



Review



Review on the Productivity and Production Quality of WC-Co and Ceramic Tools Applied in Milling Operations of Inconel 718

Vitor F. C. Sousa^{1,2,*}, Tiago E. F. Silva², Wenfeng Ding³ and Abílio M. P. de Jesus²

¹ Institute of Science and Innovation in Mechanical and Industrial Engineering—INEGI, Campus FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

² Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

³ College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

* Correspondence: vsousa@inegi.up.pt

How To Cite: Sousa, V.F.C.; Silva, T.E.F.; Ding, W.; et al. Review on the Productivity and Production Quality of WC-Co and Ceramic Tools Applied in Milling Operations of Inconel 718. *Journal of Mechanical Engineering and Manufacturing* 2026. <https://doi.org/10.53941/jmem.2026.100016>

Received: 11 December 2025

Revised: 4 February 2026

Accepted: 9 February 2026

Published: 22 April 2026

Abstract: Machining Inconel 718 remains a challenge for various industry sectors, causing high levels of tool wear only after a few minutes of machining, making it a hard to process material. Furthermore, Inconel 718 parts are crucial for sectors such as the aeronautical and aerospace, with these components being required to have high-quality and tight tolerances. This makes the machining of this alloy even more challenging, as guarantying these pre-requisites requires a high number of tool changes, ensuring that are always in good condition. To mitigate the problems associated with the machining of this alloy, many researchers and manufacturers use of coated tools, with the WC-Co tools still being widely used in this regard. However, since processing this alloy remains a challenge, there is a wide variety of studies focusing on finding even more solutions, by developing novel machining strategies, coatings and employing different tool materials. Lately there has been a focus on the study of ceramic tool materials to machine this alloy, as these materials exhibit high levels of hardness and wear resistance. Moreover, ceramic tools can be used at much higher cutting speeds than standard WC-Co tools, not only mitigating sustained wear, but also being more productive than their competitors. In the present review study, recent research papers were analysed, focusing on the milling of Inconel 718 using WC-Co tools and ceramic tool materials, particularly, SiAlON. The recent research trends and directions will be presented, as well as a comparison of the productivity and surface quality obtained with milling tools made of these tool materials. Regarding the comparison, the selected research studies focus on applications that can be replicated in industrial settings, thus facilitating this comparison. It was found that these ceramic tool materials show tremendous potential when applied to milling of Inconel 718, particularly for roughing operations, exhibiting material removal rates of up to ten times higher than standard WC-Co tools. However, the production quality is still not up to par with WC-Co tools.

Keywords: milling; Inconel 718; wear; productivity; quality; sustainability

1. Introduction

Machining is mainly used to obtain high-precision and quality parts for a wide variety of industry sectors [1,2] such as, the automotive, aeronautical, defence and even food industries. It can be applied to produce parts, with the most common being steel and aluminium alloys for more conventional processes. However, industry sectors



Copyright: © 2026 by the authors. This is an open access article under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Publisher's Note: Scilight stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

such as aerospace have tight requirements, demanding not only high-quality and precision parts, but also these parts are made from materials such as heat-resistant super alloys [3,4], such as Inconel. In fact, Inconel 718, as well as other Ni-based superalloys are well known for their superior mechanical properties and their ability to retain them at high temperatures. The chemical composition of these alloys usually has the same elements (albeit in different percentages), containing high amounts of nickel, chromium and iron, presenting traces of elements such as niobium, molybdenum, titanium and aluminium. Ni-based superalloys have high strength, resistance to thermal creep deformation and are very resistant to corrosion and oxidation phenomena. These properties make these alloys very well suited for demanding applications, particularly in aeronautical and aerospace industries [5,6], being used primarily to produce aircraft engine components, subject to high service temperature and stresses. These properties can be further improved by additive manufacturing processes as well, making these alloys well suited for more particular applications [6,7]. Nickel superalloys can make up for a considerable amount of the total weight of some aircraft in which they are applied [8]. Regarding the processes that are used to produce these parts, the most employed ones are milling and turning, with drilling being also significant and present in the part production industry [1].

As a research topic, machining processes remain very popular, usually with a focus on process optimization, aiming for higher produced quality and improved productivity, either by optimizing the machining parameters, aiming either for a faster and more efficient and controlled process, or aiming for a reduction in tool wear, thus optimizing and reducing the consumption/replacement of these machining tools [9,10]. Of course, the latter option usually results in a faster and more optimized machining process, although it does not necessarily imply better production quality [3]. Furthermore, when seeking improvement of a given process, novel strategies are devised, such as alternative lubrication strategies, or even the development of new tools [11] and tool coatings [12]. These machining studies usually focus on “popular” tool materials (including tool coatings) or on exploring less known topics, such as processing hard-to-machine materials [13,14], such as Inconel 718, which is still a relevant and favoured topic, today.

For this review article, the focus will be on the current machining practices of Inconel 718, which is, as mentioned known for its excellent mechanical properties, even when compared to other Ni-based superalloys. However, these characteristics with the addition of properties such as, high tendency to work harden and low thermal conductivity, make Inconel 718 an alloy that is quite challenging to machine [15], causing severe tool wear (commonly leading to premature/early tool failure) as well as negatively impacting the workpiece’s surface integrity, causing deformation and high surface roughness values. Additionally, to mitigate these problems, using more conventional solutions, such as coated and uncoated tools, relatively conservative machining parameters should be applied [16]. This, on one hand, retards the wear progression sustained by the cutting tools; however, it also hinders the productivity of the machining process itself [17]. To preserve productivity or to improve the production quality associated with a given machining process, some techniques can be applied, mainly cooling and lubrication techniques, with the flood-cooling being one of the most used when machining this alloy (particularly true, when referring to processes that use coated or uncoated carbide tools). However, the use of these cooling techniques is quite unsustainable [5]. In fact, the machining of Inconel 718 is, currently, not a sustainable practice, as it stands, using high amounts of cutting fluid to produce the desired parts, as well as consuming a lot of cutting tools during the process itself, due to the elevated levels of wear that are induced during cutting. The main problems associated with the machining of Inconel 718 are [16,18]:

- (1) Cutting tools sustain high levels of wear leading to premature/early failure;
- (2) Difficulty in producing machined parts with good surface integrity, this is, the machining of this alloy usually induces deformations and defects on the workpieces’ machined surfaces. It is then necessary to give special attention to the machining parameters adjustment as well as cutting tool condition;
- (3) Machining Inconel 718 is a process with low sustainability. These operations require a high number of consumables such as, machining tools and cutting fluid. Additionally, there are high operation times when trying to optimize the cutting tools life, during machining, causing high equipment energy consumption.

These are the three main problems associated with machining this alloy and they are somewhat connected. For example, the high levels of tool wear will cause some alteration in tool geometry, which can negatively impact the machined surface integrity [19].

2. Methodology

To conduct this research study, the scientific search platform SCOPUS was used to explore the machining of Inconel 718, particularly aimed for recent research studies that focus on the mitigation of the identified problems, commonly encountered when milling this alloy, which are presented in the introductory chapter to this document.

An advanced search was performed on the platform, selecting research studies between 2017 and 2025, aiming for the novel solutions that are being devised to answer the problems encountered during milling operations of Inconel 718. In order to contextualize the conducted research, some research studies that fall before this time period have been included, but preference has been given to papers and research studies no older than 10 years.

This review work is divided into chapters describing these novel solutions and methods in the milling of this alloy, starting with a more general look on these solutions, focusing on what authors are discovering and employing to improve the process itself, be it the use of novel strategies, coatings, tools and tool materials (this is shown in Section 3). After this initial step, two tool materials were identified as having high potential to be applied for milling operations of Inconel 718, the WC-Co and SiAlON tool materials. With these identified, further research was conducted about the specific use of these tools' materials in the machining of the alloy (Sections 4 and 5). Moreover, specific research papers were selected for each of these tool materials, focusing now on the industrial application of these tools. Although some of these selected papers do not describe a specific industrial setting, they were chosen based on the parameters that were being used on the selected paper, making sure that these were equivalent to an industrial application. This enables the comparison of these two tool materials performance, which is presented in Section 6 of this review article. As performance metrics, machining parameters, productivity (material removal rate), sustained tool wear and tool life (VB, flank wear, and tool life measurements) and production quality (obtained machined surface roughness/machined surface integrity evaluations) were used. These are presented in two tables, to facilitate the comparison between the two materials. Additionally, these results are discussed and a balance of the both WC-Co and SiAlON strengths and weaknesses is made in Section 7.

3. Recent Advanced in Machining of Inconel 718

Regarding the commonly encountered problems when milling Inconel 718, presented in Section 1, these are currently under study, with researchers aiming for the continuous improvement of the process and the mitigation of these problems, by employing devised solutions, namely the employment of novel coatings, either to reduce tool wear or to improve the machined surface quality [12]. Of course, most of these coatings are applied to WC-Co tools, which are tools that usually require the use of flood-cooling during the machining of this alloy. There is also the development/application of different tool materials, such as CBN and PCBN tools [20] or other ceramic tools such as SiAlON tools [21]. These tool solutions differ in their modes of application, for example, although WC-Co tools can be used in dry machining operations, which are sustainable, their allowed parameter range is quite low/conservative. However, for the ceramic and CBN tools, a higher parameter range can be used [22], and in the case of operations conducted with SiAlON tools, these are mostly dry machining operations.

Still regarding solutions for the improvement of the mentioned drawbacks of machining Inconel 718, as stated, there are different cooling techniques that can be employed during machining to improve the processes' productivity. Usually, machining operations performed in Inconel 718 use lubrication or cutting fluid flooding the cutting zone, this is particularly true for finishing operations [23]. In fact, there are a significant number of studies conducted using this refrigeration method, as it still is the most employed in the industry. However, due to sustainability issues, researchers and practitioners are moving towards alternative methods, such as dry machining. Although more sustainable than flood cooling, dry machining operations induce high levels of wear and limit the range of allowed machining parameters, usually resulting in a less productive process. Additionally, machined surface roughness is generally always higher when performing dry machining operations [24]. Nevertheless, authors still focus on these topics seeking improvement, and contributing with quite interesting work, from the development of tool coatings suited for these dry operations [11], to the employment of techniques such minimum quantity lubricant (MQL) that not only are more sustainable but can also improve the machining process' efficiency (less sustained tool wear and better surface quality) [16,25].

MQL is quite promising in the machining of Inconel 718, being seen as an alternative to dry machining (in some cases). This method delivers the lowest amount possible of lubricant to the cutting area, lowering the generated heat during machining and promoting better chip evacuation, as well as slow/mitigate build-up edge (BUE) on the tools' surface [5]. In some cases, the produced surface finish using MQL methods can be better than flood cooling, as reported by Shokrani et al. [26] in a study conducted using tungsten disulphide nanoparticles dispersed in a vegetable oil which is sprayed in the cutting area through pressurized air, to serve as a cooling and lubricating agent. The authors reported that this method was found to improve the tool life by 10%, when compared to flood cooling methods, achieving satisfactory results in terms of lower generated surface roughness. Additionally, the authors also reported that this method yielded better results in terms of tool life by 90%, when compared to conventional MQL (spraying of cutting lubricants through pressurized air nozzle into the cutting area). It is important to highlight that the solution proposed by the authors is highly sustainable, presenting a good

alternative to commercially available lubricants. There are other authors researching this addition of particles to MQL systems, yielding satisfactory results [27]. However, there is still room for expanding this research, as most studies performed are conducted using coated and uncoated carbide tools. Thus, there is the possibility to contribute and explore the behaviour of different tool materials under these conditions.

Other cooling methods that show some potential in improving Inconel 718 machining operations are the cryogenic cooling methods [5]. Cryogenic cooling methods deliver various cryogenic liquids to the cutting area, trying to eliminate the negative impacts of the generated high temperatures during machining. Usually, liquid nitrogen or carbon monoxide are used during machining operations, with reported benefits regarding the increase in tool-life, as well as improving the machined surface integrity [18,28]. However, this is not always the case, although these methods are very effective at lowering the cutting temperature, since the machined surface is generally harder [18]. This can cause abrasion of the cutting tool and negatively impact the produced machined surface roughness, this because there is no lubrication during cutting [18]. However, there are some researchers employing a hybrid cryo-cooling method, such as cryogenic cooling coupled with a MQL delivery system, as shown by Zhang et al. [29], where the authors study the use of supercritical carbon dioxide cryogenic cooling in milling operations of Inconel 718. These tools are usually used for dry machining operations, however, there are some cases that cooling/lubrication techniques can be useful. Regarding the study, the authors evaluate the performance of cryogenic cooling and compare it with dry milling, and with cryogenic cooling couples with MQL and cryogenic cooling coupled with oil droplets (oil and water mixture). It was noticed that the tools used under dry conditions produced the worse machined surface roughness, with it having suffered considerable grain distortion as well. Furthermore, high levels of abrasive and adhesive wear were reported for the dry condition. When using solely cryogenic cooling, the tool still suffers considerable wear (albeit less than in dry conditions), however, there is very little grain distortion on the machined surface, despite having the second worst machined surface roughness value of all tested conditions. Regarding the use of cryogenic cooling couples with MQL and oil droplets, these yielded the best results in terms of tool wear and machined surface roughness, with the most effective method being the oil droplets coupled with the supercritical carbon dioxide. However, there was some grain distortion registered when using these, as their cooling potential is not as good as sole cryogenic machining. Although these methods are quite interesting, and seem quite sustainable, particularly the processes that use liquid nitrogen as coolant [30], these methods are still quite hard and costly to implement, requiring complicated setups and expensive materials. Still regarding cooling methods used in Inconel 718 machining, Pedrosa et al. [28], explore these in recent literature, identifying the use of nanofluids during cutting. These cutting fluids contain nanoparticles, being primarily used to obtain better machined surface quality, although their use is tied to tool wear mitigation. Additionally, high pressure cooling is also listed as a promissory method to improve the quality of Inconel 718 machining operations, contributing to significant reduction in cutting temperature as well as improving tool-life and machined surface quality.

Given the wide variety of different possible solutions for the problems associated with machining Inconel 718, exploring and optimizing these solutions is a popular research topic with authors having conducted several machinability studies using different tools and techniques, while closely monitoring the process [31]. This process monitoring is crucial for machining optimization, monitoring factors such as tool wear and wear mechanisms [12], generated cutting forces [32], machined surface roughness and integrity, vibrations and cutting temperature [33,34] will yield valuable information to improve the process. Of course, there are additional factors that can be considered, especially when from an environmental/sustainable point of view, for this case power consumption and use of lubricants should be considered (as well as the fabrication of the used cutting tools). Authors also analyse these sustainable factors, optimizing the processes in this regard [5,15].

These machinability studies are usually experimental ones, which are considerably expensive, due to being time-consuming and requiring high amounts of machining consumables (such as tools and cutting fluid) as well as workpiece material (which will not be made into parts that will be applied in the industry). There are, however, numerical methods that can be applied, which although time-consuming, can prove to be quite useful from a sustainability standpoint, as well as more cost efficient. Numerical methods do not require as many experimental runs as conventional machinability studies, by employing popular numerical methods. For example, the Taguchi method, which, when applied, enables the optimization of a process without requiring a full factorial design, and thus performing less experimental runs. Authors use methods such as the Taguchi, usually combined with response surface methodology (RSM) to find optimal machining conditions for a given tool [35]. These methods can prove to be quite useful, for example, Zhujani et al. [36] conducts a study on finding the ideal cutting parameters for machining Inconel 718, using a PVD AlTiSiN coated tool for dry turning operations. The authors were able to determine the ideal cutting conditions with the Taguchi method, highlighting its potential when optimizing Inconel 718 processes. Of course, there is still the need for the conduction of experimental tests, this is also true for

simulation methods. However, by conducting these experimental tests and using these numerical methods such as the previously mentioned one, it generates valuable information that can be “fed” to a simulation software, or even to a genetic algorithm, which can also be used to optimize the outputs of the machining process [37].

Machining process simulations is quite an important topic, as it can be used to predict machining outputs while not necessarily requiring the performance of experimental tests [38]. It can be used to predict generated cutting forces, for example, which are tied to chip formation, tool wear, material machinability as well as power consumption [39]. Nowadays, the most employed simulation methods are the Finite Element (FE) simulation methods, mainly applied to turning of Inconel 718 [40]. This is because the turning process is a much less dynamic process, when compared to milling, making it somewhat easier to simulate [5,18]. There have been several improvements made over the years in the field of FE simulations of Inconel 718, as reported by Pedroso et al. [41], however, the focus seems to be on the simulation of the turning process, which is considerably more straightforward than the other machining processes. Despite the improvements, there are still some challenges with simulation to be addressed, namely some of the models do not account for thermal softening, which can occur at elevated temperatures when machining Inconel 718. Furthermore, there are still some problems regarding the wear prediction and estimation, as the wear models usually applied are Usui’s and Taylor’s empirical models, with the latter requiring extensive calibration. Nevertheless, the simulation of Inconel 718 cutting processes is still quite relevant, especially given these identified challenges.

As previously mentioned, the use of different tools in machining Inconel 718 can help mitigate some of the problems associated with the processing of these alloys, as some of these have higher hardness or are more inert [42], such is the case for ceramic tool materials. This can help prevent abrasive wear problems and material adhesion on the tools’ surface, for example. However, this also comes at a cost, given that the use of ceramic materials can cause deformation and hinder the machined surface integrity of a produced part (if not assisted by any cooling/lubrication method) [19]. As such, there is a need for improvement and optimization of the processes using these “alternative tool materials”, being that the more conventional machining tools are coated cemented carbides (WC-Co), with these being heavily researched and widely used in the machining industry [1,2,12]. Although WC-Co tools are the most employed in the machining of Inconel 718, there are two more materials that show high potential to be applied in the processing of this alloy these being PCBN and ceramic tool materials [18].

As reported by Dudzinsky et al. [43], the ideal properties for a tool material to machine Inconel 718 are: high hardness at high temperatures; high chemical stability; high strength and toughness; high wear resistance and high thermal shock resistance. This is because when machining Inconel 718, there are high generated cutting temperatures, however, Inconel 718 resists thermal softening phenomena up to 750 °C (which generally improve machinability). As explained by Bartolomeis et al. [18], the hardness varies with increasing temperature for the mentioned tool materials, such as CBN, ceramics and carbides. CBN is the tool material that has the highest hardness, even at higher machining temperatures, being followed by the ceramic materials and lastly, carbide tool materials. This highlights their potential in the machining of Inconel 718, being employed in various experimental studies focused on this alloy [18,22]. While carbides have the lowest hot hardness value of the three tool coatings may prove to be useful in improving the performance of these tools in Inconel 718 machining operations.

Although CBN’s exhibit the highest level of hot hardness and high potential for machining Inconel 718, the tools produced can be quite expensive. Additionally, these tools usually are made of a substrate, WC-Co and a tip of CBN material is brazed on the tool body. This increases the tool cost with each replacement, as well as the repair times for these tools. Furthermore, in recent years research regarding the use of this tool material for machining Inconel 718 particularly has fallen, with the focus now being primarily on WC-Co and ceramic tool materials, concretely SiAlON for the latter.

As such, in this review article, there will be a focus on two tool materials applied to Inconel 718 milling operations, these being: Tungsten carbide tools (WC-Co), usually coated; and ceramic tool materials. The most relevant and current trends, practices and research work being conducted about this matter and using these materials will be analysed and presented in this review. Furthermore, an insight into the productivity of each of these tool types will be given, offering comparisons on their performance, tool-life and sustainability while machining Inconel 718.

4. Recent Uses of WC-Co for Inconel 718 Machining Operations

Tungsten carbide tools (WC-Co) are very common in the machining industry, being widely used to produce machined parts made from various materials [1,2]. Their introduction elevated the machining process’ efficiency, by significantly improving tool-life and produced quality, these factors make them very popular and the most used tool types for all machining processes. One great advantage of WC-Co tools used in industry is the fact that these

are commonly coated. Tool coatings further improve the performance of these machining tools, conferring them properties best suited for their application. Indeed, coatings can be tailored for a specific function/application, for example, TiAlN coated tools are commonly used for high-speed machining operations, in some cases being used in machining of hard-to-cut materials [12,44]. This is due to a phenomenon that occurs at high speeds when machining with these coated tools, consisting of an oxide layer formation on the tool's coated cutting edge, conferring it higher wear resistance. TiAlN and TiAlN-based coatings show high potential for machining applications [45], and machining of Inconel 718 is no exception. One popular research topic is the study of the influence of doping agents introduced in these TiAlN hard coatings. These doping agents can help improve coating hardness and toughness, as well as mitigate some problems associated with chemical compatibility. The use of doping elements such as Ta and Y have been studied recently, revealing that the addition of these would improve coating wear resistance [12]. However, the number of research studies made under the specific application of these coatings in machining is still quite low, as the coatings are quite novel. As such, there is a gap in literature that can be filled with experimental studies on the application of these coatings, particularly in hard-to-machine alloys, as the improvement of coating hardness seems to be a common recent research trend [18]. Some authors have started to evaluate the influence of some of these elements. For example, Silva et al. [23] conducted a study evaluating the performance of TiAlYN coated tools in finishing operations of Inconel 718, evaluating machined surface roughness and sustained tool wear. For the experimental tests, cutting speed (V_c), feed-per-tooth (f_z) and cutting length were varied, as to study the influence of these parameters in cutting behavior. Regarding the used cutting speeds, the lowest value was 75 m/min, and the maximum value was 125 m/min. As for f_z , three values were tested: 0.0525 mm/tooth, 0.07 mm/tooth and 0.1050 mm/tooth. For this case, it was noticed that although higher cutting speeds promote more wear, the feed-per-tooth parameter had considerably more influence, with lower values of this parameter promoting higher values of flank wear (especially if paired with high cutting speed values). However, the authors reported problems with the coating's performance, with high levels of delamination occurring at lower values of cutting length, this was attributed to poor coating adhesion to the tool substrate. Despite this fact, the authors reported less abrasive wear sustained by the tool coating than the substrate, highlighting the potential of doping TiAlN coatings with Y, thus increasing coating hardness by improving coating adhesive strength and stability, adding an interlayer between the tool substrate and "main" coating could improve the coating's wear behaviour [1,2]. Still regarding the use of doping elements in the machining of Inconel 718, Pandey et al. [46] studied the use of TiAlN coating doped with Si in dry machining operations. As mentioned by the authors, the use of coated carbides for machining of these hard-to-cut alloys usually requires the use of cooling, generally having negative implications regarding worker safety and environmental protection. As such, the authors propose the application of a novel developed Si-doped TiAlN supernitride nanocomposite coating, deposited on WC-Co, for dry machining operations. The researchers have then compared the performance of this novel coating with an uncoated tool; it was found that the generated cutting temperature was 17% lower than that generated with coated tools. Furthermore, it was reported that there was a 15% reduction in flank wear when using the coated tool. Regarding machined surface quality, it was found that the chips produced with the coated tools were more stable being more segmented. Studies such as this are quite valuable, providing new information and ideas on tool coating development that enables the mitigation of problems associated with machining this alloy, such is the case of Grigoriev et al. [47], that present a study on multilayered nanostructured coatings containing Zr, concretely, Zr-ZrN-(Zr,Cr,Al)N and Zr-ZrN-(Zr,Mo,Al)N. The authors compare the performance of another nanostructured coating, however, this one is more commonly employed in machining operations, the Ti-TiN-(Ti,Cr,Al)N. Nanostructured coatings can prove to be quite useful, albeit hard to develop and produce/deposit effectively, improving the tools' wear behavior significantly. Additionally, high crack resistance and hardness values are associated with these types of coatings [18]. Still regarding the study by Grigoriev et al. [47], the authors evaluated the tribological properties of these coatings on dry turning operations of Inconel 718 alloy. It is important to mention that tool coatings, particularly TiAlN based coatings, enable the machining of the alloy at considerably higher speeds, than those used for uncoated tools, which are used at around 50 m/min (or even lower) when machining Inconel 718. Even at these lower speeds, with uncoated tools cutting temperature easily reaching over 600 °C. Nevertheless, the authors study the mentioned nanostructured coatings, yielding better results than the TiAlN based one. Additionally, the authors state that it is possible to machine at around 300 m/min using these coatings, which is very useful from a productivity standpoint. Indeed, tool coatings can help with improving sustainability of machining processes using coated tungsten carbide tools. In fact, Behera et al. [48] use MT-CVD TiCN-Al₂O₃ coated tools in dry machining operations of Inconel alloy, comparing the results with uncoated tools. Again, it was found that these tools performed better than the uncoated ones at considerably higher cutting speeds, suffering considerably less wear. When using coated tools, the machining temperature is typically lower, even at lower cutting speeds, this was also registered by Zhao et al. [49] when conducting orthogonal cutting tests of

Inconel 718, under dry conditions, using PVD AlTiN coated tools and comparing them with uncoated tools. The authors found that the AlTiN coated tools generated a lower cutting temperature at the maximum value of tested cutting speed, which was 120 m/min. Even then, this value would be lower than that generated by uncoated tools at lower cutting speed values. This proves the potential of using these types of coatings for dry machining operations of Inconel 718, thus improving the process' sustainability.

Although the improvement of tool coatings' mechanical properties to eventually enable stable dry machining of Inconel 718 alloy seems to be quite a popular research topic [5], another common research trend is the improvement of already existing processes, either by numerical [50] or practical optimization. Machining process improvement can be achieved in many ways, by studying the application of novel tool and tool coating technologies [2,12], or implementing new machining strategies and cooling methods [16,18]. One strategy usually adopted in the improvement of Inconel 718 machinability with coated carbide tools is the high-speed ultrasonic vibration assisted machining [51]. This machining strategy has already proven to be useful in obtaining of good, machined surface quality of titanium alloys, which also causes high tool wear with high adhesion of machined material. Peng et al. [14], studied the application of this strategy on Inconel 718, using a TiAlN coated tool. The authors state that, despite coated carbide tools being employed with low cutting speeds and having low productivity, the machined surface quality is higher than that obtained by more productive ceramic tools. As such, there is also an interest in improving the machined surface quality of coated carbide tools while mitigating their wear problems. The authors have used 80 to 249 m/min of cutting speed on their tests, obtaining a tool life 2.5 times higher than the uncoated tool and a reduction in generated cutting forces by almost 33%. The use of ultrasonic vibration during machining significantly improved machined surface quality when compared to conventional machining, having a beneficial impact on the machined surface micro-hardness (surface integrity). Recently, Namli et al. [27], have tested this ultrasonic vibration assisted machining method, while employing MQL and Hybrid-MQL cooling techniques. The hybrid MQL consisted of using Al₂O₃-CuO nanofluid, added to the MQL system. The authors have also tested this method using conventional cutting fluid (flood cooling method), finding that this produced the worst results in terms of machined surface quality. Indeed, MQL improved the machined surface integrity, with the hybrid MQL method achieving the best results in this regard, also average measured cutting forces were lower for the MQL tests. As such, the authors concluded that ultrasonic assisted vibration machining strategy outperforms conventional machining strategies. Moreover, by pairing this "new" strategy with MQL methods, a high-quality machined surface can be obtained, thus highlighting the importance and potential of the studied strategy.

Indeed, the use of alternative cooling and lubrication strategies can bring many advantages, improving the process' productivity and quality as well as its sustainability, such as MQL and cryogenic cooling alternatives [16]. It seems that there are quite a few researchers conducting studies using MQL and cryogenic cooling methods while machining Inconel 718 with coated tungsten carbide tools, this is a trend that is observed for other machining operations conducted in other hard-to-cut alloys [1,2]. There are some studies already being conducted on use of cryogenic cooling to mitigate tool wear problems [52], with positive results. However, these methods can prove to be quite hard to implement, requiring complicated machining setups, to ensure the correct delivery of the cryogenic liquid to the cutting area [53]. However, there might be some added benefits to using these methods as way to mitigate machined surface integrity problems, such as producing high grain deformation as well as refinement, in addition to producing surfaces with high roughness. There are some studies conducted in this regard, such as Pusavec et al. [19], which study the use of this method in machining of Inconel 718, finding that by using cryogenic cooling, a fine surface layer with higher hardness is obtained, than obtained with MQL or dry machining. Additionally, using cryogenic machining, in this case, led to obtaining the best machined surface quality. Although very useful, these methods show more potential for other tool materials, for example ceramic tool material, as the use of these ceramic tools usually leads to low machined surface quality and high (deep) grain deformation on the workpiece's surface [16,25].

There are, however, some interesting recent applications of MQL method in machining of Inconel 718. However, these studies expand on traditional MQL systems, which consist of spraying the cutting area with lubricant oil dispersed in pressurized air. For example, Khosrowshahi et al. [54] propose a more sustainable alternative to MQL methods, using vegetable oils, thus focusing on further improving process sustainability. The authors have tested two vegetable oils, namely castor and sunflower oil during machining operations of Inconel 718, conducted at a cutting speed of 30 m/min, 50 m/min and 70 m/min, while testing three values of feed rate value, name 0.168, 0.281 and 0.393 mm/rev. Authors found that, under these conditions, the tool wear increases with an increase in cutting speed and feed rate value. However, there is a clear influence of the tested MQL methods, with the MQL using sunflower oil yielding the best results, both in terms of tool wear and machined surface quality. This highlights the potential of using more environmentally friendly consumables without the need to give up on machining process quality. The use of solid lubricants in machining of Inconel 718 has also seen some use recently, as proposed by Paturi et al. [15], with

the authors obtaining quite satisfactory results when comparing the performance of the presented system with conventional MQL, achieving production quality using these solid lubricants up to 35% better than the conventional method. The use of these solid lubricants can also help mitigate problems related to machined surface integrity, being tied to not only machined surface roughness improvement, but also the reduction in grain deformation and grain refinement layer formed on the machined surface [54].

Analysing recent research trends, it seems that the main areas of interest on machining operations using WC-Co tungsten carbides are:

- Increasing the mechanical properties of coatings and evaluate how these perform during machining operations with a focus on using them for dry machining operations;
- Use of novel tool coatings, geometries and machining strategies to mitigate tool wear problems as well as improve machined surface quality;
- Use of MQL paired with solid lubricant methods to improve coated tool machining operations and produce an overall machined surface;
- Studies on the surface integrity produced by coated tools for different machining strategies and cooling/lubrication conditions.

5. Recent Uses of Ceramic Tools for Inconel 718 Machining Operations

Ceramic tool materials are a great candidate to be used on Inconel 718 machining operations. These cutting tools can be employed at very high cutting speeds, up to ten times higher cutting speed than that used when machining using WC-Co tools. Additionally, these tools show high abrasive wear resistance, which leads to higher tool life. They also possess high thermal and chemical stability. However, these tools have low toughness. Also, they cannot be employed together with cooling during machining operations, as they have low resistance to thermal shock. Cyclic heat generated on some cutting processes also hinders the integrity of these cutting tools [18]. Nevertheless, these tools remain a very popular research topic due to its better performance than coated WC-Co tools, as exemplified by Çelic et al. [55], where SiAlON milling tools are used in dry milling operations of Inconel 718, carried out with a cutting speed value of 585 m/min. The authors reported that the tool sustained 38 min of machining time, a considerably high value to achieve at these cutting speed values. Due to these high cutting speeds, the tool generates very high cutting temperatures, over 1000 °C, this promoting diffusion wear mechanisms. Çelic et al. [55] were researching these same wear mechanisms, comparing a SiAlON tool, with other with TiN particles added into its matrix. It was found that the addition of TiN promoted the tools' resistance to form diffusion zones. In addition to diffusion wear, the authors have reported high levels of material adhesion on the tools' flanks. On this adhered material, a diffusion scale was formed, causing the oxidation of Al and Ti atoms. Studies such as these are quite important, as understanding the wear types and wear mechanisms of the cutting tools is crucial when wanting to improve a cutting process [2,12]. There is quite a significant number of studies performed about the wear behaviour of ceramic tools, such as this by Zimmerman et al. [56], where the authors evaluate a SiAlON tool wear progression when machining a BLISK component made of Inconel 718. The authors have also used a carbide tool to produce the part. The use of ceramic tool proved to be highly productive, being used at 503 m/min, while the carbide tool was used at 40 m/min. Only air cooling was used during the machining operation using ceramic tools, while flood cooling was required for the carbide tool. Regarding machining time, the total machining time for the carbide tool was 4 min and 30 s, while with the ceramic tool the operation time was 1 min and 35 s. Regarding the wear analysis, the authors have reported high levels of adhered material to the tools' edges, resulting in BUE formation. Additionally, adhesive wear was reported as well as alteration in tool geometry. Flank wear measurements could not be performed due to high amounts of adhered material at this area. Still regarding wear analysis of ceramic tools used in Inconel 718 machining operations, Ma et al. [57], evaluated cutting performance and tool wear of SiAlON and TiC-whisker-reinforced Si₃N₄ ceramic tools in dry side-milling operations. The authors tested the tools at 200 m/min, 275 m/min and 350 m/min, at a depth of cut of 5 mm. Additionally, they tested three feed-per-tooth values, 0.08 mm/tooth, 0.10 mm/tooth and 0.12 mm/tooth. Tools had a cutting diameter of 10 mm and had six flutes. It was concluded that both tools presented very similar wear behaviour, presenting high levels of adhered material to the cutting edges. Additionally, there was evidence of BUE formation for both tools, although for the TiC-whisker-reinforced tools, this BUE was stripped off the tools' edge more easily for higher cutting speed values. Adhesive wear and crater wear were also reported on the tools.

The high cutting speeds and, consequently, the high cutting temperatures associated with machining operations carried out using ceramic tools, cause deformation on the machined surface damaging the workpiece's surface integrity. There are studies conducted on this regard, as the one presented by Finkeldei et al. [58], where the authors evaluate the surface integrity of the workpiece after machining Inconel 718 alloy with Si₃N₄ ceramic

tools. Solid ceramic tools were used, having a tool diameter of 12 mm and six flutes. These tools were employed at 625 m/min of cutting speed, a feed-per-tooth value of 0.032 mm/tooth and a depth of cut of 1 mm. The authors assess that the machined surface quality is quite poor, with the workpiece's surface presenting micro-cracks as well as grain deformation on a layer with a thickness of 75 μm . Low machined surface quality and damaged workpiece surface integrity seems to be one of the downsides of using ceramic tools for machining Inconel 718. Similar conclusions were drawn by Zimmerman et al. [59], this time using SiAlON end-mills. The higher surface roughness layer, or even damaged layer at the surface of workpiece material needs to be removed with an extra finishing operation using a different tool, which hinders process productivity.

To mitigate these surface integrity problems, as well as the wear problems commonly found when machining with ceramic tools, alternative cooling/lubrication conditions can be applied, with some cases of use of MQL paired with SiAlON tools on hard-to-cut materials, such as titanium alloys, producing satisfactory results [60,61], in some cases MQL can improve the tool-life by 75% when compared to dry cutting, due to the method's capacity in reducing thermal shock phenomena during machining [62]. Marques et al. [63], studied turning operations of Inconel 718 with whisker-reinforced ceramic tools using vegetable-based cutting fluid MQL mixed with solid lubricants, MoS_2 . The authors have tested the influence of cutting speed on the sustained tool wear as well as on the machined surface integrity. They selected 250 m/min to evaluate tool-life, however, they have selected values between 100 and 300 m/min, with 50 m/min increments, to evaluate the influence on the machined surface. Regarding feed rate and depth of cut, these values were 0.1 mm/rev and 0.5 mm, respectively. Regarding tool life, it was concluded that the addition of solid lubricants in the MQL system caused an improvement in tool-life by approximately 22%, when compared to just MQL. However, tool life was improved by 46% when compared to dry turning conditions. Despite retarding the sustained tool wear, the use of these lubrication methods did not change the main wear types developed during machining. The cutting tools presented mainly evidences of material adhesion, abrasive wear and diffusion. Regarding machined surface quality, it was significantly improved when using these methods, although MQL and MQL with solid lubricants proved to be quite close in terms of measured surface roughness, which was $R_a = 0.6 \mu\text{m}$, lower than the value produced for dry turning conditions, which was $R_a = 0.8 \mu\text{m}$. As for machined surface integrity, for the start of the machining tests, no clear influence was noted on the workpiece's surface. However, as the machining continues and tool wear progresses, the alteration in cutting edge geometry causes deformations on the workpiece surface.

Analysing the current research studies conducted on the use of ceramic tools in machining operations of Inconel 718, the most popular topics are:

- Studying wear behaviour of ceramic cutting tools, as well as of wear mechanisms and wear evolution for different machining conditions;
- Testing of alternate lubrication and cooling conditions while machining Inconel 718 with ceramic tools— This is mainly due to the poor surface quality obtained with ceramic cutting tools;
- Tests regarding analysis of surface integrity, as these tools induce high levels of deformation on the machined surface, as well as producing poor surface quality.

There are not a large amount literature and research studies performed about these types of cutting tools, despite the material not being novel itself. Only now, researchers and practitioners are focusing more on the application of ceramics, such as SiAlON to produce machining tools. This is due to its high potential, high productivity and material removal rates, while sustaining less wear (particularly in more aggressive machining conditions) than the WC-Co and CBN tools. Also worthy of noting the potential of these tools from a sustainability standpoint, with them being used primarily under dry conditions, these tools are not as hard or unsustainable to produce as their WC-Co and CBN counterparts [15,18].

6. Comparison of Tool Material Performance during Milling Operations of Inconel 718

An analysis of recent machining studies was made, focusing solely on the milling operations of Inconel 718, using ceramic tools as well as cemented carbide tools. The articles and studies selected for this analysis were based on experimental studies, published from 2017 onward, on the application of these two tool materials, using parameters and setups that emulate or can be compared to real-life industry applications. Information on productivity and production quality will be presented for both tool materials, namely the material removal rate (MRR), expected surface roughness (R_a), as well as tool-life and registered wear mechanisms. Tables 1 and 2 will show this information, facilitating the comparison of these two tool materials' potentials when machining Inconel 718. Additionally, good machining practices identified, when machining this alloy, will be presented, these are practices that lead to increase in productivity or production quality as well as reduction of sustained tool wear.

Table 1. Study summary of ceramic cutting tool productivity and production quality.

Title	Tool Material and Geometry	Cutting Parameters	Results	
Wear behavior of solid SiAlON milling tools during high-speed milling of Inconel 718 [55]	- SiAlON (T1); - TiN reinforced SiAlON (T2); - 12 mm diameter; - 6 flutes.	$V_c = 585$ m/min $ae = 0.635$ mm $ap = 9.652$ mm $fz = 0.18$ mm/rev Strategy: - Side milling; - Spiral strategy; - Dry.	Material removal rate	17.6 cm ³ /min
			Surface quality	N/A
Tool wear progression of SiAlON ceramic end mills in five-axis high-feed rough machining of an Inconel 718 BLISK [56,59]	- SiAlON; - 8 mm diameter; - 35 mm length (T1); - 51 mm length (T2) - 4 flutes.	$V_c = 503$ m/min $ae = 8$ mm $ap = 0.4/0.24$ mm $fz = 0.15/0.08$ mm/tooth Strategy: - Full diameter milling; - Multiple roughing passes varying ap and fz ; - Dry.	Material removal rate	8.28 cm ³ /min
			Surface quality	N/A
Cutting performance and tool wear of SiAlON and TiC-whisker-reinforced Si ₃ N ₄ ceramic tools in side milling Inconel 718 [57]	- SiAlON (T1); - TiC-whisker reinforced Si ₃ N ₄ (T2); - 10 mm diameter; - 6 flutes	$V_c = 200/275/350$ m/min $ae = 0.5$ mm $ap = 5$ mm $fz = 0.08/0.10/0.12$ mm/tooth Strategy: - Side milling; - Linear strategy; - Dry.	Material removal rate	[7.6–20.1] cm ³ /min
			Surface quality	- Ra values measured between 1 and 3 μm; - Higher cutting speed values produced better Ra;
End milling of Inconel 718 using solid Si ₃ N ₄ ceramic cutting tools [58]	- Solid Si ₃ N ₄ (T1); - 12 mm diameter; - 6 flutes.	$V_c = 625$ m/min $ae = 12$ mm $ap = 1$ mm $fz = 0.032$ mm/tooth Strategy: - Full diameter milling; - Dry.	Material removal rate	38.19 cm ³ /min
			Surface quality	N/A
Suitability of the full body ceramic end milling tools for high-speed machining of nickel-based alloy Inconel 718 [62]	- Solid SiAlON, CVD coated Al ₂ O ₃ ; - 6 mm diameter; - 6 flutes.	$V_c = 600$ m/min $ae = 4$ mm $ap = 0.35$ mm $fz = 0.024$ mm/tooth Strategy: - Roughing, spiral strategy (facing); - Dry/MQL/Air-blast	Material removal rate	6.88 cm ³ /min
			Surface quality	N/A
			Tool-life and wear	- 36 min (for both tools); - Diffusion wear; - High material adhesion.
			Tool-life and wear	- Up to 45 cm ³ of machined material for T1; - Up to 30 cm ³ of machined material for T2.
			Tool-life and wear	- T2 produced better surface quality than T1. - Sustained tool wear more severe on T2; - Main wear mechanisms are chipping for T1 and chipping as well as material adhesion for T2.
			Tool-life and wear	- Tools present severe damage after 3 min of machining; - Main wear mechanisms are chipping and material adhesion
			Tool-life and wear	- Tool life for dry and air-blast machining at 3.1 min; - For MQL, maximum tool life is 0.8 min; - Main wear mechanisms are chipping and material adhesion

Table 1. Cont.

Title	Tool Material and Geometry	Cutting Parameters	Results
Influence of process parameters on the cutting performance of SiAlON ceramic tools during high-speed dry face milling of hardened Inconel 718 [64]	- SiAlON cutting inserts; - 63.5 mm of tool diameter; - 6 cutting teeth.	$V_c = 500/700/900/1100/1300$ m/min $ae = 34.5$ mm $ap = 1$ mm $fz = 0.04$ mm/tooth Strategy: - Horizontal face-milling; - Air-blast cooling; - Variation of cutting speed.	Material removal rate [22.91–59.59] cm ³ /min
			Surface quality N/A
Investigation of machinability in milling of Inconel 718 with solid SiAlON ceramic tool using supercritical carbon dioxide (scCO ₂)-based cooling conditions [29]	- SiAlON; - 8 mm diameter; - 4 flutes.	$V_c = 100/150/200$ m/min $ae = 8$ mm $ap = 0.5$ mm $fz = 0.05$ mm/rev Strategy: - Full diameter milling; - Dry; - CO ₂ ; - MQL + CO ₂ ; - Oil droplets (OoW) + CO ₂ ;	Material removal rate [0.80–1.59] cm ³ /min
			Surface quality - Ra values measured between 0.8 and 2.5 μm; - Increase in V_c parameter decreases quality; - Lowest Ra value obtained using OoW + CO ₂ condition.
Roughing Milling with Ceramic Tools in Comparison with Sintered Carbide on Nickel-Based Alloys [65]	- SiAlON tools; - 12 mm diameter; - 4 flutes	$V_c = 452/680$ m/min $ae = 1$ mm $ap = 5.6$ mm $fz = 0.03$ mm/tooth Strategy: - Side-milling; - Dry.	Material removal rate [8.13–12.1] cm ³ /min
			Surface quality N/A
Life Cycle Assessment for Rough Machining of Inconel 718 Comparing Ceramic to Cemented Carbide End Mills [66]	- SiAlON tools; - 16 mm diameter; - 4 flutes.	$V_c = 800$ m/min $ae = 16$ mm $ap = 0.4$ mm $fz = 0.1$ mm/tooth Strategy: - Roughing of a blade shaped component (full diameter milling); - Dry.	Material removal rate 40.74 cm ³ /min
			Surface quality N/A
Tool life and wear mechanisms of CVD coated and uncoated SiAlON ceramic milling inserts when machining aged Inconel 718 [67]	- Use of coated and uncoated SiAlON inserts; - Uncoated (T1); - TiN + TiCN + Al ₂ O ₃ CVD coated SiAlON (T2); - TiN + Al ₂ O ₃ bilayer CVD coated SiAlON (T3); - 40 mm diameter; - 4 inserts.	$V_c = 700/800/900/1000$ m/min $ae = 30$ mm $ap = 1$ mm $fz = 0.1$ mm/tooth Strategy: - Linear up-milling roughing strategy; - Dry.	Material removal rate [66.84–95.50] cm ³ /min
			Surface quality N/A
Tool life and wear mechanisms of CVD coated and uncoated SiAlON ceramic milling inserts when machining aged Inconel 718 [67]	- Use of coated and uncoated SiAlON inserts; - Uncoated (T1); - TiN + TiCN + Al ₂ O ₃ CVD coated SiAlON (T2); - TiN + Al ₂ O ₃ bilayer CVD coated SiAlON (T3); - 40 mm diameter; - 4 inserts.	$V_c = 700/800/900/1000$ m/min $ae = 30$ mm $ap = 1$ mm $fz = 0.1$ mm/tooth Strategy: - Linear up-milling roughing strategy; - Dry.	Tool-life and wear - Uncoated inserts (T1) achieved the more consistent cutting performance, removing 170 cm ³ of material before failing, at 900 m/min; - Coated inserts tested at different cutting speed values performed better than the uncoated ones; - Main wear mechanisms were adhesive and abrasive wear, with the former being more prominent on coated tools; - Heating and cooling cycles induced greater levels of flank wear on the coated tools, indicating that CVD coatings should be avoided on SiAlON tools.

Table 2. Study summary of WC-Co cutting tool productivity and production quality.

Title	Tool Material and Geometry	Cutting Parameters	Results	
			Material removal rate	
Investigations on the Surface Integrity and Wear Mechanisms of TiAlYN-Coated Tools in Inconel 718 Milling Operations [23]	Use of TiAlYN coated end-mills; 6 mm diameter; 4 flutes.	$V_c = 75/100/125$ m/min $ae = 4.5$ mm $ap = 0.08$ mm $f_z = 0.0525/0.07/0.105$ mm/tooth Cutting length = 5/15 m Strategy:	Material removal rate	[0.30–1.00] cm ³ /min
			Surface quality	<ul style="list-style-type: none"> - As expected, increasing cutting length leads to higher measured Ra values; - Lower f_z values paired with lower V_c leads to a better surface quality, with the best Ra value being 0.372 μm, obtained at these lowest parameters; - Increasing V_c, even for cutting lengths of 5 m leads to an increase in Ra values.
			Tool-life and wear	<ul style="list-style-type: none"> - Main wear mechanisms identified were: material adhesion; abrasive wear and coating delamination; - Increasing V_c leads to an increase in sustained flank wear; - Even at 5 m of cutting length, cutting tools show maximum VB (flank wear) values of 0.6 mm (for $V_c = 125$ m/min), while the lower value registered at this V_c being 0.341 mm; - Lower f_z value lead to an increase in sustained flank wear (due to workpiece contact period being higher); - Maximum registered wear value was near 0.800 mm, for $f_z = 0.0525$ mm/tooth and $V_c = 125$ m/min; - Tools should not machine over 5 m of cutting length, VB values are quite high.
The effect of chip formation on the cutting force and tool wear in high-speed milling Inconel 718 [68]	PVD TiAlN coated square inserts; Use of a cutting tool with 63 mm diameter; 5 cutting inserts.	$V_c = 60/80//100/120$ m/min $ae = 10$ mm $ap = 0.2$ mm $f_z = 0.15$ mm/tooth Strategy:	Material removal rate	[0.45–0.90] cm ³ /min
			Surface quality	N/A
			Tool-life and wear	<ul style="list-style-type: none"> - The inserts sustained mainly abrasive wear, registered for all cutting speeds; - Increasing the V_c value resulted in more severe abrasive wear as well as crater wear, chipping and cracking of the tools' substrate.
Wear Behavior of TiAlVN-Coated Tools in Milling Operations of INCONEL 718 [69]	Use of TiAlVN coated end-mills; 6 mm diameter; 4 flutes.	$V_c = 75/100/125$ m/min $ae = 4.5$ mm $ap = 0.08$ mm $f_z = 0.0525/0.07/0.105$ mm/tooth Cutting length = 5/15 m Strategy:	Material removal rate	[0.30–1.00] cm ³ /min
			Surface quality	<ul style="list-style-type: none"> - There is an influence of f_z parameter on the obtained surface quality, with an increase in this parameter resulting in higher surface roughness, particularly for tests conducted at 15 m of cutting length; - An increase in cutting length increases the measured Ra value; - Best measured Ra, 0.563 μm value is for the $V_c = 125$ m/min, $f_z = 0.0525$ mm/tooth and at 5 m of cutting length; - Maximum Ra value is 2.142 μm, being registered at $V_c = 100$ m/min, $f_z = 0.105$ mm/tooth and at 15 m of cutting length; - The cutting speed seems to not influence much the obtained Ra values, with it being mainly affected by an increase in f_z parameter.
			Tool-life and wear	<ul style="list-style-type: none"> - The main identified wear mechanisms were coating delamination, followed by abrasive wear and some material adhesion; - It is important to note that the tool coating suffered severe delamination on all tested tools; - It seems that, for cutting lengths of 5 m, an increase in cutting speed leads to less sustained VB wear, with the best result being obtained for $V_c = 125$ m/min, $f_z = 0.07$ mm/tooth and a cutting length of 5 m, this being 371 μm; - For higher values of cutting length it seems that V_c has a reverse impact, with an increase resulting in lower sustained VB; - Highest measured flank wear was 667 μm, registered at $V_c = 100$ m/min; $f_z = 0.105$ mm/tooth and a cutting length of 15 m.

Table 2. Cont.

Title	Tool Material and Geometry	Cutting Parameters	Results
Wear Behavior Analysis of TiN/TiAlN Coated Tools in Milling of Inconel 718 [70]	- Use of TiN/TiAlN coated end-mills; 6 mm diameter; 4 flutes.	$V_c = 75/100/125$ m/min $ae = 4.5$ mm $ap = 0.08$ mm $f_z = 0.07$ mm/tooth Cutting length = 5/15 m Strategy: - Spiral facing strategy (center to periphery); - Flood-cooling.	Material removal rate [0.40–0.67] cm ³ /min - There is a clear influence of cutting length on the measured surface roughness, as expected, as the sustained flank wear negatively impacts the machined surface quality; - Increasing the cutting speed causes the machined surface roughness to also increase, this may be related to sustained flank wear, as higher speeds also contribute to higher flank wear; - The lowest measured R_a value was of 0.370 μ m, for the condition of 75 m/min and cutting length of 5 m; - Still regarding this cutting length value, the maximum measured R_a value for these tests as of 0.502 μ m, registered after machining at 125 m/min; - At 15 m of cutting length, the same trend was registered, the values were considerably higher, however, with the maximum R_a value being registered at 125 m/min, and being 0.786 μ m, followed by the condition at 100 m/min, being 0.737 μ m.
			Tool-life and wear - Main wear mechanisms identified were: material adhesion; abrasive wear and coating delamination; - There is a significant influence of cutting speed and length on the sustained flank wear; - For cutting speeds of 75 m/min the flank wear increases from 80.24 μ m to 256.55 μ m (from 5 m to 15 m of cutting length); - For cutting speeds of 100 m/min the flank wear increases from 89.37 μ m to 536.60 μ m; - For cutting speeds of 125 m/min the flank wear increases from 190.05 μ m to 545.34 μ m; - This indicates that the tools sustain flank wear more rapidly at higher cutting speed values (over 75 m/min).
Wear Behavior Phenomena of TiN/TiAlN HiPIMS PVD-Coated Tools on Milling Inconel 718 [71]	- Use of TiN/TiAlN coated end-mills; 6 mm diameter; 4 flutes.	$V_c = 100/125$ m/min $ae = 4.5$ mm $ap = 0.08$ mm $f_z = 0.0525/0.07/0.105$ mm/tooth Cutting length = 5/15 m Strategy: - Spiral facing strategy (center to periphery); - Flood-cooling.	Material removal rate [0.40–1.00] cm ³ /min - There was an increase in machined surface roughness for longer tests, due to sustained flank wear; - Best machined surface quality, $R_a = 0.40$ μ m was obtained for lower f_z values, as well as lower V_c , being followed by the condition with $V_c = 125$ m/min and the lowest f_z ; - Increasing both f_z and V_c will result in higher machined surface roughness, even at low cutting length values (5 m); - Highest R_a value was of 0.82 μ m registered for highest f_z and V_c value, at a cutting length of 15 m.
			Tool-life and wear - Main wear mechanisms identified were: material adhesion; abrasive wear and coating delamination; - Increasing V_c leads to an increase in sustained flank wear; - Even at 5 m of cutting length increasing V_c to 125 m/min, will result in an increase in measured flank wear, the tools tested at $V_c = 100$ m/min, had VB near the 100 μ m, while the ones tested at $V_c = 125$ m/min, showed VB values near 200 μ m; - For lower cutting lengths there seems to be a decrease in flank with an increase in f_z parameter (albeit slight); - There are no clear trends identified for cutting lengths of 15 m, as the tools already sustained considerable flank wear, exhibiting over 500 μ m of flank wear for all tested conditions, reaching a maximum of 613 μ m for tools tested at $V_c = 125$ m/min; - Tools should not machine over 5 m of cutting length, VB values are quite high.
Influence of milling direction in the machinability of Inconel 718 with submicron grain cemented carbide tools [72]	- Use of two WC-Co grades (T1 and T2), uncoated; T1 is 1614 HV and T2 is 1567HV; T1 has 10% Co, whereas T2 has 9% Co; 10 mm diameter; 4 flutes.	$V_c = 15/75$ m/min $ae = 0.5$ mm $ap = 6$ mm $f_z = 0.016/0.031$ mm/tooth Strategy: - Up and down-milling strategies; - Dry machining.	Material removal rate [0.09–0.89] cm ³ /min - Best results were obtained with down-milling mode for all tested conditions; - Best surface roughness values were obtained by T1, at $V_c = 75$ m/min and $f_z = 0.016$ mm/tooth, this being 0.7 μ m; - Increasing parameters to their maximum value would result in an increase in R_a to 2 μ m; - There is a greater influence of f_z on measured R_a than that of V_c .
			Tool-life and wear - Maximum VB wear defined as 0.4 mm (end of tool-life); - Down-milling is more beneficial in terms of tool life for all tested parameters and tools; - Maximum tool-life is achieved by T1 in down-milling mode, removing 27 cm ³ before failing at $V_c = 15$ m/min and $f_z = 0.016$ mm/tooth; - Under the same conditions, T2 only removed 22 cm ³ ; - Increasing V_c and f_z reduces tool-life, with the lowest values being obtained by using the maximum parameters; - The main wear mechanism was cutting edge micro-chipping for lower cutting speeds; - For 75 m/min the registered wear mechanisms were material adhesion and abrasion.

Table 2. Cont.

Title	Tool Material and Geometry	Cutting Parameters	Results	
Effects of tool wear on machined surface integrity during milling of Inconel 718 [73]	Cemented carbide tool, PVD Nano-TiAlN coating; all end-mill with 8 mm diameter; 4 cutting flutes.	$V_c = 40$ m/min $ae = 0.25$ mm $ap = 0.4$ mm $f_z = 0.02$ mm/tooth Strategy: - Down-milling linear strategy of an angled surface (60°); - Flood-cooling.	Material removal rate 0.20 cm ³ /min	
			Surface quality	- The machined surface roughness increases as wear progresses, starting at around 0.6 μm at the start of testing, and increasing significantly at $VB = 0.2$ mm, to a Ra value of 1.25 μm; - At the end of testing, when tools reached maximum VB of 0.3 mm, the measured Ra values were 2.5 μm.
			Tool-life and wear	- End of tool-life defined for a VB value of 300 μm; - With tested parameters tools were able to machine for 350 min; - Wear stages are defined as initial wear, followed by steady wear (that increases not as sharply as the initial); - The final wear stage is characterized as sharp wear, rising very rapidly from the 340-min mark up until the end of the test; - Flank wear progresses steadily up until the $VB = 0.1$ mm, then wear grooves start appearing on the tools' flanks, deepening as the test progresses (notching, and abrasive wear).
Characterization of Tool Wear Mechanisms and Failure Modes of TiAlN-NbN Coated Carbide Inserts in Face Milling of Inconel 718 [74]	Use of coated PVD multi-layer TiAlN/NbN inserts; 32 mm diameter; 4 cutting inserts.	$V_c = 40/70$ m/min $ae = 12.5$ mm $ap = 1$ mm $f_z = 0.07/0.1/0.13$ mm/tooth Strategy: - Linear facing strategy; - Flood-cooling	Material removal rate [1.39–5.17] cm ³ /min	
			Surface quality	N/A
			Tool-life and wear	- End of tool-life defined for a VB value of 500 μm; - Higher values of V_c negatively impact tool-life, with the best wear results being obtained for tools tested at 40 m/min; - Increasing f_z parameter will also cause a more rapid increase in flank wear, with the best results being obtained for the $f_z = 0.07$ mm/tooth; - It was registered that at lower V_c and f_z values, the tools are subject to higher cutting temperatures, with wear mechanisms being associated with adhesive wear; - For higher speeds and feeds, the tools sustained considerably more abrasive wear and diffusion wear, failing more rapidly; - The main registered wear mechanisms were chipping, adhesive wear, abrasion and BUE.
A machine learning model for flank wear prediction in face milling of Inconel 718 [75]	Use of coated PVD multi-layer TiAlN/NbN inserts; 32 mm diameter; 4 cutting inserts.	$V_c = 40/60/80$ m/min $ae = 12.5$ mm $ap = 0.5/0.75/1$ mm $f_z = 0.07/0.1/0.13$ mm/tooth Strategy: - Linear facing strategy; - Flood-cooling (85% oil + 15% additives).	Material removal rate [0.69–5.17] cm ³ /min	
			Surface quality	N/A
			Tool-life and wear	- End of tool-life defined for a VB value of 500 μm; - Best tool-life obtained for a $f_z = 0.07$ mm/tooth and an $ap = 0.75$ and $V_c = 40$ m/min, reaching 5000 mm of cutting length; - Second best tool-life result obtained for the same f_z value but with an $ap = 1$ mm and $V_c = 40$ m/min. - There is a clear influence of f_z parameter on tool-life, as the latter decreases with an increase in f_z ; - Increasing ap also negatively impacts the tool-life, although, for tests conducted at 0.5 mm, the tools suffered high levels of localized chipping; - Regarding V_c , the tools sustained less wear for 40 m/min, followed by 60 m/min and achieving lowest values of tool-life for 80 m/min.
Wear behavior of ultrafine WC-Co cemented carbide end mills during milling of Inconel 718 [76]	Use of uncoated WC-Co end-mills; Two grades are tested, WC-Co (C1) and WC-(Ti,W)C-Co composite (C2); 5 mm diameter; 2 flutes.	$V_c = 20/30/40$ m/min; $ae = 2$ mm $ap = 0.1$ mm $f_z = 0.02$ mm/tooth Strategy: - Linear down-milling strategy; - Oil based lubrication	Material removal rate [0.010–0.051] cm ³ /min	
			Surface quality	- There is an influence of V_c and cutting length on the measured Ra values, this increasing with increase of both V_c and cutting length; - For C1 tools the measured Ra values were between 0.1 μm and 0.2 μm, rising throughout the test (for all tested V_c values), reaching a maximum of 0.25 μm at the end of testing; - For C2, there is a greater influence of V_c , with the tools tested at 40 m/min reaching higher values of Ra, between 0.15 μm and 0.25; For the rest of tested V_c values the measured Ra was between 0.10 and 0.15 μm, however, these tools did not machine a length as great as the C1 tools.
			Tool-life and wear	- For end of tool life criteria, a maximum VB value of 0.3 mm was chosen; - There is a clear influence of machining parameters on the tool-wear for both C1 and C2 tools, however, C1 tools had a greater tool-life; - For C1 tools, tested at 20 m/min, the tool life was 89.5 min; while at 40 m/min this value was 28.2 min; the main wear mechanism was adhesion, for all tested V_c values; - For C2 tools tested at 20 m/min the tool life was only 9.4 min, with material adhesion, and slight notch wear being registered; for V_c values of 40 m/min, the tool life was 3.8 min, with adhesion, crater, notch wear and chipping being registered.

7. Analysis of Presented Research

Analyzing both the information presented in Tables 1 and 2 as well as the presented in chapter 1, there is a clear difference of the machining parameters used for SiAlON and coated WC-Co tools, with the former needing to operate at high cutting speeds to be used effectively. This is also corroborated by a study conducted by Molaiekiya et al. [64], where the authors state that the optimal parameter range for these tools would be near the 900 m/min of cutting speed value. Of course, there are exceptions to this “rule”, however, these tools require high cutting speed values, especially when compared to coated WC-Co tools used to machine Inconel 718. If fact, analyzing the parameters presented in Table 2, the cutting speed values that are used to machine this alloy with coated WC-Co tools is around 10 times lower than those used with SiAlON tools. This, however, may cause some problems when using these tools, particularly solid SiAlON end-mills of a diameter less than 8 mm, as the rotational speed that is required to reach the optimal parameter range (in terms of cutting speed) can be very high, requiring more potent machining centers and CNC machines, which is not always possible by some manufacturers. However, productivity gains when using SiAlON tools compared against standard WC-Co, especially when looking at material removal rates, is undeniable. When using these tools for Inconel 718 milling operations, it is possible to achieve removal rates of up to 10 times higher than when using the more common coated WC-Co tools. Despite this, there are still problems regarding tool wear, but more importantly, the machined surface quality and integrity. As mentioned in the introductory section of this article, and as can be seen from the measured surface roughness values of the studies presented in Tables 1 and 2, the operations carried out using SiAlON tools produce a lower quality machined surface when compared to the coated WC-Co tools, this is not only due to the fact that these SiAlON tools can only be used under dry cutting conditions, but due to the fact that the high cutting speeds generate high cutting temperatures, which plasticize the workpiece material and cause adhesion to the workpiece’s surface itself. Additionally, these high temperatures cause grain deformation and refinement, as well as damage to the workpiece’s surface itself, causing micro-cracks as well as poor surface finish quality [77,78]. Looking once again, to the results presented in the above tables, it can be observed that in some cases the measured surface roughness is more than 3 times higher than that of what is achieved with coated WC-Co tools. Since the Inconel 718 components are required to be high quality and have high dimensional accuracy are somewhat preferable to the SiAlON tools and guarantee their use in milling operations of Inconel 718.

In the following Tables 3 and 4, a SWOT analysis is made for each of the analyzed tool materials, SiAlON and WC-Co, respectively.

Table 3. SWOT analysis on the use of SiAlON as a tool material to machine Inconel 718.

	Positive Factors	Negative Factors
Internal factors	<p>Strengths</p> <p>Highly productive, as it can be employed at very high cutting speeds. Optimally, it should operate at around 900 m/min.</p> <p>Is used in dry machining operations, making it a more sustainable alternative, especially when compared to more common flood cooling machining operations.</p>	<p>Weakness</p> <p>As they are used at very high cutting speeds, manufacturers are somewhat limited on the parameter range, requiring more potent machining centres overall, which can be quite expensive.</p> <p>High cutting speeds and temperatures cause damages to the workpiece’s surface, hindering quality and surface integrity. SiAlON and ceramic tool materials shatter easily, as such, there is a need to minimize impacts as well as the tool deflection itself, thus limiting cutting depth with end-mills made of these materials.</p>
	<p>Opportunities</p> <p>Given their high productivity these tools have a very high potential for roughing operations, as well as some semi-roughing operations.</p> <p>Pairing this tool material with other more conventional (and already in use) materials can improve the machining process itself, not only in terms of sustainability but also productivity.</p>	<p>Threats</p> <p>With the improvement of machining strategies, tool coatings and tool geometry, there are some competitive alternatives, in terms of productivity, to the SiAlON tools. Such as the use of coated carbide tools paired with trochoidal milling strategies. These have improved productivity while not sacrificing the quality of the machined surface.</p> <p>PCBN tools might offer a potential alternative to this tool material, in terms of productivity, surface quality and sustained tool wear.</p>
External factors		

Table 4. SWOT analysis on the use of WC-Co as a tool material to machine Inconel 718.

	Positive Factors	Negative Factors
Internal factors	<p>Strengths</p> <p>Most used tool material, heavily researched and optimized. As such, their parameter range is well known and usually easier to optimize than other, more novel, tool materials.</p> <p>High machined surface quality and dimensional tolerance is guaranteed when machining with coated cemented carbide tools. It is one of the main reasons as to why these are employed in the machining of Inconel 718.</p>	<p>Weakness</p> <p>Suffers considerable amounts of wear when machining Inconel 718, even only after machining few cm³.</p> <p>Low productivity, as it is required to operate at very conservative machining parameters (cutting speed and feed-per-tooth values).</p> <p>The process is not sustainable, from an environmental point of view, as it requires flood cooling during machining of Inconel 718.</p>
	External factors	<p>Opportunities</p> <p>With the development of improved machining strategies and tool coatings some problems associated with machining Inconel 718 can be mitigated, ensuring that WC-Co tools can keep being used in the machining of these alloys.</p> <p>Alternative cooling methods are also being developed which can improve the sustainability of the machining process when using these tools.</p>

Analyzing Tables 3 and 4, each of the tool materials have clear advantages and drawbacks. SiAlON is more suited for roughing operations; however, the production quality of SiAlON tools is not a match for WC-Co tools. Despite this, WC-Co tools are significantly less productive than their counterpart, requiring more conservative machining parameters, focusing on preserving and extending tool-life, while retaining a good production quality.

Focusing on industrial application of both tool materials is quite beneficial, as sometime researchers conduct studies under circumstances that are not replicable in an industrial setting, which is the most common setting in which these tools are used.

8. Conclusions

In the present review study, the recent trends regarding SiAlON tools and WC-Co tools applied in milling operations were analyzed, identifying them as well as presenting an analysis of studies that emulate industrial milling conditions while using these tools.

Inconel 718 machining remains quite relevant with authors still exploring ways to mitigate problems associated with the processing of this alloy, particularly aiming to mitigate problems such as tool wear and process sustainability. Regarding the coated WC-Co tools, authors focus on the study of new coatings, geometries and strategies. However, these studies reveal that these tools sustain high amounts of wear, even only after a few minutes of machining time. Rapid tool-wear remains a problem when machining with these tools that authors still seek to improve. However, the production quality obtained with these coated WC-Co tools is still unmatched, especially when compared to SiAlON tools. These ceramic tools have been heavily researched recently, particularly when applied to Inconel 718. They offer a more sustainable alternative than that of WC-Co, as they can only be employed for dry-milling operations. Furthermore, they boast a much higher productivity when compared to coated WC-Co tools. Despite this, there is still much room for improvement, especially when discussing machined surface integrity. Due to their operating range these SiAlON tools damage the machined surface, not being able to satisfy the requirements when producing Inconel 718 parts. As such, researchers continue to find ways to improve milling operations using these tools.

There is a clear gap in studies that evaluate and compare these tool materials directly, focusing not only on productivity and production quality but also on the environmental impact that these materials have. Additionally, by analyzing each of these tool materials individually it would not be beneficial, for example, SiAlON tools and WC-Co tools complement each other, as the former is more suited for roughing operations that involve high material removal rates. As such, this review study is quite beneficial, as it presents a clear comparison between these two material types while also considering industrial applications. Analyzing the obtained results, it can

clearly be seen that SiAlON tools are more suited for roughing operations, when compared to WC-Co tools, boasting high wear resistance and significantly more productivity. Furthermore, the operations carried out with SiAlON tools are more sustainable than ones carried out with WC-Co tools, as they do not require as much machining time and do not use cutting fluids or lubricants. Despite this, coated WC-Co tools remain in use as a standard in the part production industry. It is a well-known and researched material that can achieve the tight tolerances required when producing Inconel 718 parts. As such, the combination of these two tool materials for part production could be highly beneficial for the industrial scene, combining high productivity of SiAlON tools with high production quality of WC-Co tools.

Regarding future research directions, this work could be expanded to turning and other machining operations involving the processing of Inconel 718, focusing on other potential tool materials, for example PCBN. Furthermore, a detailed cost analysis per tool material could also be made, however this is quite difficult, and many researchers do not include cost information on their work. Additionally, CO₂ footprint and sustainability analysis of the use of SiAlON and coated WC-Co tools could also be made, some researchers are beginning to conduct such analyses, however, a detailed “production” cost and sustainability analysis should be made as such as a “in use” cost and sustainability analysis.

Author Contributions

Conceptualization: V.F.C.S., T.E.F.S., A.M.P.d.J. and W.D.; Data curation: V.F.C.S.; Formal analysis: V.F.C.S. and T.E.F.S.; Investigation: V.F.C.S. and T.E.F.S.; Methodology: V.F.C.S.; Project administration: A.M.P.d.J. and W.D.; Supervision: W.D. and A.M.P.d.J.; Validation: T.E.F.S., W.D. and A.M.P.d.J.; Writing—original draft: V.F.C.S.; Writing—review & editing: V.F.C.S., T.E.F.S., W.D. and A.M.P.d.J. All authors have read and agreed to the published version of the manuscript.

Funding

The authors would like to acknowledge the contribution of the FCT-MIT grant gratefully, with the reference PRT/BD/154305/2023 (<https://doi.org/10.54499/PRT/BD/154305/2023>). Additionally, the authors acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support to LAETA via the project UID/50022/2025 (DOI: <https://doi.org/10.54499/UID/50022/2025>).

Data Availability Statement

No applicable.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editorial Board Members, W.D. and A.M.P.d.J. had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Sousa, V.F.C.; Silva, F.J.G. Recent Advances in Turning Processes Using Coated Tools—A Comprehensive Review. *Metals* **2020**, *10*, 170. <https://doi.org/10.3390/met10020170>.
2. Sousa, V.F.C.; Silva, F.J.G. Recent Advances on Coated Milling Tool Technology—A Comprehensive Review. *Coatings* **2020**, *10*, 235. <https://doi.org/10.3390/coatings10030235>.
3. Mersni, W.; Boujelbene, M.; Ben Salem, S.; et al. Machining Time and Quadratic Mean Roughness Optimization in Ball End Milling of Titanium Alloy Ti-6Al-4V—Aeronautic Field. *Mater. Today Proc.* **2020**, *26*, 2619–2624. <https://doi.org/10.1016/j.matpr.2020.02.553>.
4. Kulkarni, H.B.; Nadakatti, M.M.; Kulkarni, S.C.; et al. Investigations on Effect of Nanofluid Based Minimum Quantity Lubrication Technique for Surface Milling of Al7075-T6 Aerospace Alloy. *Mater. Today Proc.* **2020**, *27*, 251–256. <https://doi.org/10.1016/j.matpr.2019.10.127>.
5. Singh, A.; Ghosh, S.; Aravindan, S. State of Art for Sustainable Machining of Nickel-Based Alloys Using Coated and Uncoated Tools and Machining of High Strength Materials Using Surface Modified Cutting Tools. *Tribol. Int.* **2022**, *170*, 107517. <https://doi.org/10.1016/j.triboint.2022.107517>.

6. Barros, R.; Silva, F.J.G.; Gouveia, R.M.; et al. Laser Powder Bed Fusion of Inconel 718: Residual Stress Analysis Before and After Heat Treatment. *Metals* **2019**, *9*, 1290. <https://doi.org/10.3390/met9121290>.
7. Teixeira, Ó.; Silva, F.J.G.; Atzeni, E. Residual Stresses and Heat Treatments of Inconel 718 Parts Manufactured via Metal Laser Beam Powder Bed Fusion: An Overview. *Int. J. Adv. Manuf. Technol.* **2021**, *113*, 3139–3162. <https://doi.org/10.1007/s00170-021-06835-8>.
8. Asala, G.; Andersson, J.; Ojo, O.A. A Study of the Dynamic Impact Behaviour of IN 718 and ATI 718Plus® Superalloys. *Philos. Mag.* **2019**, *99*, 419–437. <https://doi.org/10.1080/14786435.2018.1540891>.
9. Zhou, X.; Wang, K.; Li, C.; et al. Effect of Ultrafine Gradient Cemented Carbides Substrate on the Performance of Coating Tools for Titanium Alloy High Speed Cutting. *Int. J. Refract. Met. Hard Mater.* **2019**, *84*, 105024. <https://doi.org/10.1016/j.ijrmhm.2019.105024>.
10. Ji, W.; Zou, B.; Zhang, S.; et al. Design and Fabrication of Gradient Cermet Composite Cutting Tool, and Its Cutting Performance. *J. Alloys Compd.* **2018**, *732*, 25–31. <https://doi.org/10.1016/j.jallcom.2017.10.187>.
11. Uddin Siddiqui, T.; Kumar Singh, S. Design, Fabrication and Characterization of a Self-Lubricated Textured Tool in Dry Machining. *Mater. Today Proc.* **2021**, *41*, 863–869. <https://doi.org/10.1016/j.matpr.2020.09.259>.
12. Sousa, V.F.C.; Da Silva, F.J.G.; Pinto, G.F.; et al. Characteristics and Wear Mechanisms of TiAlN-Based Coatings for Machining Applications: A Comprehensive Review. *Metals* **2021**, *11*, 260. <https://doi.org/10.3390/met11020260>.
13. Sateesh Kumar, C.; Majumder, H.; Khan, A.; et al. Applicability of DLC and WC/C Low Friction Coatings on Al₂O₃/TiCN Mixed Ceramic Cutting Tools for Dry Machining of Hardened 52100 Steel. *Ceram. Int.* **2020**, *46*, 11889–11897. <https://doi.org/10.1016/j.ceramint.2020.01.225>.
14. Peng, Z.; Zhang, X.; Zhang, D. Performance Evaluation of High-Speed Ultrasonic Vibration Cutting for Improving Machinability of Inconel 718 with Coated Carbide Tools. *Tribol. Int.* **2021**, *155*, 106766. <https://doi.org/10.1016/j.triboint.2020.106766>.
15. Paturi, U.M.R.; Darshini, B.V.; Reddy, N.S. Progress of Machinability on the Machining of Inconel 718: A Comprehensive Review on the Perception of Cleaner Machining. *Clean. Eng. Technol.* **2021**, *5*, 100323. <https://doi.org/10.1016/j.clet.2021.100323>.
16. De Bartolomeis, A.; Newman, S.T.; Biermann, D.; et al. State-of-The-Art Cooling and Lubrication for Machining Inconel 718. *J. Manuf. Sci. Eng.* **2021**, *143*, 050801. <https://doi.org/10.1115/1.4047842>.
17. Thakur, A.; Gangopadhyay, S. State-of-the-Art in Surface Integrity in Machining of Nickel-Based Super Alloys. *Int. J. Mach. Tools Manuf.* **2016**, *100*, 25–54. <https://doi.org/10.1016/j.ijmachtools.2015.10.001>.
18. De Bartolomeis, A.; Newman, S.T.; Jawahir, I.S.; et al. Future Research Directions in the Machining of Inconel 718. *J. Mater. Process. Technol.* **2021**, *297*, 117260. <https://doi.org/10.1016/j.jmatprotec.2021.117260>.
19. Pusavec, F.; Hamdi, H.; Kopac, J.; et al. Surface Integrity in Cryogenic Machining of Nickel Based Alloy—Inconel 718. *J. Mater. Process. Technol.* **2011**, *211*, 773–783. <https://doi.org/10.1016/j.jmatprotec.2010.12.013>.
20. Matos, F.; Silva, T.E.F.; Marques, F.; et al. Machinability Assessment of Inconel 718 Turning Using PCBN Cutting Tools. *Procedia CIRP* **2023**, *117*, 468–473. <https://doi.org/10.1016/j.procir.2023.03.079>.
21. Bhattacharyya, S.K.; Jawaid, A.; Lewis, M.H.; et al. Wear Mechanisms of Syalon Ceramic Tools When Machining Nickel-Based Materials. *Met. Technol.* **1983**, *10*, 482–489. <https://doi.org/10.1179/030716983803291415>.
22. Matos, F.; Silva, T.E.F.; Sousa, V.F.C.; et al. On the Influence of Binder Material in PCBN Cutting Tools for Turning Operations of Inconel 718. *Materials* **2023**, *13*, 934. <https://doi.org/10.3390/met13050934>.
23. Silva, F.J.G.; Sebbe, N.P.V.; Costa, R.D.F.S.; et al. Investigations on the Surface Integrity and Wear Mechanisms of TiAlYN-Coated Tools in Inconel 718 Milling Operations. *Materials* **2024**, *17*, 443. <https://doi.org/10.3390/ma17020443>.
24. Meng, G.; Gong, Y.; Zhang, J.; et al. Microstructure Effect on the Machinability Behavior of Additive and Conventionally Manufactured Inconel 718 Alloys. *J. Mater. Process. Technol.* **2024**, *324*, 118228. <https://doi.org/10.1016/j.jmatprotec.2023.118228>.
25. Pimenov, D.Y.; da Silva, L.R.R.; Machado, A.R.; et al. A Comprehensive Review of Machinability of Difficult-to-Machine Alloys with Advanced Lubricating and Cooling Techniques. *Tribol. Int.* **2024**, *196*, 109677. <https://doi.org/10.1016/j.triboint.2024.109677>.
26. Shokrani, A.; Betts, J.; Jawahir, I.S. Improved Performance and Surface Integrity in Finish Machining of Inconel 718 with Electrically Charged Tungsten Disulphide MQL. *CIRP Ann.* **2022**, *71*, 109–112. <https://doi.org/10.1016/j.cirp.2022.04.068>.
27. Namlu, R.H.; Lotfi, B.; Kılıç, S.E. Multi-Axial Ultrasonic Vibration-Assisted Machining of Inconel 718 Using Al₂O₃-CuO Hybrid Nanofluid MQL. *Procedia CIRP* **2024**, *123*, 89–94. <https://doi.org/10.1016/j.procir.2024.05.018>.
28. Pedroso, A.F.V.; Sousa, V.F.C.; Sebbe, N.P.V.; et al. Cooling and Lubricating Strategies for INCONEL® Alloys Machining: A Comprehensive Review on Recent Advances. *J. Tribol.* **2025**, *147*, 060801. <https://doi.org/10.1115/1.4066955>.
29. Zhang, H.; Dang, J.; An, Q.; et al. Investigation of Machinability in Milling of Inconel 718 with Solid Sialon Ceramic Tool Using Supercritical Carbon Dioxide (ScCO₂)-Based Cooling Conditions. *Ceram. Int.* **2022**, *48*, 4940–4952. <https://doi.org/10.1016/j.ceramint.2021.11.032>.

30. Shah, P.; Khanna, N.; Arora, A.; et al. Comparison of LN2 and LCO2 Based on Machining Performance Indicators for Drilling Inconel 718. *J. Manuf. Process.* **2022**, *81*, 444–466. <https://doi.org/10.1016/j.jmapro.2022.07.002>.
31. Betts, J.; Glanvill, S.; Shokrani, A. Impact of Directionality and Heat Treatment on Machining of Additively Manufactured Inconel 718. *CIRP Ann.* **2024**, *73*, 69–72. <https://doi.org/10.1016/j.cirp.2024.04.057>.
32. Sousa, V.F.C.; Silva, F.J.G.; Fecheira, J.S.; et al. Cutting Forces Assessment in CNC Machining Processes: A Critical Review. *Sensors* **2020**, *20*, 4536. <https://doi.org/10.3390/s20164536>.
33. Pereira Guimarães, B.M.; da Silva Fernandes, C.M.; Amaral de Figueiredo, D.; et al. Cutting Temperature Measurement and Prediction in Machining Processes: Comprehensive Review and Future Perspectives. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 2849–2878. <https://doi.org/10.1007/s00170-022-08957-z>.
34. Guimarães, B.; Rosas, J.; Fernandes, C.M.; et al. Real-Time Cutting Temperature Measurement in Turning of AISI 1045 Steel through an Embedded Thermocouple—A Comparative Study with Infrared Thermography. *J. Manuf. Mater. Process.* **2023**, *7*, 50. <https://doi.org/10.3390/jmmp7010050>.
35. Li, C.; Zhao, G.; Meng, F.; et al. Multi-Objective Optimization of Machining Parameters in Complete Peripheral Milling Process with Variable Curvature Workpieces. *J. Manuf. Process.* **2024**, *117*, 95–110. <https://doi.org/10.1016/j.jmapro.2024.03.004>.
36. Zhujani, F.; Todorov, G.; Kamberov, K.; et al. Mathematical Modeling and Optimization of Machining Parameters in CNC Turning Process of Inconel 718 Using the Taguchi Method. *J. Eng. Res.* **2025**, *13*, 320–330. <https://doi.org/10.1016/j.jer.2023.10.029>.
37. Hegab, H.; Salem, A.; Rahnamayan, S.; et al. Analysis, Modeling, and Multi-Objective Optimization of Machining Inconel 718 with Nano-Additives Based Minimum Quantity Coolant. *Appl. Soft Comput.* **2021**, *108*, 107416. <https://doi.org/10.1016/j.asoc.2021.107416>.
38. Pedroso, A.F.V.; Sousa, V.F.C.; Sebbe, N.P.V.; et al. A Brief Review of INCONEL® Alloys Numerical Analysis on Traditional Machining Predictability. *Procedia Comput. Sci.* **2024**, *232*, 1109–1120. <https://doi.org/10.1016/j.procs.2024.01.109>.
39. Kumar, M.S.; Reddy, S.R.; Vasu, V. A 3-D Simulation and Experimental Study of Cutting Forces in Turning Inconel-718. *Mater. Today Proc* **2017**, *4*, 9942–9945. <https://doi.org/10.1016/j.matpr.2017.06.298>.
40. Paturi, U.M.R.; Methuku, S.; Siripragada, S.S.; et al. Finite Element Simulations of Machinability Parameters in Turning of Inconel 718. *Mater. Today Proc.* **2021**, *38*, 2658–2663. <https://doi.org/10.1016/j.matpr.2020.08.275>.
41. Pedroso, A.F.V.; Sebbe, N.P.V.; Costa, R.D.F.S.; et al. INCONEL® Alloy Machining and Tool Wear Finite Element Analysis Assessment: An Extended Review. *J. Manuf. Mater. Process.* **2024**, *8*, 37. <https://doi.org/10.3390/jmmp8010037>.
42. Klocke, F.; Kuchle, A. Cutting Tool Materials and Tools. In *Manufacturing Processes 1*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 95–196. https://doi.org/10.1007/978-3-642-11979-8_4.
43. Dudzinski, D.; Devillez, A.; Moufki, A.; et al. A Review of Developments towards Dry and High Speed Machining of Inconel 718 Alloy. *Int. J. Mach. Tools Manuf.* **2004**, *44*, 439–456. [https://doi.org/10.1016/S0890-6955\(03\)00159-7](https://doi.org/10.1016/S0890-6955(03)00159-7).
44. Sousa, V.F.C.; Silva, F.J.G.; Alexandre, R.; et al. Study of the Wear Behaviour of TiAlSiN and TiAlN PVD Coated Tools on Milling Operations of Pre-Hardened Tool Steel. *Wear* **2021**, *476*, 203695. <https://doi.org/10.1016/j.wear.2021.203695>.
45. Lopes Correia Pinto, G.F.; Almeida, D.; Silva, F.; et al. Correlating Cutting Performance and Surface Roughness under Different Bias Using TiAlTaN Coated Milling Tools. *J. Mech. Eng. Manuf.* **2025**, *1*, 7. <https://doi.org/10.53941/jmem.2025.100007>.
46. Pandey, K.; Datta, S. Performance of Si-Doped TiAlxN Supernitride Coated Carbide Tool during Dry Machining of Inconel 718 Superalloy. *J. Manuf. Process.* **2022**, *84*, 1258–1273. <https://doi.org/10.1016/j.jmapro.2022.10.078>.
47. Grigoriev, S.; Vereschaka, A.; Uglov, V.; et al. Influence of Tribological Properties of Zr-ZrN-(Zr,Cr,Al)N and Zr-ZrN-(Zr,Mo,Al)N Multilayer Nanostructured Coatings on the Cutting Properties of Coated Tools during Dry Turning of Inconel 718 Alloy. *Wear* **2023**, *512–513*, 204521. <https://doi.org/10.1016/j.wear.2022.204521>.
48. Chandra Behera, G.; Prasad Sahoo, S.; Kumari, S.; et al. Study on Wear Morphology of Uncoated and MT-CVD TiCN-Al2O3 Coated Carbide Inserts during Dry Machining of Inconel 825 Superalloy. *Mater. Today Proc.* **2023**, *in press*. <https://doi.org/10.1016/j.matpr.2023.02.013>.
49. Zhao, J.; Liu, Z.; Wang, B.; et al. PVD AlTiN Coating Effects on Tool-Chip Heat Partition Coefficient and Cutting Temperature Rise in Orthogonal Cutting Inconel 718. *Int. J. Heat. Mass. Transf.* **2020**, *163*, 120449. <https://doi.org/10.1016/j.ijheatmasstransfer.2020.120449>.
50. Kumar, S.; Saravanan, I.; Patnaik, L. Optimization of Surface Roughness and Material Removal Rate in Milling of AISI 1005 Carbon Steel Using Taguchi Approach. *Mater. Today Proc.* **2020**, *22*, 654–658. <https://doi.org/10.1016/j.matpr.2019.09.039>.
51. Pedroso, A.F.V.; Sousa, V.F.C.; Sebbe, N.P.V.; et al. A Review of INCONEL® Alloy’s Non-Conventional Machining Processes. In Proceedings of FAIM 2023, Porto, Portugal, 18–22 June 2023; pp. 773–783. https://doi.org/10.1007/978-3-031-38241-3_86.
52. Iturbe, A.; Hormaetxe, E.; Garay, A.; et al. Surface Integrity Analysis When Machining Inconel 718 with Conventional and Cryogenic Cooling. *Procedia CIRP* **2016**, *45*, 67–70. <https://doi.org/10.1016/j.procir.2016.02.095>.
53. Sivarupan, T.; Bermingham, M.; Ng, C.-H.; et al. A Review of the Use of Cryogenic Coolant during Machining Titanium Alloys. *Sustain. Mater. Technol.* **2024**, *40*, e00946. <https://doi.org/10.1016/j.susmat.2024.e00946>.

54. Khosrowshahi, J.H.; Aramesh, M. Surface Integrity Enhancement of Inconel 718 in Dry Turning Using Novel Soft Metallic Coated Lubricants. *Procedia CIRP* **2024**, *123*, 505–510. <https://doi.org/10.1016/j.procir.2024.05.088>.
55. Çelik, A.; Sert Alağaç, M.; Turan, S.; et al. Wear Behavior of Solid SiAlON Milling Tools during High Speed Milling of Inconel 718. *Wear* **2017**, *378–379*, 58–67. <https://doi.org/10.1016/j.wear.2017.02.025>.
56. Zimmermann, R.; Welling, D.; Venek, T.; et al. Tool Wear Progression of SiAlON Ceramic End Mills in Five-Axis High-Feed Rough Machining of an Inconel 718 BLISK. *Procedia CIRP* **2021**, *101*, 13–16. <https://doi.org/10.1016/j.procir.2021.02.003>.
57. Ma, Z.; Xu, X.; Huang, X.; et al. Cutting Performance and Tool Wear of SiAlON and TiC-Whisker-Reinforced Si₃N₄ Ceramic Tools in Side Milling Inconel 718. *Ceram. Int.* **2022**, *48*, 3096–3108. <https://doi.org/10.1016/j.ceramint.2021.10.084>.
58. Finkeldei, D.; Sexauer, M.; Bleicher, F. End Milling of Inconel 718 Using Solid Si₃N₄ Ceramic Cutting Tools. *Procedia CIRP* **2019**, *81*, 1131–1135. <https://doi.org/10.1016/j.procir.2019.03.280>.
59. Zimmermann, R.; Michel-Angeli, N.; Welling, D.; et al. Surface Integrity in High-Feed Roughing of Inconel 718 with SiAlON End Mills. *Procedia CIRP* **2022**, *108*, 595–600. <https://doi.org/10.1016/j.procir.2022.03.094>.
60. Gautam, A.; Bartarya, G.; Dutta, P.; et al. Environment-Friendly Machining of Aerospace-Grade Ti Alloy Using SiAlON Ceramic and AlTiN Coated Carbide Inserts under Sustainable Biodegradable Mist Condition. *CIRP J. Manuf. Sci. Technol.* **2022**, *39*, 185–198. <https://doi.org/10.1016/j.cirpj.2022.08.006>.
61. Sun, H.; Zou, B.; Chen, P.; et al. Effect of MQL Condition on Cutting Performance of High-Speed Machining of GH4099 with Ceramic End Mills. *Tribol. Int.* **2022**, *167*, 107401. <https://doi.org/10.1016/j.triboint.2021.107401>.
62. Grguraš, D.; Kern, M.; Pušavec, F. Suitability of the Full Body Ceramic End Milling Tools for High Speed Machining of Nickel Based Alloy Inconel 718. *Procedia CIRP* **2018**, *77*, 630–633. <https://doi.org/10.1016/j.procir.2018.08.190>.
63. Marques, A.; Paipa Suarez, M.; Falco Sales, W.; et al. Turning of Inconel 718 with Whisker-Reinforced Ceramic Tools Applying Vegetable-Based Cutting Fluid Mixed with Solid Lubricants by MQL. *J. Mater. Process. Technol.* **2019**, *266*, 530–543. <https://doi.org/10.1016/j.jmatprotec.2018.11.032>.
64. Molaiekiya, F.; Stolf, P.; Paiva, J.M.; et al. Influence of Process Parameters on the Cutting Performance of SiAlON Ceramic Tools during High-Speed Dry Face Milling of Hardened Inconel 718. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 1083–1098. <https://doi.org/10.1007/s00170-019-04210-2>.
65. Fernández-Lucio, P.; Pereira Neto, O.; Gómez-Escudero, G.; et al. Roughing Milling with Ceramic Tools in Comparison with Sintered Carbide on Nickel-Based Alloys. *Coatings* **2021**, *11*, 734. <https://doi.org/10.3390/coatings11060734>.
66. Fricke, K.; Zimmermann, R.; Ganser, P.; et al. Life-Cycle-Assessment for Rough Machining of Inconel 718 Comparing Ceramic to Cemented Carbide End Mills. In Proceedings of the ASME Turbo Expo 2022: Turbomachinery Technical Conference and Exposition, Rotterdam, Netherlands, 13–17 June 2022. <https://doi.org/10.1115/GT2022-82910>.
67. Osmond, L.; Cook, I.; Curtis, D.; et al. Tool Life and Wear Mechanisms of CVD Coated and Uncoated SiAlON Ceramic Milling Inserts When Machining Aged Inconel 718. *Proc. Inst. Mech. Eng. B J. Eng. Manuf.* **2024**, *238*, 1069–1083. <https://doi.org/10.1177/09544054231180653>.
68. Zhang, G.; Zhang, J.; Fan, G.; et al. The Effect of Chip Formation on the Cutting Force and Tool Wear in High-Speed Milling Inconel 718. *Int. J. Adv. Manuf. Technol.* **2023**, *127*, 335–348. <https://doi.org/10.1007/s00170-023-11551-6>.
69. Sebbe, N.P.V.; Fernandes, F.; Silva, F.J.G.; et al. Wear Behavior of TiAlVN-Coated Tools in Milling Operations of INCONEL[®] 718. *Coatings* **2024**, *14*, 311. <https://doi.org/10.3390/coatings14030311>.
70. Sebbe, N.P.V.; Fernandes, F.; Silva, F.J.G.; et al. Wear Behavior Analysis of TiN/TiAlN Coated Tools in Milling of Inconel 718. In Proceedings of FAIM 2023, Porto, Portugal, 18–22 June 2023; pp. 784–795. https://doi.org/10.1007/978-3-031-38241-3_87.
71. Filho, A.F.; da Silva, L.R.R.; de Souza Ruzzi, R.; et al. Influence of Milling Direction in the Machinability of Inconel 718 with Submicron Grain Cemented Carbide Tools. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 1343–1355. <https://doi.org/10.1007/s00170-019-04328-3>.
72. Sousa, V.F.C.; Fernandes, F.; Silva, F.J.G.; et al. Wear Behavior Phenomena of TiN/TiAlN HiPIMS PVD-Coated Tools on Milling Inconel 718. *Metals* **2023**, *13*, 684. <https://doi.org/10.3390/met13040684>.
73. Tan, L.; Yao, C.; Zhang, D.; et al. Effects of Tool Wear on Machined Surface Integrity during Milling of Inconel 718. *Int. J. Adv. Manuf. Technol.* **2021**, *116*, 2497–2509. <https://doi.org/10.1007/s00170-021-07626-x>.
74. Banda, T.; Ho, K.Y.; Akhavan Farid, A.; et al. Characterization of Tool Wear Mechanisms and Failure Modes of TiAlN-NbN Coated Carbide Inserts in Face Milling of Inconel 718. *J. Mater. Eng. Perform.* **2022**, *31*, 2309–2320. <https://doi.org/10.1007/s11665-021-06301-2>.
75. Banda, T.; Liu, Y.; Farid, A.A.; et al. A Machine Learning Model for Flank Wear Prediction in Face Milling of Inconel 718. *Int. J. Adv. Manuf. Technol.* **2023**, *126*, 935–945. <https://doi.org/10.1007/s00170-023-11152-3>.
76. Wang, B.; Wang, Z.; Yin, Z.; et al. Wear Behavior of Ultrafine WC-Co Cemented Carbide End Mills during Milling of Inconel 718. *Wear* **2024**, *546–547*, 205359. <https://doi.org/10.1016/j.wear.2024.205359>.

77. Molaiekiya, F.; Aliakbari Khoei, A.; Aramesh, M.; et al. Machined Surface Integrity of Inconel 718 in High-Speed Dry Milling Using SiAlON Ceramic Tools. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 1941–1950. <https://doi.org/10.1007/s00170-020-06471-8>.
78. Devillez, A.; Le Coz, G.; Dominiak, S.; et al. Dry Machining of Inconel 718, Workpiece Surface Integrity. *J. Mater. Process Technol.* **2011**, *211*, 1590–1598. <https://doi.org/10.1016/j.jmatprotec.2011.04.011>.