MALAYSIAN JOURNAL OF SCIENCE
MJS
ISSN 1394-3065

Regular Issue

Malaysian Journal of Science 44 (2): 104-114 (June 2025) https://mjs.um.edu.my

Study on Machinability Issues of Hard to Machining Inconel 718 - A Review

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Abstract: In the aerospace and automobile industries, there has been a recent growing demand for tough and heat-resistant materials. Processing these materials is difficult, primarily due to their mechanical properties, which include strong wear resistance, abrasion resistance, and low heat conductivity. This results in short tool lifetimes and high cutting temperatures and forces. Variations in machinability may be brought on by changes in material microstructures brought on by changes in chemical composition, forging methods, casting, and heat treatment. Because of their remarkable greater efficiency and effectiveness, Inconel 718 nickel superalloys are employed in numerous automotive, marine, and aviation applications. In contrast, Inconel 718's poor thermal conductivity and quick strain hardening made fabrication difficult and compromised the surface's machining ability. This study examines Inconel 718 machining problems, and the issue of dry machining and machining with nanofluids, which demonstrates advancements in research on improving surface quality and material removal rate by reviewing the properties of alumina (Al_2O_3)-based nanofluids.

Keywords: *Inconel 718, microstructure, machinability, tool wear, nanofluids.*

1. Introduction

Having an alloy proportion of more than 4%, high-alloy cast irons fall under this category of materials. Low-alloy cast iron, which has a Brinell hardness range of 350–550, is defined as cast iron with less than 4% alloy (HB). High alloy cast iron (450-850 HB) has significantly higher wear, heat, and corrosion resistance compared to unalloyed or Cast iron with low or moderate levels of alloy [1-5]. Nickel, vanadium, molybdenum, chromium, and copper are cast iron alloys most commonly used. Based on the amount of alloy in these materials, they are labelled Ni-Hard, Cr-Hard, etc. With a Rockwell C (HRC) hardness range of 58–65 and wear resistance, Ni-Hard is a high-alloy white cast iron.

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The result of these two factors is the material's resistance to corrosion. It is a nickel-based alloy commonly employed in aerospace applications with heat resistance and exceptional strength. With the alloy's extraordinary hardness and work-hardening properties, Inconel 718 machining is becoming increasingly difficult. Some researchers investigated the machinability of Inconel 718 by studying the effects of cutting conditions.

Cutting Condition

The cutting situations for white cast iron and its results, such as average surface roughness (Ra) and cutting force (Fc), were predicted and optimised using Taguchi's L18 orthogonal array (Ni-Hard). Output factor (Fc and Ra) to select the exact cutting parameters use “smaller-is-better" to evaluate the (Input) signal-to- (output) noise (S/N) ratio for the machining [18,26].

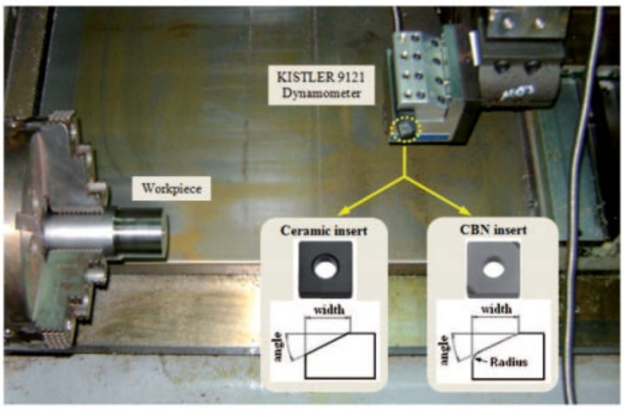

Figure 1. Experimental setup for turning operation of Inconel 718 bar [25]

DOI:https//doi.org/10.22452/mjs.vol44no2.10
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Figure 1 shows the experimental setup for turning the Inconel bar. Multiple researchers introduce various cutting conditions in Fig. 1. The cutting conditions include the Hardness of the workpiece, which is cast and has a hardness of 50 HRC, and after cooling, it has a hardness of 62 HRC. It is also in a vacuum furnace, with a pressure of 3 bar, and the job is tempered for a homogeneous microstructure. This indicates that for experimentation, we must prepare for cutting conditions.

The pineapple is believed to originate from Brazil. Once discovered, the pineapple was imported to Europe. Christopher Columbus and his men are thought to have tasted the pineapple initially. The word pineapple started to be used in English in 1938 which refers to the organs of conifer trees (Jungle Dragon, 2024). The European pioneers named the fruit as a 'pineapple' according to what is known as a pinecone. The term pinecone was first recorded in 1694, that is to supplant the importance of the pineapple (Hoque *et al*., 2019). According to Sun, (2015), the pineapple or *Ananas comosus L. Merr*. is widely accepted to have come from South America, Argentina, and Paraguay. The pineapple is known by the people of South America just before Christopher Columbus arrived in 1493. The European pilgrims use the word pineapple to present the natural product as to have come from pinecones. Meanwhile, the word Ananas is the initial name of the natural product that comes from the word for pine 'nanas' and 'comosus' referring to the tuft of the stem of the natural product (Jungle Dragon, 2024).

Pineapple is a significant nourishment crop which is planted widely in the tropical and sub-tropical regions of the world. It is a significantly produced natural product for business in Malaysia and is, for the most part, utilized as organic ingredients for pastry or to produce canned pineapple as cuts or rings, squeezes, and sticks. There are five assortments of pineapples in Malaysia; these include the Morris, Sarawak, Gandol, Josapine and N36 (Lasekan & Hussein, 2018). Pineapple processing such as canning and juice produces wastes including pineapple peels. Discharge of pineapple peels during this process will produce waste and lead to serious environmental pollution. In artificial practices, pineapple waste is either used as animal feed or disposed to the soil as waste. Natural enzyme contained in pineapple is called bromelain. Bromelain is an enzyme which is believed to have numerous benefits and is veritably promising to the development of food and medicinal diligence. Bromelain can be found in several parts of the pineapple. The specific part from which it is extracted lends its name to the enzyme; thus, we have fruit bromelain and stem bromelain (Bala *et al*., 2012). Bromelain activity has been reported to be within a pH range of 3 to 8 and a temperature range of 30–70 ºC (Kumar *et al*., 2011;Liang *et al*., 2012;Ramli *et al*., 2018). The natural bromelain enzyme has been used as a meat tenderizer, anti-browning agent and in the processing of formulas for babies (Tochi et al., 2008). As a protease, it hydrolyses proteins in these formulas, therefore making amino acids more readily available to babies. Bromelain is utilized in some applications including cosmetic and pharmaceutical and in textile industry as reported by (Aehle, 2007;B.K. Bhattacharrya, 2008;Ataide *et al*., 2018;Sancesario *et al*., 2018).

Some successful methods have been used for bromelain extraction and purification. Purification of enzymes is important to determine the three-dimensional structure of an enzyme and its impact on the functionality of the enzyme (A. Illanes, 2008). The successful methods in bromelain purification include aqueous two phase systems (Ketnawa *et al*., 2010;Ferreira *et al*., 2011), ammonium sulphate precipitation (G & Viswanathan, 2013;Gautam *et al*., 2010), ethanol precipitation (Martins *et al*., 2014), ion exchange chromatography (G & Viswanathan, 2013;Gautam *et al*., 2010; Bresolin *et al*., 2013), membrane separation (Seguí & Fito Maupoey, 2018) and adsorption using functionalized Santa Barbara Acid-15 (Arumugam & Ponnusami, 2013).

The pineapple variety Josapine was chosen because it is abundantly planted in Malaysia which covers about 41.5% or 6725 hectares. This shows that the waste produced by the pineapple industry is large at about 150 000 kg. Other than that, the pineapple variety Josapine was easily obtained and the price was affordable and cheap. Also, the pineapple variety Josapine was suitable for the canning industry (MPIB, 2022). The main reason to select the maturity index 5 and 7 is to determine whether there is a significant difference of bromelain activity among them. As a justification, the maturity index 3 and 4 is not chosen because their difference is too narrow while maturity index 5 is in the middle and maturity index 7 is overripe. Maturity index 1 is too young while maturity index 2 is usually selected for harvesting. Thus, the aim of this study was to determine the bromelain activity, protein content and specific enzyme activity of bromelain extracted from pineapple variety Josapine peel with maturity indices 2, 5 and 7.

2. Materials and Methods

Tool Life

Tool The challenges encountered when machining nickel-based alloys include shorter tool lifespans, low metal removal rates, high cutting pressures, increased power consumption, swarf disposal issues, and reduced metal removal efficiency. It emphasises the importance of CVD and PVD tool coatings in addressing these challenges. The study also examines the quality and consistency achieved through high-speed complex machining of hardened D2 tool steel using PCBN inserts. The research investigates the crystal and electrical structure analysis, micromechanical properties assessment, and resistance to short-term oxidation. Furthermore, it investigates the performance of coated tools in machining hardened H13 tool steel, nickel-based superalloys, and Ti alloys such as TiAl6V4 during ball nose end milling. The study includes tool life measurements with uncoated carbide inserts under varying coolant pressures and environments.

Received: December, 2023
Accepted: May, 2024
Published: June, 2025

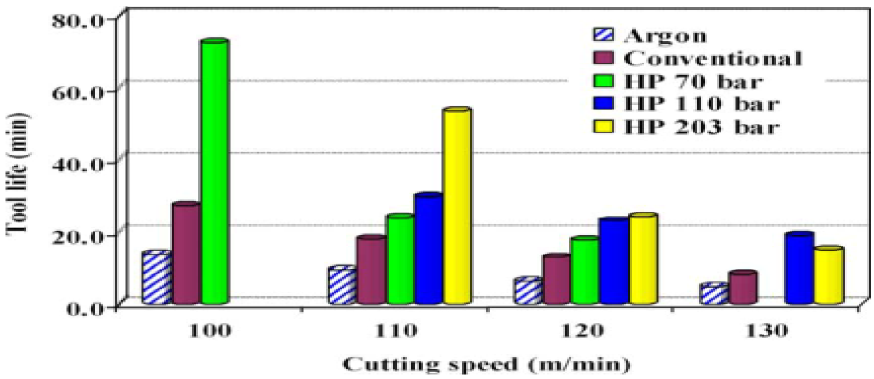

Figure 2a. Tool life Graph for uncoated carbide inserts [31]

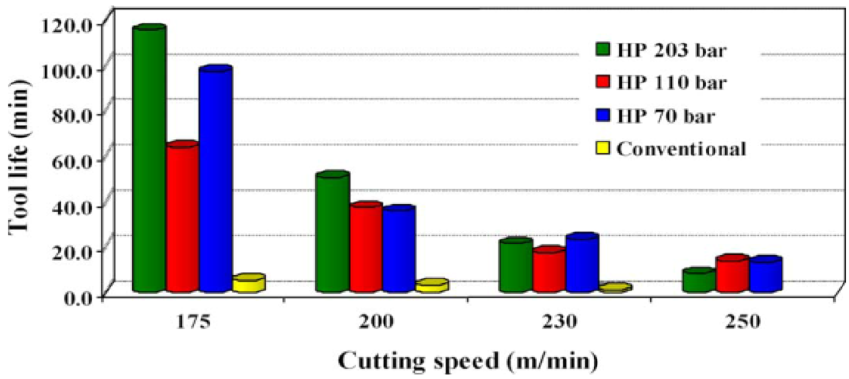

Figure 2b. Tool life Graph for uncoated Polycrystalline tool [31]

Figure 2b Tool life measurements were made when cutting titanium alloy with Polycrystalline diamond inserts and conventional coolant.

Tool wear

The research investigates various types of damage and wear in cutting operations. Different loading scenarios were used to simulate wear reliably in PCBN inserts. Understanding wear mechanisms significantly impacting component quality is essential to improve tool materials, primarily by reducing flank wear rates. It explores high-speed complex machining (HSHM) with hardened D2 tool steel, using PCBN inserts. It also investigates the use of CBN-TiN-coated inserts for turning tough materials. Additionally, it examines the effects of process parameters such as depth of cut, tool feed rate, cutting speed, and cutting pressures on surface finish, tool wear, and machining cost. The study identifies wear processes, including tribochemical reactions, fracture, abrasion, material transfer, and plastic flow, influenced by thermal and mechanical demands on the tool. Additionally, the research assesses the cutting environment's impact on the machinability of Inconel 718, using performance indicators like workpiece surface roughness, insert flank wear, and cutting pressures when utilizing a CNC lathe.

Turning is performed using coated carbide inserts with a standard of K05-K25 and a grade of WNMA 060408. The tool's average burn rate is relatively low at slower cutting speeds since the cutting zone has a low temperature. Faster tool wear-out at high cutting speeds leads to more severe patterns of tool failure, like severe notching. Better tool performance of a coating results from the tool being unable to operate within a particular temperature range. The performance of Inconel 718 with carbide tips was found to be inferior while cutting at a high pace. Due to the integrity of the surface being compromised by high cutting speeds, uncoated carbide tips are recommended over coated tips. Coated tips cannot improve high-speed performance. The tool-life wear diminishes below 250 m/min, and the maximum tool-life is found.

Diffusion loss occurs due to heat when cutting Inconel 718 using carbide tools. Figure 3a illustrates the wear of the tool as observed under the microscope. The measured levels for level 7 consist of a depth of cut of 0.25 mm, a feed rate of 100 mm/min, a spindle speed of 10,000 rpm, and tools with and without coating. Figures 3a and 3b show the tool effect of material loss for both tools (uncoated and coated).

DOI:https//doi.org/10.22452/mjs.vol44no2.10
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Figure 3a. Coated tool b) Uncoated tool [16]

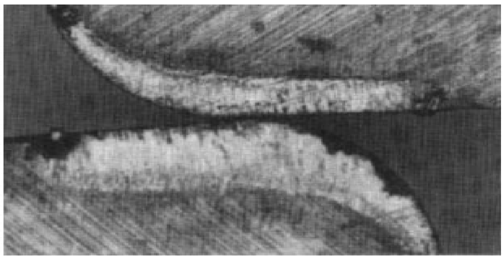

Figure 3b. Worn Tool [16]

The workpiece typically only receives 10% of the heat produced during machining, with the remaining 90% going to the chip and cutting tool. Figure 3a illustrates the coated tool's minimal wear. The induction heat source's radiant and friction heat harm the uncoated tool. The used tool is shown in Figure 3b after being machined. Figure 3c shows that the tool chip contact duration was reduced on the worn inserts' rake faces when cutting with a high-pressure coolant supply. [31]. This impact is displayed in Figure 4.

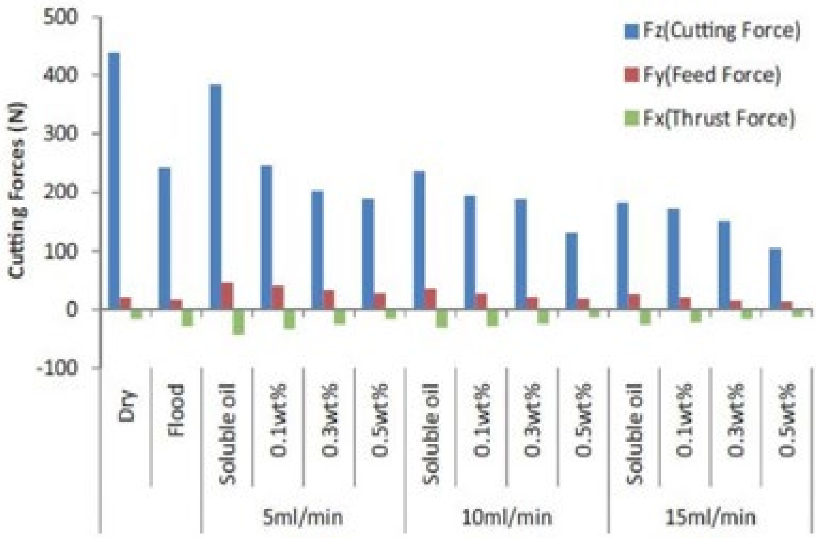

Figure 4. Variation in cutting forces with a cemented carbide tool under changing cutting parameters [3]

This might be the case because when air pressure rises, oil vaporises faster, forming tiny droplets of aerosol that get smaller as air pressure increases. This little aerosol is easy to insert into the tool, providing a low-cost heat-removal interface that reduces tool wear [33]. Tool life in the machining process utilising a CuO-based Nano fluid was investigated by Vazquez et al. By using CuO Nano fluid, the tool's service life was increased by 604%. CuO nanoparticles exhibit an anti-wear property. This results in a lower frictional coefficient caused by rolling action and CuO deposition on worn surfaces [33,34].

Effect of Contact Angle on Tool Wear

Using Al2O3 as a nano fluid, Mathew et al. adjusted the cutting parameters and nanoparticle concentration during the turning of EN8. Speed, feed, depth of cut, and nanoparticle concentration were the process variables used to evaluate surface roughness. Surface roughness was most significantly influenced by feed and nanoparticle concentration, according to analysis of variance (ANOVA) [37]. Several experiments evaluated the performance of the surface roughness of the H3BO3 microfluid and the MoS2 nanofluid in the MQL system while spinning the AISI 1040. They claim that while nano and

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microfluidic systems function nearly similarly at low speeds, nanofluidic systems outperform microfluidic systems at high speeds due to their superior lubricating and cooling abilities. Compared to H3BO3, MoS2 has a 30% lower surface roughness. This is due to reduced friction and associated effects caused by stable and consistent nanofluid lubrication.

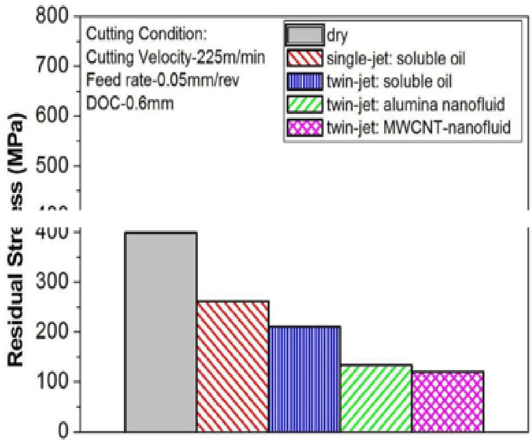

Figure 5. Residual stress on the machine surface under different cutting environments [7]

The researcher examined SiC nanoparticles for EN-24 material with 0.5, 1, and 1.5 weight percent and discovered that 1.5 weight percent SiC nanofluid showed the least surface roughness. This might be due to the cooling effect caused by the 0.5 weight percent SiC nanofluid, which has the maximum thermal conductivity and lowest coefficient of friction. As a result, decreased tool wear and surface roughness were produced [40]. Surface roughness diminishes gradually with increasing air pressure, but it lowers quickly up to 6 bar, according to research by Huang et al. on the MQL system. The creation of tiny droplets of oil aerosol, whose size decreases with rising air pressure, may cause a decrease in surface roughness because the flow rate increases as the air pressure rises. This small aerosol enters the tool with ease thanks to a low-cost interface that removes heat and, as a result, reduces surface roughness [41]. Table 1 provides a thorough analysis of surface roughness.

Table 1. Summary of surface roughness analysis.

Size	Nanoparticle	Process	Proportion	Base fluid	Remark	References
-	Al_2O_3	Turning	0.1,0.5& 1wt. %	Water	By Anova, nanoparticle concentration is the most influential factor, followed by F, S & Doc	36
90 &100	MoS2 & H3 BO3	Turning	0.25 wt %	Coconut Oil	Nanofluid provides 30% less Ra than Microfluid	37
80nm	Graphite	Running	0.3 wt %	Conventional water-soluble oil	For mist application with nanofluid Ra decreased by 42 %, 30 &, and 28% dry cut	35
30-40nm	Graphene	Turning	0,0.2,0.6,1 wt %	90 % water + 5 % servo cut the oil	Ra reduces at a higher % of grapheme in 95 % water, nano fluid with a high 5% servo cutting vel. & lower cutting 50% FR & DOC	36

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2-50 nm	MWCNT	Turning	0.6 vol %	Cutting oil	12 % improvement was observed in surface roughness	27
< 80 nm	Nano graphite	Turning	0,0.1,0.3, and 0.5 wt% %.	Water	Surface roughness was reduced with increasing nanoparticle concentration.	26
40 nm and 20 nm	CuO and Al_2O_3	Turning	0,0.25,0.5,1 %	Water-based oil	minimum surface roughness	24

Microstructure

Since the initial hardness of parts created using alloy 718 SLM print technology is larger than that made using wrought techniques, post-treatment is necessary to produce the desired conditions and characteristics. As a pre-aging treatment, these post-treatments must assess the effects on microstructure, hardening properties, and microsegregation at 1100 °C or 1250 °C. Printed samples are more complex than solutions composed of heat-treated samples because of the quantity of cooling and heating passes made during manufacturing. At the subgrain boundary, the components and leaves are thoroughly dissolved at 1200 °C for heat treatment. A coarsening effect on the grain was discovered following recrystallization during the solution treatment [27–36]. Figure 4 shows the Inconel 718 microstructure after 21 minutes of machining.

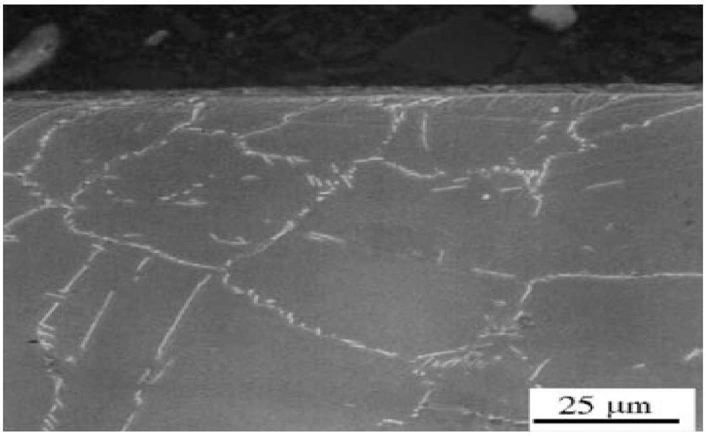

Figure 4. Inconel 718 microstructure following 21 minutes of machining with self-propelled rotary tools [31]

Grain Size

Compared to conventional material, the alloy Inconel 718 made using SLM techniques demonstrated excellent gamma size and diffusion dislocation. Both alloys' microstructures were fine-tuned, and their microhardness was raised due to the superalloy's higher torsion pressure. [21]

Hardness

Poor machinability and shorter tool life as a result of precipitated phases "Inconel 718's high hardness is also a result of and. Carbides form at temperatures between 600 and 670°C, and samples are reinforced at temperatures between 600 and 648°C ", the highest hardness rating of which has been validated and demonstrated to be 360 HV. [27,28]

Microstructure Study and Mechanical Testing

The workpiece's microstructure affected the cutting process's stability and the tool wear rate during machining the hard-to-machine titanium alloys (9Ti-6Al-4V and Ti-555). The results show that cutting tools wear differently while cutting the Ti-555 alloy than when cutting with a Ti-6Al-4V insert.

Microstructure and machining parameter research uses scanning electron microscopy (SEM), high-resolution photography as characterization techniques, transmission electron microscopy (TEM), and optical microscopy (OM).

CBN tool at the cutting conditions: v = 200 m/min, f = 0.08 mm/rev, and d = 0.2 mm result.

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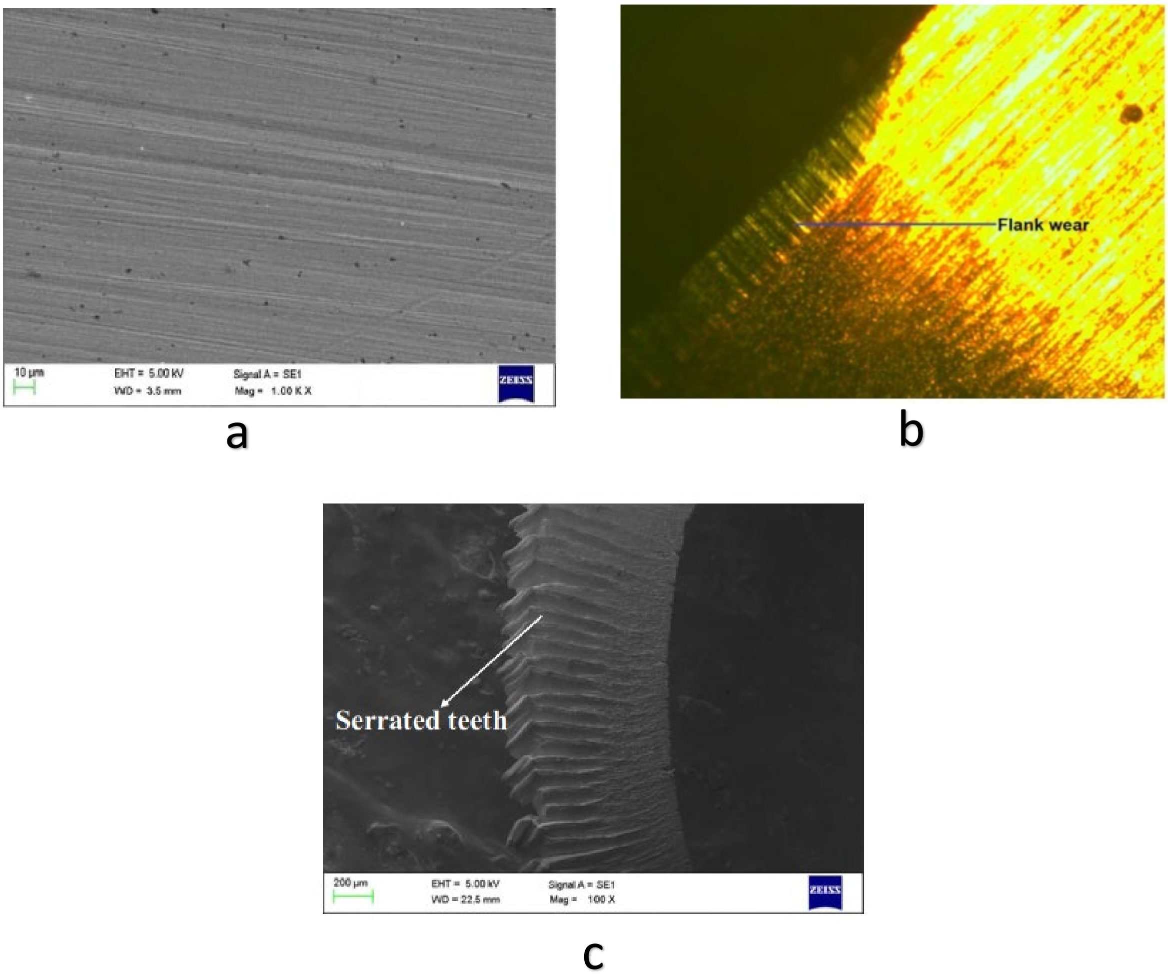

Figure 5. a) View of a machined surface using SEM [32] b) optical Image of flank wear in a CBN tool [32] c) SEM observation of chip morphology [32]

Figure 5 (A) shows a flat surface with a regular, smooth pattern and relatively few undulations, long scratch marks, and fine feed marks caused by shearing the machined work surface under the cutting edge, indicating a better surface finish. An acceptable level of surface roughness for the surface finish (Ra < 1.0 µm) was produced due to the exclusion of chatter formation, no chip entanglement, and less plastic deformation of the machined surface during machining. The scanning electron microscope (SEM) image of the challenging turned component, Figure 5 (b), shows the optical micrograph of the tool wear profile of the cBN tool at the flank face. The primary wear mechanism observed in hard turning is abrasion.

Machinability Issues

In terms of Inconel 718, significant developments and findings in its machining are discussed. Some alternatives to using coolants and various coating techniques have been researched to facilitate the switch to dry machining.

Machining Issues with Inconel 718

This study gives the significance of various cutting fluids when working with hard materials, which describes the characteristics of hard-to-machine materials and how to review and recognize them. Key environmental and health concerns related to using various coolants in the material cutting business are also examined. Finally, the review and discussion of the progress made in lowering fluid usage, reduction, or elimination. [24] By way of residual stresses, surface roughness, work hardening layers, and white layer, surface integrity (SI) issues have been characterized. Lowering constraints, the factors that most directly affect the SI of a hard-machined component are those related to the workpiece's material properties, the cutting tool's characteristics, the machine tool stiffness, and the cutting fluid qualities.[17]

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Phase and Structural Microstructure Study

Table 2. Techniques used to find various output parameters of complex machining.

Technique	Remarks	References
X-ray diffraction	Detailed microstructures and spots are scanned using a resolution between 11nm and 13nm during tool wear analysis.	15, 20
Scanning Electron Microscopy	The surface of the sample in 3D, the grain size, the tool wear morphology, and the material's texture	18

Effect of Nanofluid

Thermal conductivity increased by 19.74 % and 36.21% for Al2O3 and CuO nanofluid, respectively. For machining operation, a better heat transfer fluid was obtained at an optimum value of 0.3 volume % for Al2O3 and 0.15 volume % for CuO [22].

Table 3. The percentage of Al_2O_3 and CuO.

Reference	Base Fluid	Nanoparticle	Flow Rate	Wt Ratio
[11]	vegetable oil	Al_2O_3	100ml/h	0%, 4%, 6%vol
[12]	soluble cutting oil	Al_2O_3	-	0%, 0.1% wt.
[13]	Oil10 (SAE 10W)	CuO and AL_2O_3	-	0.2% to 1% and 0.5% to 2%
[14]	Soluble Cutting oil	Al2O3	40 ml/h	0.2%,0.4%,0.6% wt%1wt%
[15]	vegetable oil	Al2O3	2.5 mi/min	0.25,0.75and 1.25 vol%
[37]	distilled water	CuO and Al_2O_3	-	0.25%, 0.5%, 0.75% and 1.0% (wt. percentage)
[36]	Vegetable Oil	Al_2O_3	40 ml/hr	0% 2% 4% nano additives 0.2 g
[34]	E2000	Al_2O_3 and MWCNT	40 ml/hr	0, 2 and 4%
[32]	water	Al_2O_3 and CuO	-	0.05, 0.15,0.3, 0.5 and 1 vol. %.

From table 3, the percentage of Al2O3 and CuO used in the base fluid is analyzed and is shown in Figure 6.

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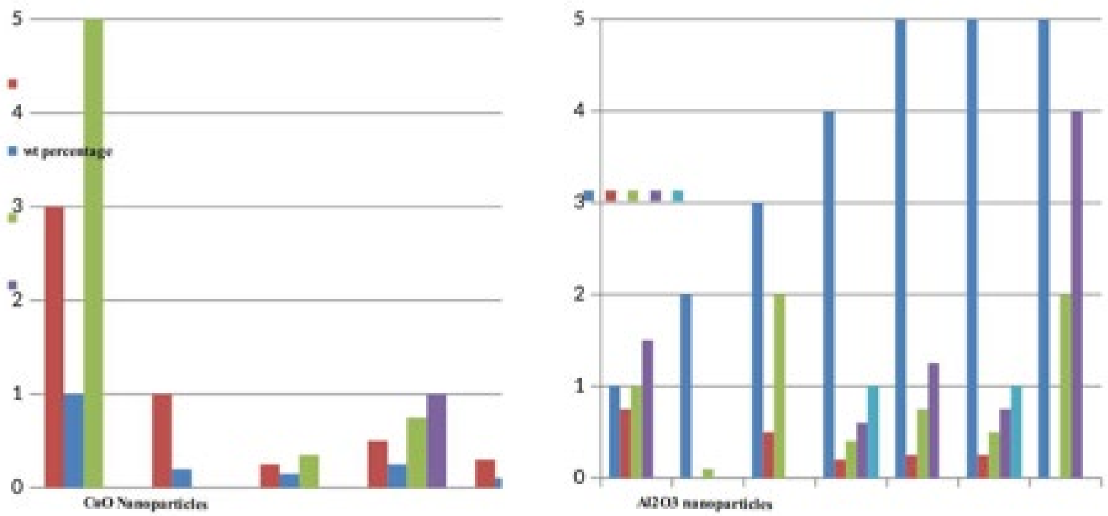

Figure 6. Weight of CuO and Al2O3 nanoparticles used by different researchers.

2. Conclusion

According to the above literature review, studies by various researchers identified several issues in terms of Machining Inconel 718

i. Since conductivity is low, thermal changes and microstructure changes make this material difficult to machine. Tool wear morphology, Grain size, material texture, and a 3D representation of the sample's surface were all examined using scanning electron microscopy.
ii. Tool wear analysis, spot scan, and microstructure area scan were performed using X-ray diffraction.
iii. Information about surface integrity and the formation of white layers is also included in the study.
iv. Investigating how to cut Inconel 718 material quickly results in BUC chips
v. Concluding that the use of coolant and dry machining has different effects on surface finish and MRR.
vi. Recognizing how tool wear and surface finish are affected by nanofluid.
vii. Recognizing how the nanofluid affects the surface roughness machining output parameter.

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