserts through the adoption of MSC.marc using a Lagrangian formulation. Lorentzon et al. (2009) simulated chip formation between 50 and 100 m/min cutting speed. They reported that transition to chip segmentation was caused by a combination of thermal softening and material damage. Zębala and Słodki (2013) applied FEA to investigate groove filling of chip breakers, forces and temperature. Yadav et al. (2015) performed a simulation using DEFORM 3D to predict flank wear of CVD coated tungsten carbide inserts. Díaz-Álvarez et al. (2014) adopted DEFORM 3D to simulate tool wear of coated carbide tools in dry turning. The same software was used in comparison with ABAQUS by Uhlmann et al. (2007), who analysed chip formation with regards to segmentation. The experimental validation revealed that DEFORM 3D had the best cutting force prediction whilst the influence of remeshing on ductile damage was found to be complicated. More recently, Razanica et al. (2020) proposed a finite element modelling and simulation of machining Inconel 718 based on induced ductile failure applied to chip formation. Different to standard models with direct damage-plasticity coupling, their model considered this coupling through visco-plastic damage driving energy.

The following points were identified as turning characteristics of Inconel 718:

- The constant contact between tool and workpiece results in higher heat generation at the cutting zone in comparison with other processes;

- Enhanced coolant/lubricant penetration between the tool and cutting chips as well as between the tool and the workpiece through specialised nozzles on the tool and/or high-pressure coolant can improve turning performance;
- Turning performance can be enhanced by controlling heat generation and improving heat dissipation whilst using cutting tool materials with high hot hardness;
- Cutting temperature limits the maximum cutting speed achievable;
- Heat dissipation is primarily achieved through coolants, chips, workpiece and cutting tools. Engineered cutting tools with enhanced thermal conductivity and heat transfer capabilities can be considered;
- Tool wear and cutting temperature are correlated, and they positively impact each other. The higher the machining temperature, the higher the wear rate and vice versa.

4.2 Milling

In aerospace manufacturing, milling forms a major part of the manufacturing process (Cai et al., 2014). According to Çelik et al. (2017), in milling applications, the cutting tool is exposed to intermittent thermal and mechanical loads, and the same alternating stresses are mirrored onto the workpiece. Compared with turning, this results in reduced thermal damage, but it increases the mechanical deterioration of the machined surface and cutting tools, as reported by Li et al. (2014). Li et al. (2014) noticed a higher level of microhardness in comparison with other applications. They suggested that there is a lower chance of developing a white layer in milling processes when compared with turning at the same level of tool wear. It is worth highlighting that such assumption cannot be assumed as universal as it depends on the particular cutting conditions. Liu et al. (2015) observed four common types of defects during milling Inconel 718: (i) grooving, (ii) tearing, (iii) cavities and (iv) BUE. Saï et al. (2001) showed that high cutting speeds developed significant residual stresses and, as cutting speed increased, the tensile residual stress component increased.

A detailed investigation of the affected depth of residual stress after milling Inconel 718 slots was presented by Holmberg et al. (2020a). They reported residual stress depth and distribution across the milled slot being affected by cutting tool material and proposed an accurate methodology to measure the depth of such stresses. Subsequently, Holmberg et al. (2020b) identified an appropriate milling strategy based on reducing its impact on residual stresses and deformation. They observed a high degree of deformation that differs for the up, centre and down milling. Based on their observations, they suggested using up milling for new inserts and, when they are worn out, switching to down milling due to a lower degree of deformation and residual stress.

According to Cai et al. (2014), surface topography and roughness are significantly dependant on cutting speed and feed rate. Abrasion marks were observed to be the main mechanism. They suggested limiting the cutting speed to 110 m/min with an optimal feed rate of 0.1 mm/z. High cutting speeds not only damage the workpiece but also accelerate tool wear. Yan et al. (2014) reported that the tool is subjected to both loading-unloading and heating-cooling cycles. Potentially, such cycles can lead to the formation of thermal and mechanical fatigue cracks. According to Kim et al. (2001), this resulted in thermo-mechanical damage at the cutting edge and consequently, a rapid decrease in tool life. Cai et al. (2014) reported that high speeds resulted in excessive tool consumption as well as limited the material removal rate.

Suzuki et al. (2014) investigated tool wear when milling with ceramic tools. They reported that the majority of cutting edge wear occurred at the beginning of machining. This led to a quick modification of cutting geometry from sharp edge to round, resulting in the ploughing of the workpiece material. In addition, Çelik et al. (2017) reported that the alternating cycles of thermomechanical stresses at the cutting edge require cutting tools that are resistant to micro-chipping and fracture; characteristics that generally are not typical of ceramic materials. This was confirmed by Ucun et al. (2013), who observed that the tool wear mechanism was related to fatigue crack development due to the cyclical nature of milling. Cracks developed to a higher degree on the cutting edges and end parts, which are locations that have a relatively low level of mechanical strength due to their topology.

As a result of having cyclical loads and different kinematics from turning, a specific cooling/lubrication strategy would be required. In milling, the cutting edge is relatively free to be reached by the coolant/lubricant. However, the synergetic combination of high-centrifugal forces and air vortex cleans the cutting edge from the lubricant itself, whose effect becomes negligible at high cutting speeds. For instance, Kim et al. (2001) show that when cutting at 210 m/min speed, tool life was the same for flood cooling, chilled-air and dry machining. Shokrani et al. (2012b) studied the effect of cryogenic milling of Inconel 718 and showed the potential to significantly reduce surface roughness when compared with dry and conventional machining techniques. However, chipping and catastrophic tool failure were also observed in all conditions due to the lack of lubrication.

In general, lubrication is more important than cooling when milling Inconel 718, specifically at low cutting speeds. Recently, Hayati et al. (2020) showed that ball nose inserts tripled tool life under MQL conditions when compared with CO_2-assisted cooling at 100 m/min cutting speed. Liao et al. (2017) studied the effect of oil-water ratio when milling Inconel 718 under MQL conditions at 60 m/min cutting speed. They found that tool wear and cutting forces decreased by increasing the oil-water ratio indicating the importance of lubrication over cooling. Shokrani et al. (2017) combined cryogenic cooling and MQL in a hybrid technique for milling Inconel 718. It nearly doubled the tool life as well as 18% improvement in surface roughness. Furthermore, they identified that the application of MQL/cryogenic in milling showed different results from MQL/cryogenic in turning. The discrepancy was attributed to the fact that in turning, the nozzle can be specifically targeted towards the cutting zone while in milling, the tool rotates, and the contact area between tool and workpiece can be larger than the area covered by MQL/cryogenic nozzle.

A though-the-tool cryogenic cooling with MQL lubrication (CryoMQL) for milling Inconel 718 was proposed by Pereira et al. (2017). In comparison to external cooling, they reported that using through the tool cooling results in 16% increased tool life when using 60 m/min cutting speed and 0.02 mm/tooth feed with a TiAlN-coated carbide end mill. The application of the CryoMQL coolant-lubricant from inside the tool may have improved the effectiveness of the cooling and bypassed the issues given by the centrifugal forces and air vortex. Pereira et al.

(Pereira et al., 2020) also highlighted the improved performances of an internal supply of CO_2 coolant as a result of a reduced cooling effect on the Inconel 718 workpiece. The hardness of Inconel 718 increases with reducing temperature and can result in additional mechanical loads that will eventually require tools with increased toughness.

Suárez et al. (2019) investigated the impact of ultrasonic vibration assisted milling of Inconel 718 on surface integrity and fatigue life in comparison with Abrasive Jet Water - AWJ, Wire Electro Discharge Machining - WEDM and conventional milling. The topology of the machined surfaces is shown in Fig. 13. The surface roughness Ra values were 0.8 µm for conventional milling, 0.2 µm for UVAM, 1.6 µm for AWJ, 3.4 µm for WEDM.

In general, WEDM surfaces showed high tensile residual stresses and the lowest fatigue endurance (less than 40000 cycles). On the other hand, UVAM surfaces presented the best fatigue performance (about 65000 cycles) as well as the highest compressive residual stresses. In particular, UVAM also extended the machined surface fatigue life by 12% over conventional milling.

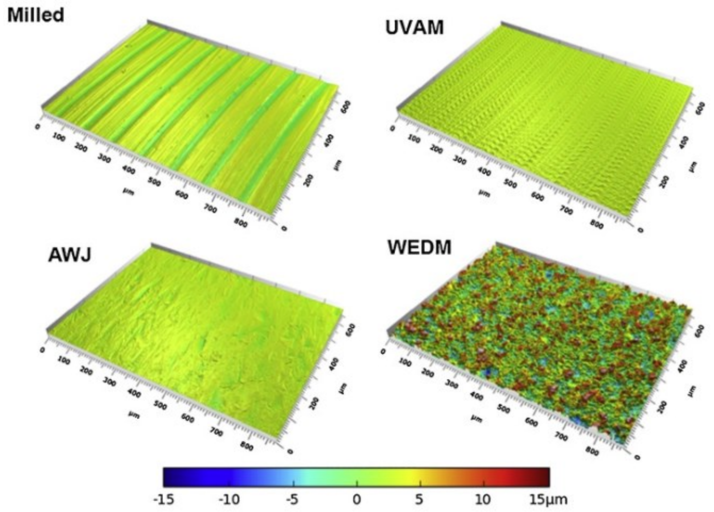

Fig. 13 - 3D view of the machined surfaces machined with conventional milling and non-conventional milling methods (Abrasive Jet Water - AWJ, Electrical Discharge Machining - WEDM and Ultrasound Vibration Assisted Milling - UVAM) observed in the work of Suárez et al. (2019).

Thermally assisted milling processes such as laser and plasma assisted machining have been used to enhance the machinability of Inconel 718. This is based on the fact that Inconel 718 undergoes thermal softening at temperatures above 700 °C. Tian et al. (2008) reported that laser assisted milling can soften the workpiece material and reduce cutting forces, chipping and maximum flank wear in comparison with conventional milling. Xu et al. (2020) studied the impact of laser assisted milling on the surface integrity of Inconel 718. They noted that the generation of the heat affected zone due to the laser can significantly deteriorate the surface integrity by inducing tensile residual stresses, which can lead to crack generation on the surface and affect the fatigue performance of the part. This indicated that whilst thermally assisted machining can enhance machining performance by reducing tool wear and cutting forces, it can adversely affect surface integrity. Therefore, this method can potentially be used for roughing to be followed by a finish machining process. However, the subsurface impact and its depth should be taken into account for subsequent finishing processes. Pan et al. (2017) reported that the depth of the melting zone in laser assisted milling can reach 1.4 mm when a 1000 W laser is used at 1000 mm/min scanning speed.

To summarise, the major attributes in milling Inconel 718 are highlighted:

- The intermittent thermomechanical load can lead to fatigue failure at the cutting edge resulting in microchipping;
- Compared with turning, the machined surface is less affected by the thermal component but prone to mechanical defects;
- Due to the intermittent nature of milling, the cutting tool can suffer from thermal shock and thermal fatigue when coolants/lubricants are used;
- Tool materials for milling should possess good toughness and resistance to micro-chipping;
- When milling Inconel 718, lubrication is more important than cooling as it acts more on the mechanical aspect. However, the best performance has been achieved when combining lubrication with cooling;
- The lubrication effect is limited by the air vortex surrounding the tool, as well as by the high centrifugal forces which clean the tool surface. Therefore, the position and geometry of the cutting fluid delivery system is paramount;
- Adhesion of the cutting fluids is believed to have a crucial role in improving milling performance.

4.3 Drilling

Drilling is one of the final processes performed in the manufacturing of parts (Sharman et al., 2008). As reported by López De Lacalle et al. (2000), the drilling process forms up to 25% of the global machining time. As a result and in accordance with Farid et al. (2008), special attention and machining reliability are required to prevent scrap production due to the cost already entailed from previous processes.

Drilling Inconel 718 is associated with three major difficulties, namely, (i) carbides dispersed inside the matrix of the alloy result in excessive abrasive tool wear on both flank and rake faces of the cutting edge (Chen and Liao, 2003), (ii) the low thermal conductivity of Inconel 718 forces the heat to dissipate only through the tool and coolant (Oezkaya et al., 2016) and (iii) low productivity, as low cutting speeds are used in order to meet close tolerances and surface integrity requirements specifically for safety-critical components.

Drilling is well known to develop higher thermo-mechanical loads when compared with turning or milling. Therefore, tool performance, hole geometry and surface integrity can be affected, as highlighted by Outeiro et al. (2015).

M'Saoubi et al. (2014) investigated surface integrity under extreme drilling conditions of Inconel 718 and compared it with RR1000, Waspaloy and Alloy 720Li. They reported that cutting speed of 35 m/min and feed rate of 0.12 mm/rev using dry machining resulted in elevated temperatures and significant mechanical loads with the development of severe plastically-deformed layers, particularly on the drilled surface of Inconel 718.

In drilling, the cutting tool is in constant contact with the workpiece and the chip, resulting in a significant thermal load. In addition, the chip has to be plastically deformed in order to climb the drill helix out of the hole, leading to strain hardening. On their way up from the hole, the chips rub against the hole surface as well as the cutting tool. This results in heat generation due to the friction between the chips rubbing against the cutting tool and the hole surface. The hot and hard chips can damage the cutting tool as well as the hole's surface and geometrical tolerance, as reported by Khanna et al. (2020a). Therefore, drilling Inconel 718 requires effective and efficient cooling and lubrication at the cutting edge as well as through the guide hole (Ahmed et al., 2019).

According to Veselovac (2012), limiting the cutting speed and feed rate can reduce the thermal and mechanical damage during drilling at the expense of productivity. Zhang et al. (2012) recommended limiting the cutting speed to 50 m/min in case of coated carbides with a feed rate of 0.1 mm/rev. Rahim and Sasahara (2011) investigated surface integrity in drilling Inconel 718 at various cutting speeds (30, 40 and 50 m/min) and feed rates (0.05 and 0.1 mm/rev) using palm oil and synthetic ester MQL lubricant. They reported that palm oil lubricant resulted in lower subsurface microhardness and surface roughness than synthetic ester. They suggested palm oil as beneficial for cooling and lubrication due to its higher viscosity. However, from the results, it is evident that the performance is dependent on the cutting parameters and cannot be generalised.

Uçak and Çiçek (2018) studied the effects of cooling/lubrication conditions in combination with coating material in drilling Inconel 718. They observed that, whilst drilling with liquid nitrogen reduced cutting temperatures, cryogenic conditions increased thrust force and shortened tool life due to excessive chipping.

The chip rubbing on the hole surface do not generate noticeable mechanical load when compared to the insufficient drill back taper that is usually found in commercial drills (Astakhov, 2014). Outeiro et al. (2015) identified the negative effect of the insufficient drill back taper on the wear of the drill margins and proposed four recommendations for designing drill bits specifically for Inconel 718:

- Increase the back taper and decrease the margins width to reduce the friction forces between the wall of the hole being drilled and the drill margins;
- Re-design the chisel edge geometry to reduce the axial force;
- Increase the bottom clearance space;
- Modify the geometry and location of the internal cooling channels.

In drilling Inconel 718, Outeiro et al. (2015) showed that chipping was localised where the temperature gradient is the highest. Fig. 14 shows the temperature distribution on rake and flank face against tool wear under cryogenic and conventional through-the-tool cooling.

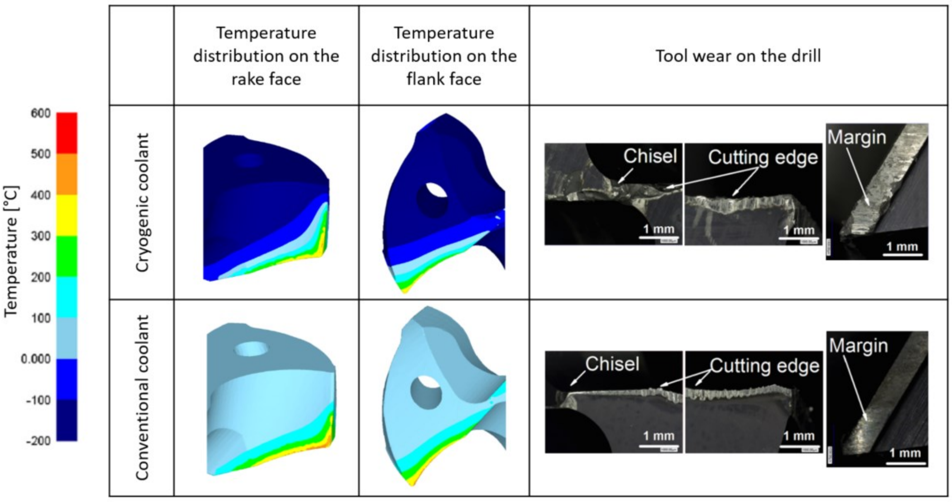

Fig. 14 - Temperature distribution on rake as well flank face and tool wear of drills under cryogenic and conventional through-the-tool cooling. Revisited from (Outeiro et al., 2015)

Modifying the drill's micro geometry has shown promising results in improving drilling performance by enhancing coolant/lubricant reachability using computational fluid dynamics (CFD) simulation. A computational method was proposed by Oezkaya and Biermann (2018) by combining FEM and CFD simulation for simulating drilling with internal cooling channels.

According to Biermann and Kirschner (2015), one of the major challenges in drilling Inconel 718 is preventing premature tool failure in small deep hole drilling. Imran et al. (2008) stated that reaching aspect ratios of 10 and higher is extremely difficult using conventional drilling. Unconventional processes such as the electro-discharge machining (EDM) adopted by Kuppan et al. (2008) and the laser drilling (LD) investigated by Chien and Hou (2007) can successfully manufacture holes with an aspect ratio of over 10.

Both EDM and LD jeopardise fatigue strength and residual stresses. Bossoli et al. (2014) reported an increase of 25% in the stress concentration factor of EDM holes when compared to conventionally drilled holes. Chien and Hou (2007) observed that LD was inclined to generate a rambling collection of defects inclusive of spattering, cracks, tapering and recast layer. This highlights the viability of conventional drilling processes for hole generation.

The drilling characteristics of Inconel 718 can be summarised as follows:

- Thermomechanical loads on the cutting tools are constant and higher when compared with other machining applications;
- The abrasive behaviour of NbC and TiC inside the workpiece matrix in combination with Inconel 718 low thermal conductivity and high strain hardening tendency makes the drilling process challenging;
- Premature tool failure is one of the major challenges in drilling of holes in Inconel 718;
- Tool micro-geometries and features can be used to improve cooling and lubrication in drilling. A combination of CFD and FEA simulation of cutting and fluid flow inside the hole can be used for optimisation;

- It is believed that high thermal gradients on the cutting tool surface contribute to the development of premature chipping at the cutting edge.

5 – Machining of additively manufactured Inconel 718

Additively manufactured (AM) Inconel 718 parts require finish machining to meet the geometrical accuracy and surface integrity requirements.

Kaynak and Tascioglu (2020) reported that powder bed AM Inconel 718 has an undesirable external layer of 80 to 130 µm thickness of partially sintered powder. This layer is characterised by poor topography and high surface roughness and can be effectively removed by machining processes. They reported that finish turning resulted in an increased surface microhardness of the AM Inconel 718 from 322 HV to a maximum of 390 HV. This constituted a 21% increased hardness due to strain hardening. A similar procedure for wrought Inconel 718 did not result in a noticeable alteration of the surface microhardness.

The AM process does not only generate an undesirable surface layer but also influences the bulk of the alloy. According to Ducroux et al. (2021) and Periane et al. (2020), AM Inconel 718 presents lower yield strength, higher elastic modulus as well as smaller TiC and NbC carbide dimensions when compared with wrought Inconel 718. Ducroux et al. (2021) suggested that small TiC and NbC carbides may reduce both mechanical loads and abrasive behaviour at the cutting edge when compared with the wrought alloy resulting in better machining performance.

AM Inconel 718 is characterised by high anisotropy and inhomogeneity at a metallurgical level. Whilst the anisotropy and inhomogeneity of AM Inconel 718 can reduce the final performance of the parts, they can result in a beneficial reduction of mechanical loads during machining. As reviewed by Hosseini and Popovich (2019), the microstructure of AM Inconel 718 is well known to have dissimilar behaviour between parallel and perpendicular build directions. Despite being dependant on the AM technology, they generally reported AM Inconel 718 having a higher elastic modulus and tensile strength in the direction perpendicular to the build. Such characteristic should be considered when comparing the machining of AM and wrought alloys, not only in the case of Inconel 718.

The anisotropic and inhomogeneous behaviour of AM Inconel 718 during machining is evident in the work of Ostra et al. (2019), where they compared Laser Metal Deposition and wrought Inconel 718. They noticed chip geometry being significantly different during end-milling at 80 m/min cutting speed. The additively manufactured alloy presented a shorter, straighter, and less homogenous chip compared with wrought Inconel 718. A similar observation has been reported by Careri et al. (2020). They noted an unexpected ductility of AM Inconel 718 made by direct energy deposition (DED), leading to the generation of continuous chips.

Park et al. (2020) compared tool wear in dry milling of AM and wrought Inconel 718. Their investigations revealed that the highest tool wear was associated with wrought alloy, whilst lower tool wear was observed when machining AM Inconel 718. They noted that when machining AM Inconel 718, tool wear was lower when cutting in parallel to the melt pool direction than when cutting in perpendicular direction.

The anisotropies in AM Inconel 718 can result in fluctuating cutting forces, potentially leading to chipping and breakage of the cutting tool. For such cases, tools with higher toughness, such as carbides, can be beneficial. Chen et al. (2021) investigated machinability proprieties of direct laser metal sintered Inconel 718 in comparison with the wrought alloy. They highlighted coated carbides are well-suited cutting tools for machining AM Inconel 718. The cutting tools lasted more than 12 min in machining AM Inconel 718 which was 278% longer than when machining the wrought alloy.

Careri et al. (2021) performed turning experiments on AM Inconel 718 produced by direct energy deposition in different conditions namely, (i) machined, (ii) heat treated and machined and, (iii) heat treated, machined and double aged. The initial machining step was performed to generate a smooth surface prior to machining experiments. The analysis indicated that the (ii) heat treatment and (iii) double ageing exacerbate machining performance in terms of cutting forces and surface finish due to the generation of a strengthening phase in the material matrix. However, machining AM Inconel 718 in condition (i) led to the generation of tensile residual stresses on the machined surface. Compressive or negligible residual stresses were obtained when turning AM Inconel 718 in condition (iii).

Overall, the differences between the machining of AM Inconel 718 and wrought can be summarised:

- AM Inconel 718 has lower hardness and higher ductility than wrought Inconel 718.
- AM Inconel 718 generally presents a smaller dimension of TiC and NbC carbides compared with wrought Inconel 718. This suggests a reduced abrasive wear on cutting tools.
- AM Inconel 718 has an anisotropic behaviour in relation to the build directions. However, due to the complex part geometries, only in rare cases, the machining direction to build direction can be controlled to enhance machining performance.
- AM Inconel 718 generally develop more fluctuation of thermomechanical loads on the cutting tool. This requires cutting tools with higher toughness compared with wrought Inconel 718.

6 - Discussion and future vision

This investigation highlights that the most adopted cutting tool materials for machining of Inconel 718 are part of three families: CBNs, ceramics and carbides. While CBNs showed the highest hot hardness, carbides exhibit higher toughness. There is no cutting tool material which possesses both the desirable high hot hardness and high toughness simultaneously for machining Inconel 718.

Further research should focus on tailored cutting tool materials with composite reinforcement to enhance the toughness of hard materials such as CBN and ceramic tools. Innovative coating materials specifically designed for machining Inconel 718 may improve surface properties of carbide tools at the cutting zone.

Carbides also have the highest thermal conductivity. Thermal conductivity has a significant impact on thermally-induced surface integrity issues. According to Balaji et al. (1999), high thermal conductivity results in low tool-chip interface temperature. Since Inconel 718 has a low thermal conductivity, effective heat dissipation through the workpiece is limited. When using a cutting tool with low thermal conductivity, heat can be accumulated, resulting in the generation of a large thermal gradient at the cutting zone. This steep thermal gradient can potentially damage surface integrity as well as the cutting tool. Using cutting tools with high thermal conductivity reduces the thermal gradient in machining Inconel 718, making near-dry cutting a viable option. The majority of heat at the cutting zone is primarily removed by conduction through the chips, cutting tool and workpiece, and therefore tools with enhanced thermal conductivity are also useful when using cutting fluids for dissipating heat from the cutting zone. So far, only very little research has been reported on the impact of cutting tool's thermal conductivity on machining performance, specifically when machining materials with low thermal conductivity, such as Inconel 718.

Further research should be carried in the field of cutting tools with enhanced thermal conductivity by design improvement or material choice. Currently, there are some machining applications outside Inconel 718, where internal cooling of the cutting tools have been investigated, such as the work of Isik (2016). The aim is to absorb the heat from the cutting zone and prevent heat accumulation. In this case, the thermal conductivity of the material would directly influence the efficiency of the cooling.

Closed- and open-loop cooling systems, integrated within the cutting tool holders and insert holders, can potentially enhance heat transfer through the cutting tool. Coolant paths can be strategically optimised to deliver cooling and lubrication where it is necessary. Recent work has shown that by using additive manufacturing, the weight of the tool holders can be reduced by 60% (Davies, 2020). Additive manufacturing also enables manufacturing insert holders with a significantly higher number of cutting inserts. This is specifically important for milling Inconel 718 with limited cutting speeds that higher material removal rates can be achieved through the increased number of inserts. A combination of FEA for cutting, prediction of cutting temperature and CFD simulations in the machining of Inconel 718 can help guide the design of such tools in the future.

External geometries on the cutting tool, such as fins and textures, can also be crafted on the machining application. Cutting tools' macro and micro geometries have shown great potential to improve the machining of Inconel 718. Rounded cutting edges presented improvements in tool life, but reduced surface integrity. In contrast, sharp cutting edges usually showed the opposite trend with excellent surface quality, but high tool wear and low productivity.

Furthermore, the influence of tool geometry on the machinability of Inconel 718 cannot be dissociated from the cutting regime parameters (Denkena and Biermann, 2014). In particular, the ratio between the uncut chip thickness and cutting edge radius has a strong influence on the cutting process (Outeiro, 2007), including the surface integrity of the machined part (Outeiro et al., 2010).

Pawade et al. (2008) also described how the sharpness reduction of the cutting edge is associated with an extended area of workpiece deformation, which delocalised the tensional state. Further investigations by combining digital image correlation and numerical simulation can provide an improved understanding of the mechanisms involved.

Micro-geometries such as textured features mainly aim at improving turbulence, reducing adhesion or extend the reachability of cutting fluids. These features can modify frictional behaviour at the cutting zone as well as heat transfer minimising heat generation and improving heat dissipation. Majority of these features are currently generated by post-processing using ultra short pulse lasers. However, this method may not be suitable for mass production of cutting tools, and new innovative solutions are required for post surface treatment of cutting tool surfaces. Precision shot peening and abrasive jet finishing of the cutting tool surfaces can be considered as a less expensive alternative (Wang et al., 2020b). These techniques can be used to alter the surface roughness of the cutting tool to reduce friction, enhance wettability and generate compressive residual stresses that can potentially enhance tool life. This is a more cost-effective method compared to laser surface texturing. However, the economic viability of the process needs to be established.

Today, cooling and lubrication technologies are still essential. Cooling and lubricating methods such as cryogenic machining, MQL and solid lubricants have shown to affect the machining performance of Inconel 718. Also, a minimal number of studies have concentrated on establishing the impact of cooling and lubricating separately. In addition, coolant/lubricant composition, delivery methods, jet parameters and nozzle designs for different processes require further investigation. In the majority of the cases, cooling/lubrication systems are developed independently of the cutting tool design, and there is very little research reported so far on interdependencies between the cutting tool and the cooling/lubrication parameters.

There is a significant industrial and academic interest in conducting research on coolant delivery methods in relation to the machining application with special regard to milling and drilling Inconel 718. There are several investigations on fluid flow in drilling operations using CFD. However, the milling operation has been neglected potentially due to the complexity of the process and changing workpiece geometries.

There is a clear thermomechanical distinction among various machining processes. However, the majority of studies are focused on turning application. The differences in the thermomechanics of cutting in different processes can affect the selection of cutting tool material, coating, geometry and cooling/lubrication methods. Novel investigations are required to identify the mechanics of the cutting and thermal effects in machining in different processes. Experimental investigations should be coupled with computational models to predict material behaviours during cutting. Further investigation on the role of lubricants and coolants as two separate mechanisms involved in machining requires additional research.

Digital technologies have recently emerged as a viable method for increasing productivity in manufacturing processes. Process control systems based on sensor data such as forces, power and acoustic emission has shown to be capable of monitoring machining and cutting tool performance. However, the majority of current research is focused on tool wear and tool wear monitoring neglecting the impact of controlling the cooling and lubrication parameters. The advances in machine learning and artificial intelligence can unlock the limitations of processing sensor signals in machining for real-time control of the process.

It is noteworthy to mention that new and modified Nickel-based alloys with enhanced thermomechanical properties are being developed. In addition, additively manufactured Inconel 718 possess different properties as wrought alloy, and therefore there is a need for improved cutting tools, coatings and processes to ensure sustainable and economic production in future.

The current and novel research directions identified by the authors are summarized and presented in Table 3, with an outlook for future research.

Table 3 - Current and novel research directions in the field of tool materials, geometries, machining applications and sensors in the machining of Inconel 718

Field	Current research directions	Novel research directions proposed by the authors
Tool materials	• Increasing the toughness of CBNs and ceramics • Increasing the hardness of carbides	• Studies on the effects of thermal conductivity on surface integrity • Studies on the effects of thermal conductivity on tool wear
Tool geometries	• Preparation of cutting edges • Micro texturing of cutting tool surfaces	• Tool design with internal cooling channels • Improvements in cooling and lubrication supply in tool design. • Design methodologies on a macro, micro and nano scales. • Additive manufacture of tool holders and assemblies.
Machining applications	• Differentiation of the applications in relation to cooling and lubrication • Tool design based on machining application in relation to cooling and lubrication • Combined CFD and FEA models	• Investigation of tool wear mechanisms in relation to cooling and lubrication. • Development of novel techniques for though-the-tool and though-the-holder supply of coolants/lubricants • Hybrid tool design for mechanical and thermal resistance based on the machining application • Innovative cooling and lubrication methods • Developing the digital twin of cutting tool and workpiece to show the real-time condition of the tool and the workpiece based on sensor data
Sensors	• Regression models for signal processing • Positioning of the sensors • Monitoring of tool wear • Monitoring of cutting forces and power consumption	• Monitoring of surface integrity • Machine learning and deep learning methods applied to signal processing

7 - Conclusions

Inconel 718 is the most used superalloy in industry due to its high temperature thermomechanical properties. However, the machining of Inconel 718 is a challenging process. High machining power requirements and short tool life combined with low cutting speeds and poor machined surface integrity result in high manufacturing costs and limited productivity. Despite significant progress in cutting tool designs, cutting tool materials as well as cooling and lubrication strategies, the machining of Inconel 718 is still considered a grand challenge due to short tool life and the high surface integrity requirements.

In this work, the recent advances in cutting tool materials, geometries and machining applications are investigated. This investigation shows that:

- Most adopted tool materials for machining of Inconel 718 are part of three families: CBNs, ceramics and coated carbides;
- Thermal conductivity of cutting tools was found to be an impactful parameter of interest;
- Cutting tools' macro and micro geometries have shown the potential to improve the machinability of Inconel 718. Rounded cutting edges presented improvements in tool life, but reduced surface integrity, whilst sharp cutting edges usually showed the opposite trend;
- There is a clear thermomechanical distinction among various machining processes such as turning, milling and drilling which may require different tools and strategies;
- The research on cutting tools for machining Inconel 718 is mainly focused on turning, while little cutting tool innovation effort has been reported for drilling and milling;
- There is a lack of research in process control systems based on real-time sensor data for detecting and preventing tool wear and surface integrity anomalies for machining safety critical Inconel 718 parts;
- Very limited predictive models have emerged for evaluation and analysis of Inconel 718 machining processes, and the validation of current models in real machining applications is also somewhat limited;
- Digital manufacturing using sensor data collection and combination of data-driven, physics-based and computational models can potentially increase productivity in machining of Inconel 718. Further development in machine learning for developing real time simulation models and superimposed computational models can provide invaluable tools for monitoring, control and a greater understanding of machining processes of Inconel 718.

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