

RESEARCH ARTICLE

Effect of wear mechanism using dry and cryogenic cutting conditions on Inconel 718 using milling CNC

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Abstract - Dry and cryogenic machining are green machining methods that offer environmental sustainability. Dry machining eliminates any use of cutting fluids, while cryogenic machining uses very low machining temperatures. The current implementation method (cutting fluid assistance) exposes machine operators to health risks and negatively impacts the environment through waste disposal. Therefore, to overcome this problem, sustainable alternatives such as dry and cryogenic machining are required. However, both methods pose significant challenges due to increased wear and heat generation (overheating and overcooling). This study aimed to evaluate and differentiate the machining performance of dry and cryogenic methods while observing the tool wear mechanism. The methodology used was through: cutting speed (80 m/min), depth of cut (0.5 mm), feed rate (0.05 mm/tooth), and various radial depths of cut (5, 7.5, 10, and 20 mm). At the same time, the wear mechanism was observed through scanning electron microscopy (SEM). The study demonstrated that cryogenic machining significantly outperformed dry machining, consistently delivering 50% to 100% longer cutting lengths under aggressive cutting conditions and achieving a maximum tool-life extension of 42% at a radial depth of 5 mm. In contrast, dry conditions led to severe thermochemical wear mechanisms, including diffusion, oxidation, and adhesive wear, whereas cryogenic conditions primarily exhibited chipping and catastrophic failure modes. Based on studies, cryogenic machining is better than dry machining because it can significantly extend cutting tool life and reduce severe tool wear.

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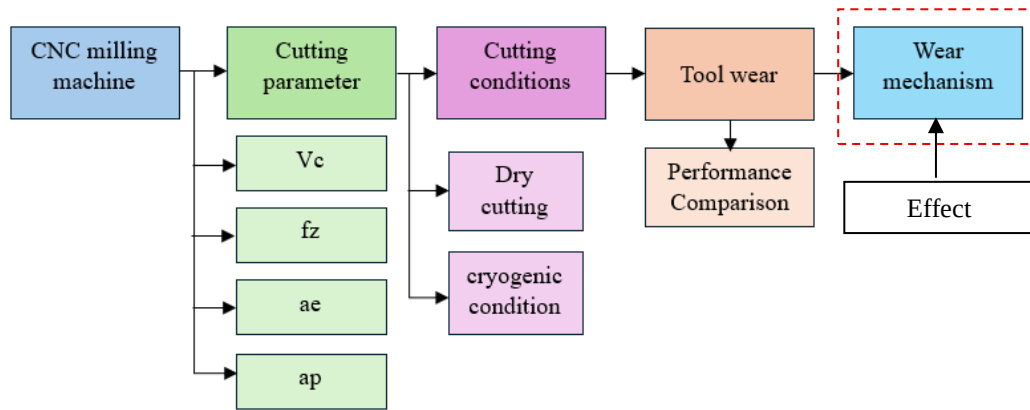
Tool wear

Wear mechanism

1. Introduction

Computer numerical control (CNC) milling is a subtractive manufacturing process that utilises pre-programmed computer software to control and automate the precise movement of cutting tools. Two machining methods were employed in this study: dry cutting and cryogenic cutting. Dry machining is a machining method that operates without a fluid or coolant. In contrast, cryogenic machining involves the introduction of extremely low-temperature coolants, typically liquid nitrogen or carbon dioxide. The problem being investigated is how dry cutting and cryogenic conditions affect tool life and wear mechanisms during CNC milling, using a variety of cutting parameters and radial depth of cut (ae), particularly for difficult-to-cut materials such as Inconel 718.

Dry cutting techniques are recognised for their positive environmental impact, but they can cause high thermal loads on the tool. The high temperatures generated by this friction result in forms of wear such as adhesive and abrasive wear. Both types of wear are major causes of reduced cutting tool life [1][2][3]. Although this dry cutting method offers advantages such as direct monitoring of the machining process without interrupting the cutting fluid, it has significant disadvantages that need to be addressed. These include the risk of heat generation during friction, which can subsequently form burrs on the cutting tool edge [4][5][6]. To overcome this problem, one method is the use of cooling agents, such as CO₂, which can effectively control the heat load and extend the life of the cutting tool. The use of CO₂ agents via cryogenic methods can reduce friction, thereby improving surface quality [7] and increasing the material's brittleness, thereby improving the machinability of difficult-to-cut materials [8]. Although superior at handling high heat generation, this method has certain limitations, especially under aggressive cutting parameters, which can cause the cutting tool to become brittle or crack [9][10]. Another factor to consider is the increase in cutting force due to material hardening at low temperatures, which can compromise the workpiece's structural integrity by forming microcracks if temperature management is not carefully controlled [11][12]. The main objective of this study was to compare the performance of cryogenic and dry machining and to observe and evaluate the wear mechanism during milling of Inconel 718 alloy. The main focus was on the temperature differences in the cutting zone that trigger different tool failure modes. Using various radial depths of cut (ae), this study tracked the evolution of wear, including abrasion, built-up edges (BUE), and crater wear, all of which affect tool integrity. In addition, this study provides critical insights into the inherent challenges of Inconel 718, particularly its low thermal conductivity and tendency to work-harden. Visually, the overall methodology of this study is illustrated in the pipeline shown in Figure 1.



Compared to the existing literature that focuses on comparing tool performance and surface quality between wet and dry methods [7][13][14], this study adopts a more in-depth approach. In addition to conventional experimental methods, the determination of tool life and milling stability regimes is now largely influenced by dynamic interactions, including cutting forces, cutting zone temperatures, and chatter phenomena. To address this complexity, previous studies have begun to integrate hybrid modelling methods and artificial intelligence, such as artificial neural network (ANN)-based approaches combined with optimisation algorithms (e.g., MPSO) to predict stability limits and maximise tool life optimally [15][16]. In particular, ANN models have been paired with PSO- or MOPSO-style approaches to predict cutting responses and then optimise parameters under multiple objectives, such as productivity, tool wear, and process quality [17]. However, a fundamental understanding of the shift in physical wear mechanisms, especially flank wear, under extreme environments (dry vs cryogenic) still requires in-depth microstructural analysis. The main focus of this study is to explore differences in wear mechanisms between dry and cryogenic machining, including rough groove morphology, diffusion layer profile, and material adhesion level, covering a wide range of ae . A notable difference in this study is the detailed correlation of the influence of ae on tool failure modes. In addition, a differential analysis is conducted between cryogenic (ultra-low) thermal shock and extreme thermal rise in dry cutting methods. Both methods can generally alter tribological conditions at the cutting tool tip, as shown. To date, the complex interactions between temperature, material dynamic properties, and wear evolution in such extreme environments have not been comprehensively discussed in the Inconel 718 machining literature.

2. Materials and Methods

This study outlines a comprehensive methodology for investigating the tool wear mechanisms in dry and cryogenic machining of Inconel 718. The objective is to systematically identify and characterise the dominant wear mechanisms, especially at varying ae while keeping V_c , f_z , and ap constant.

2.1 Materials

Inconel 718 is a nickel-chromium-based superalloy (UNS N07718) that maintains mechanical strength and corrosion resistance at extreme temperatures [18]-[19]. These properties make it a prime choice for the automotive and aerospace sectors. However, the advantages of this material make it very difficult to machine, posing significant technical challenges during machining [20]. Details of the chemical composition and mechanical properties of this alloy are summarised in Tables 1 and 2, respectively.

Table 1. Chemical composition of Inconel 718

Element	Ni	Cr	Mo	Ti	Al
Weight (%)	50.00 - 55.00	17.00-21.00	2.80-3.30	0.65 – 1.15	0.20-0.80

Table 2. Mechanical properties of Inconel 718

Properties	Density (g/cm ³)	Melting range (°C)	UTS (MPa)	Hardness Vickers (HV)
Value (Metric units)	8.19-8.22	1260-1336	1240-1540	360-480

2.2 Cutting Tool

The effectiveness of the machining process in dry and cryogenic modes depends on the type of cutting tool. This also accounts for the aggressive working environment, particularly the work hardening and high thermal loads encountered during the machining of Inconel 718. Special carbide cutting tools are used to ensure stability during milling. The selection of these cutting tools is based on their mechanical properties, which are enhanced by a titanium aluminium nitride (TiAlN) coating that provides additional friction shielding. For measuring cutting tool wear, the tool life criterion is set at an average flank wear (VB) of 0.3 mm, as specified in ISO 3685. Figure 2 shows the cutting tool (insert) located in the tool holder.

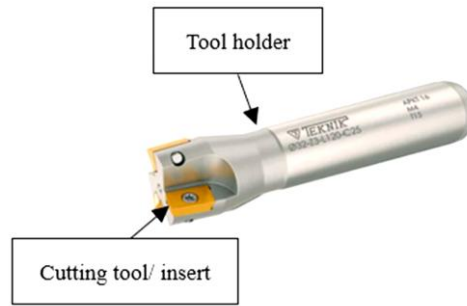


Figure 2. Cutting insert

2.3 CNC Milling Machine

CNC milling machines were used to study and compare the machining performance in dry and cryogenic conditions (as shown in Figure 3). For dry-cutting conditions, machining was performed without using cutting fluid or compressed air. It was carried out under ambient conditions of 20-25°C and relied entirely on natural air convection for heat dissipation. In comparison, cryogenic machining involved installing a system on a CNC milling machine (as shown in Figure 4).



Figure 3. CNC Milling machine (Model: Hwacheon)

The cryogenic system is achieved by connecting a compressed-air supply to the mixing chamber via an FRL (filter, regulator, and lubricator). At the same time, a CO₂ tank is connected to the mixing chamber, and a pressure gauge is installed to monitor the pressure, with an average CO₂ temperature of -78.5°C. In the CO₂ cooling technique, only carbon dioxide gas is used during machining. It is important to maintain the pressure at 1500 psi. Therefore, the pressure gauge must be monitored continuously. Finally, the nozzle, fed from the mixing chamber, was precisely placed in the cutting zone at a controlled flow rate (2-8 L/min) towards the cutting tool and Inconel 718. The cryogenic flow rate is increased in phases to prevent the cutting tool from experiencing sudden thermal surges. For example, a cryogenic flow rate of 2 L/min is used at a low a_e of 5 mm to minimise thermal load and avoid extreme cooling that could make the cutting tool too brittle early. A higher flow rate, i.e., up to 8 L/min, is progressively delivered at higher a_e (20 mm) to address extreme thermal surges resulting from greater volumetric interaction between the materials. [Post-machining analysis involved measuring tool wear with an optical microscope, and a scanning electron microscope (SEM) was used to observe the cutting tool's wear mechanism.

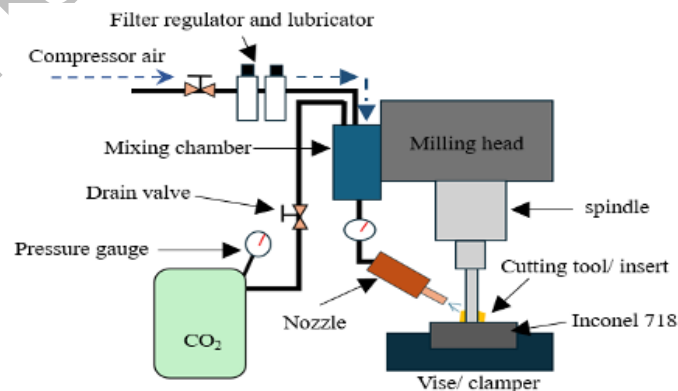


Figure 4. Cryogenic concept on CNC milling machine

To effectively study the tool wear mechanisms, a systematic experiment is detailed in Table 3. This study was specifically designed as a structured experimental matrix to evaluate the effects of evolution under varying a_e and cryogenic flow conditions. Other critical parameters, such as V_c , a_p , and f_z , were held constant to ensure that the results were attributable

solely to variations in a_e . This structured approach, comprising five distinct experimental conditions, enables a comprehensive analysis of how combinations of cutting parameters affect the dominant tool-wear mechanisms during machining of Inconel 718.

Table 3. Cutting parameters

Experiments (cutting tool)	V_c (m/min)	a_p (mm)	a_e (mm)	F_z (mm/tooth)	cryogenic flow rate L/min
1	80.0	0.5	5.0	0.05	2.0
2			7.5		4.0
3			10.0		6.0
4			20.0		8.0

3. Results and Discussion

Figure 5 shows a comprehensive comparison of flank wear versus cutting length for cryogenic and dry machining. Each figure displays a different a_e , namely 5 mm, 7.5 mm, 10 mm, and 20 mm. All figures clearly show that cryogenic machining outperforms dry cutting conditions in reducing side wear and thus extending tool life. The performance comparison shows that the effect of cryogenic cooling consistently dominates the cutting length results (regardless of a_e). However, its absolute effect on total tool life decreases as a_e increases. At lower a_e (5 mm), both dry and cryogenic machining recorded the longest cutting lengths, compared to the other a_e , before significant wear occurred under dry machining conditions. This situation is clearly seen after the cutting length reaches 2500 mm, and then increases significantly at 3500 mm.

In contrast, cryogenic machining maintains stable, minimal flank wear, reaching cutting lengths exceeding 5000 mm at an a_e of 5mm. In dry machining, high temperatures in the cutting zone increase the diffusion of elements from the workpiece into the cutting tool, leading to increased thermal and mechanical loads on the cutting edge and oxidation [21] [22]. This effect accelerates flank wear, especially when the tool is exposed for longer periods at low a_e , where heat dissipation is less efficient. In dry machining, this extreme heat accumulation causes thermal softening of the tool's bonding matrix, thereby accelerating micro-wear, including adhesive and abrasive wear. In contrast, the application of CO_2 maintains the tool's mechanical hardness at high temperatures (hot hardness) and stabilises the microstructural integrity of the TiAlN coating against premature degradation. This stability is particularly pronounced at low a_e , where the risk of excessive local heating is reduced by rapid heat extraction from the cutting zone [7][23]. As a_e increases from 7.5 mm to 10 mm and then to 20 mm, the wear rate increases progressively with decreasing cutting length under both cutting conditions. Increasing a_e can lead to accelerated wear rates due to higher mechanical loads that outweigh the benefits of cooling [11]. However, the performance of cryogenic machining consistently outperforms all other methods by reducing flank wear and allowing longer cutting lengths than dry cutting. For example, at $a_e = 10$ mm, dry machining fails quickly (1000 mm), while cryogenic machining achieves twice the cutting length (2000 mm) with comparable wear. Even under the most aggressive conditions ($a_e = 20$ mm), both machining conditions increase significantly early in the process, yet cryogenic machining still outperforms dry machining, recording cutting lengths exceeding 50%. The relative advantage of cryogenic cooling may persist at higher a_e , but absolute tool life will still decrease as a_e increases [11].

Comparisons of cryogenic and dry cutting conditions have shown that increasing the a_e indirectly increases the cutting temperature and force, thereby accelerating tool wear. However, cryogenic cooling effectively delays cutting tool wear and can extend tool life. This relationship has been consistently observed across studies, in which higher material removal rates are often achieved by increasing tool life, thereby reducing tool life during operation [24][25][26]. The consistently lower cryogenic flank wear compared to dry cutting indicates that very low coolant temperatures can efficiently remove heat from the cutting zone. This prevents thermal softening of the tool material, reduces adhesive and abrasive wear, and may influence chip formation during the interaction between the cutting tool and the chip [7].

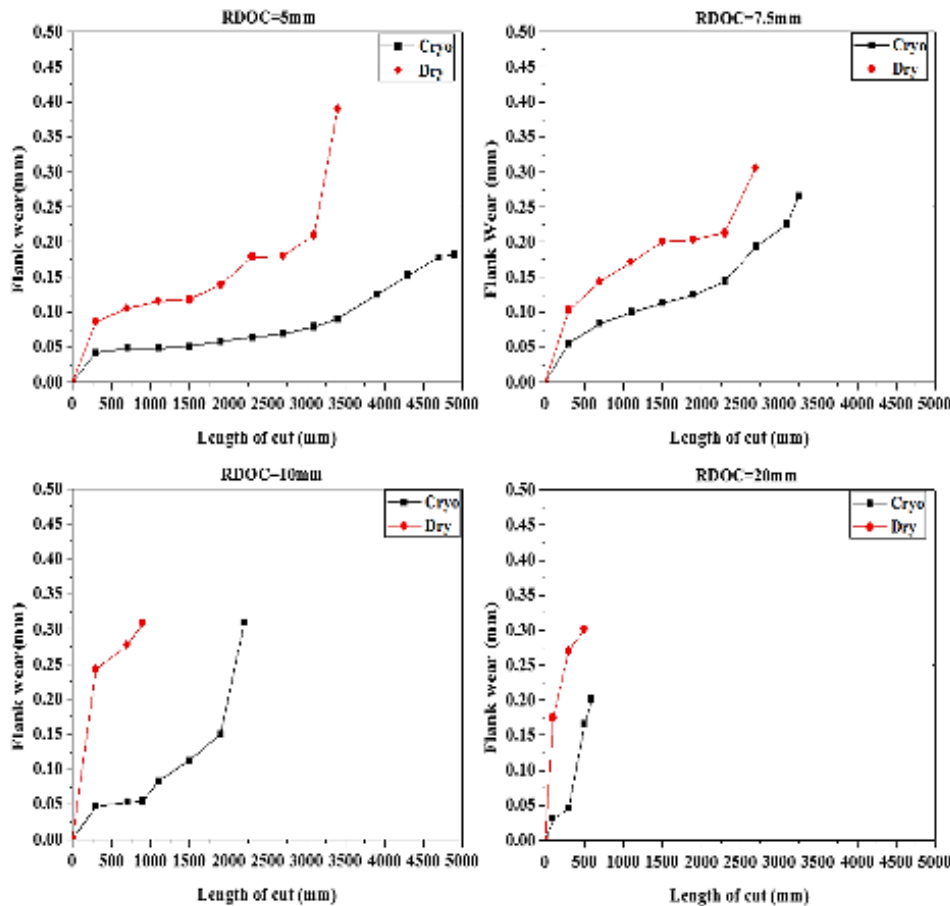


Figure 5. Performance comparison between dry and cryogenic cutting at ae of (a) 5mm, (b) 7.5mm, (c) 10 mm, and (d) 20 mm

3.1 Effect of Wear Mechanism in Dry Cutting

The SEM images in Figure 6 show a clear progression of wear mechanisms on the cutting tool at various radial depths of cut (ae). At an ae of 5 mm, as shown in Figure 6(a), the wear appears relatively uniform and limited, primarily exhibiting abrasive wear characterised by fine grooves or scratches on the tool surface. This wear pattern results from limited contact between the cutting tool and Inconel 718. Wear pattern consistent with the sliding action of the superalloy material against the cutting tool, where hard particles or asperities on the workpiece remove material from the tool surface [27].

Figure 6(b), which is at 7.5 mm, shows an abrasion mark with significant flank wear and chipping on the cutting edge. According to Liu et al. [28], flank wear occurs at the tool clearance angle caused by friction between the cutting tool and the workpiece. As a result of abrasive action, the hard grains of Inconel 718 scratch and gouge the material from the cutting tool. Although abrasion is the most obvious contributor, phenomena such as adhesion and friction involving localised welding and tool material fracture are also contributors [29][30]. In addition, the image clearly shows chipping at the cutting edge. This condition results from mechanical impact or excessive stress concentration [31]. This type of wear can lead to premature tool failure. Figure 6 (c) shows the appearance of flakes or grains of Inconel 718 material. This type of wear can also be characterised as a concave depression, often resulting from diffusion and chemical reactions between the workpiece and tool materials at the high temperatures generated during machining [20][32]. The presence of adherent Inconel 718 fragments or areas of material pulled out in the crater indicates that abrasive wear and adhesion are contributing factors. Adhesive wear, in which small particles of workpiece material adhere to the tool surface and are subsequently torn off, often manifests as material transfer and localised microcracking [33]. Cracking, characterised by the rupture of small fragments from the cutting edge, indicates a localised stress concentration that leads to brittle fracture. This mechanism becomes more pronounced as cutting force and temperature increase with greater depth of cut [34]. This increased wear is closely related to changes in the dynamic nature of the cutting process, including increased heat generation and friction at the cutting tool-workpiece interface, which accelerate the wear mechanism and reduce tool life [35].

At the largest ae (20 mm), as shown in Figure 7, the cutting tool shows an irregular wear pattern with large grain loss at the cutting edge and notch wear. According to Niu [2], wear increases under higher mechanical and thermal loads, accelerating the failure of the cutting tool. The increased material removal rate at higher ae leads to higher cutting forces, greater contact pressure between the cutting tool and Inconel 718, resulting in higher temperatures in the cutting zone. As the volume of material removed per unit time increases, the mechanical load, heat on the cutting tool, and heat of the

workpiece also increase [36][37]. The cumulative effect of these intensified interactions results in accelerated, more catastrophic tool degradation observed at higher radial depths of cut.

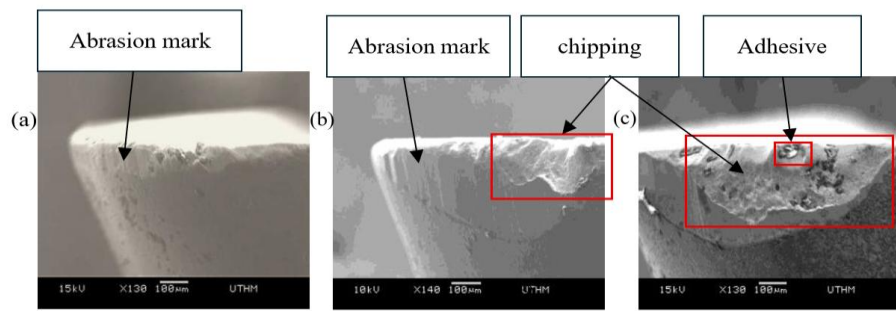


Figure 6. Wear mechanism at various ae on (a) 5mm, (b) 7.5 mm, and (c) 10 mm

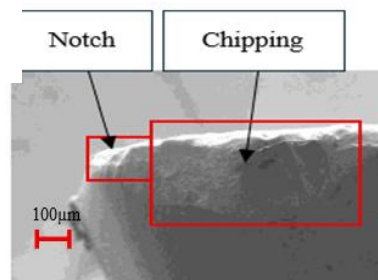


Figure 7. Wear mechanism at ae 20 mm

Figure 8(a) shows that Energy-Dispersive X-ray (EDX) spectroscopy was conducted to identify material transfer and elemental composition, which complements the morphological identification of the wear mechanisms at V_c 80 m/min and ae 7.5 mm. EDX analysis shows prominent peaks for Fe, Cr, and Ni, along with elements from the cutting tool coating (Ti, Nb, Mo). The spectral evidence indicates that the material adhering to the cutting tool surface is Inconel 718. In addition, this SEM image shows abrasion as another wear mechanism concentrated in Area A. Abrasion is characterised by the mechanical removal of cutting-tool material by the abrasive action of hard particles from the workpiece and chips [37]. EDX analysis of 'Region A' (Fig. 8a) clearly demonstrates two distinct tribological phenomena, namely the degradation of the cutting tool coating and the transfer of material (Inconel 718). The degradation of the tool coating was identified by the presence of prominent Ti and N peaks, indicating exposure of the TiAlN coating layer due to physical abrasion by hard particles. Meanwhile, the transfer of material from Inconel 718 was confirmed by the presence of minor peaks of Fe, Cr, and Ni in the same region. The presence of these peaks indicates that residual microfragments from Inconel 718 were mechanically adhered to the exposed TiAlN surface under the high temperatures and pressures during dry cutting. This indicates that the observed wear in this region is primarily due to degradation of the tool coating itself caused by abrasive contact. This experiment involves a close-up observation of the worn surface of the insert cutting tool, as shown in Figure 8(b). A region is shown at a higher magnification (1000x) than the 80x. The magnified regions were mainly adhesion wear. Adhesion wear occurs when two bodies are in sliding contact, whether lubricated or not; in this case, the condition was run dry. Essentially, adhesion is caused by high temperatures and pressures. Welding will occur between the tool and the workpiece at the rake face. This type of wear was observed during machining at high V_c , where the temperature can exceed the chemical dissolution temperature of tungsten carbide, 1100 °C [38]. Dry cutting conditions mainly trigger BUE formation on the cutting edge. Under these conditions, high local pressure and high temperature at the tool-chip interface result in micro-welding between the Inconel 718 and the wiper surface. 80 mm V_c and ae 7.5 mm do not produce sufficient thermal softening to allow smooth chip flow over the cutting edge, leading to the accumulation of adhering material and the formation of a stable BUE. Adhesion on the rake face of the cutting tool forms a BUE at the tool edge, which is present there due to the low V_c .

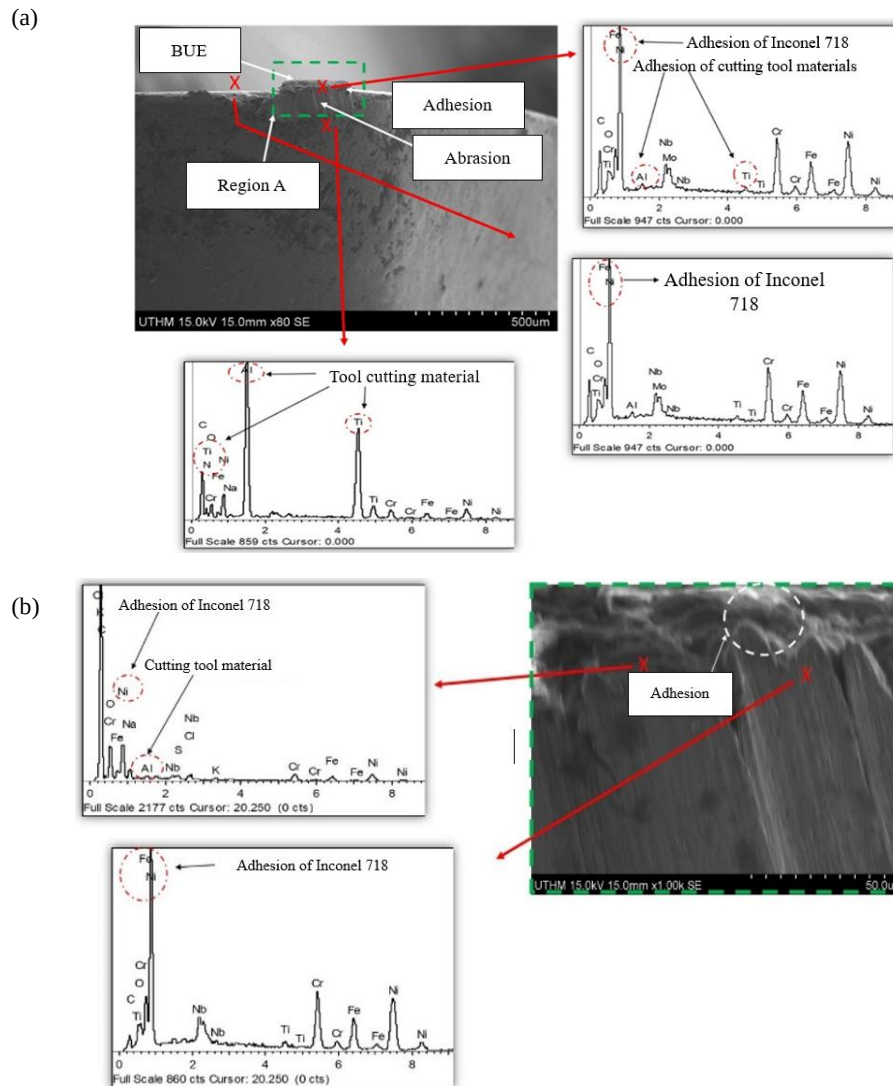


Figure 8. EDX analyses at 80 m/min Vc in dry cutting condition (a) cutting edge and (b) close-up observation (1000x)

3.2 Effect of Wear Mechanism in Cryogenic

Figure 9 shows the wear mechanisms in cryogenic milling of Inconel 718 at various ae and 80 m/min Vc. It was observed that the dominant failures in cryogenic milling are chipping and catastrophic failures. Wang et al. [7] also came to the same result, in which chipping of the cutting edge was the dominating failure in cryogenic machining. The exceedingly low temperature associated with cryogenic cooling can lead to brittleness in the tool material [10][34], which in turn can cause chipping of the tool. It was observed that cracks are present at an average of 5 mm ae in cryogenic milling. The substantial drop in cutting temperature from cryogenic cooling significantly increases the mechanical strength and hardness of Inconel 718 due to low-temperature embrittlement. At the same time, ultra-low temperatures induce rapid heat extraction from the cutting zone, altering dynamic material properties and thermal gradients at the tool-chip interface. This occurs when the tool is rendered extremely cold during the spray of supercritical carbon dioxide and subsequently heated during chip removal. These rapid, dramatic temperature changes cause the tool to contract and expand repeatedly. Finally, the tool develops fatigue and a propensity for cracking. This will lead to the development of cracks, drag, and smears that can diminish the tool's fatigue strength and reduce its resistance to more severe damage. This study also found severe crater wear.

Figure 10 (a) shows an 80× magnification SEM image of a cutting tool used under cryogenic machining conditions, accompanied by three Energy-Dispersive X-ray (EDX) analyses to characterise its wear mechanisms. The main SEM image reveals two primary wear mechanisms: chipping and abrasion. Chipping is distinctly visible along the cutting edge, characterised by the fracturing and removal of discrete pieces of tool material. This brittle fracture is often exacerbated in cryogenic machining due to the reduced ductility of both the cutting tool and Inconel 718 at very low temperatures.

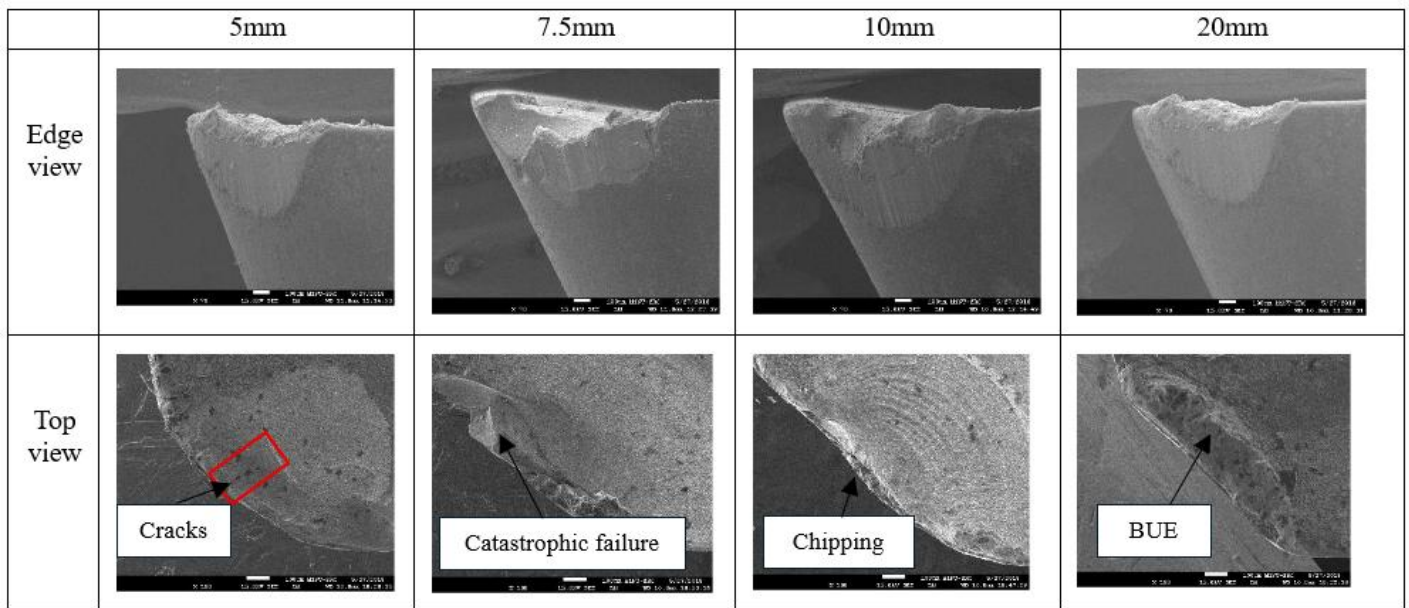


Figure 9. Wear mechanisms in cryogenic milling at 80 m/min Vc

The EDX spectrum taken from the region labelled "Chipping" supports this by showing peaks for elements from both the tool substrate material (W, C, Co, Cr, characteristic of cemented carbides) and the Inconel 718 adhesion (Fe, Ni, Cr). The workpiece elements, along with the coating material, are present in this chipped region of the tool upon separation. Abrasion is evident on the flank face of the tool, characterised by a smooth or appearance indicative of mechanical wear from the rubbing action of the workpiece or hard particles. This confirms that the wear in this area is due to the removal or degradation of the tool's protective coating, resulting from a reaction with carbon dioxide and subsequent heating during chip removal. These rapid and dramatic temperature changes cause the tool to contract and expand repeatedly. Finally, the tool develops fatigue and a tendency to crack. Sufiiarov and Borisov [39] also stated that the cause was abrasive force. Furthermore, the EDX analysis labelled "Inconel 718 Adhesion" in the Fe, Cr, and Ni sections, which showed dominant peaks, clearly indicated material transfer to the open areas of the cutting tool. The presence of significant Inconel 718 flakes or grains on the tool surface indicates that adhesive wear continues under cryogenic conditions. However, the morphology may be different due to the low temperature.

Compared to dry cutting, where adhesion often appears as BUE (as shown in Figure 8), cryogenic cooling aims to reduce temperature-dependent phenomena such as diffusion and severe adhesion. However, Figure 10(b) clearly shows that although thermal effects are reduced, low temperatures shift the wear mechanism towards mechanical wear, especially cracking. This indicates that under cryogenic conditions, the tool's main failure mode can shift from brittle fracture to severe plastic deformation and abrasive adhesion. The combination of high mechanical loads and reduced material ductility at cryogenic temperatures is among the main reasons for cracking [41][42].

Although the ae parameter values were limited to 5, 7.5, 10, and 20 mm, the performance comparison between cryogenic and dry machining showed a consistent trend in tool life across all ae levels. This consistency in the flank wear profile along the length of the cut reduces reliance on typical random-variance statistical analysis. Cutting tool failure mechanisms, such as chipping, abrasive wear, BUE, and brittle transition due to cryogenic thermal shock, are physically confirmed through tribological interactions at the tool-chip interface. This physical evidence directly supports the empirical findings without requiring large-scale statistical analysis

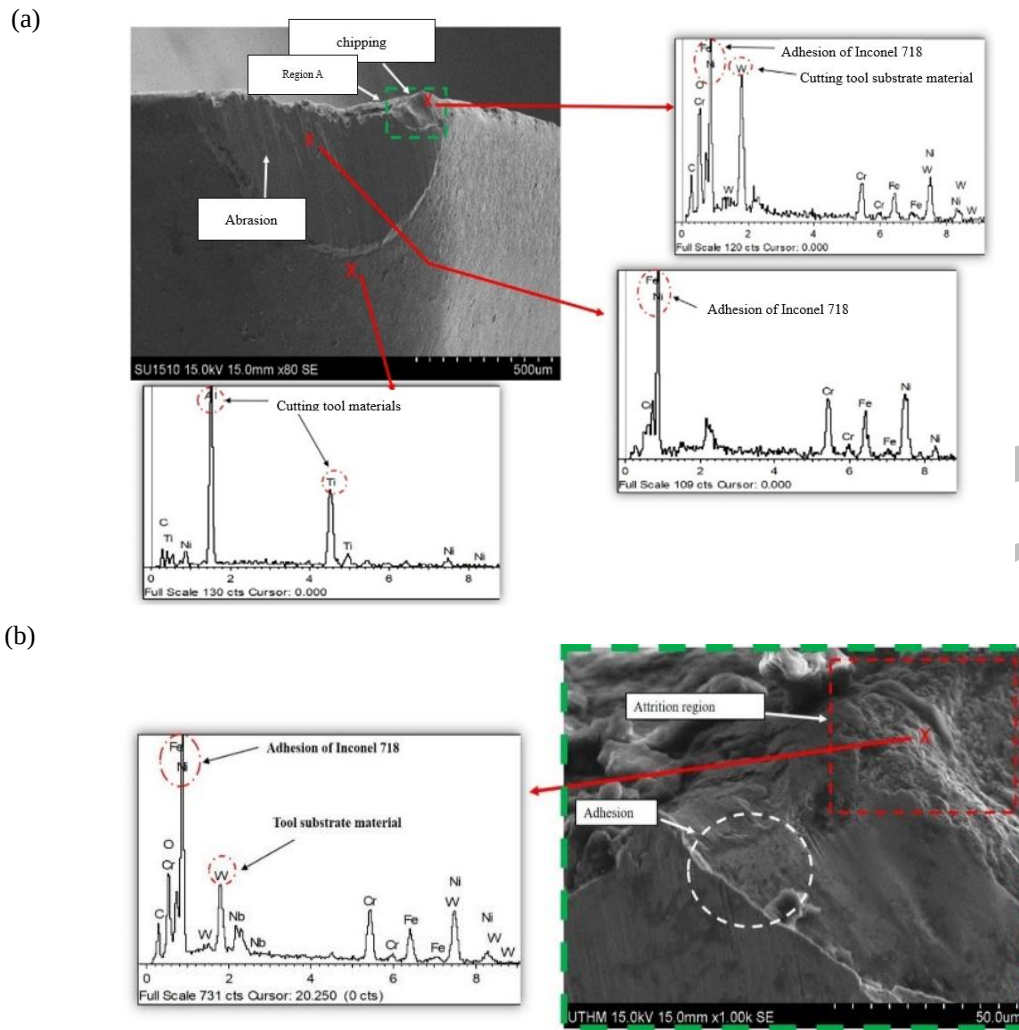


Figure 10. EDX analyses at 80 m/min Vc in cryogenic cutting conditions (a) cutting edge and (b) close-up observation (1000x)

4. Conclusions

Based on a study comparing the performance of dry and cryogenic machining on Inconel 718, the conclusions are:

- 1) Cryogenic machining shows significantly better performance than dry cutting. It can systematically handle high thermal loads and successfully extend cutting tool life across all ae tested.
- 2) Under extreme, aggressive machining conditions, cryogenic machining produces cutting lengths 50% to 100% longer than those of dry cutting. In particular, a maximum tool life extension of up to 42% was achieved at a low temperature of 5 mm.
- 3) The cutting tool's failure mode shifts radically between the two extreme environments. Dry conditions trigger severe wear mechanisms, including diffusion, oxidation, and adhesive wear. In contrast, ultralow (cryogenic) temperatures effectively eliminate thermal effects but shift the failure mode towards mechanical wear, such as cracking, and catastrophic failure due to tool embrittlement.
- 4) Quantitatively, increasing ae from 5 mm to 20 mm significantly increases volumetric interactions, cutting forces, and mechanical loads. At a moderate ae = 10 mm, dry machining leads to tool failure (at a cutting length of 1000 mm), while cryogenic cooling doubles the capability, reaching a cutting length of 2000 mm under comparable wear. Even at the most aggressive ae (20 mm), cryogenic cooling still outperforms dry cutting, exceeding 50% of the cutting length.

Future research should focus on optimising the CO₂ cryogenic fluid delivery flow rate (currently dynamically ranging from 2 to 8 l/min) to balance cooling efficiency and avoid rapid thermal shock. In addition, exploring hybrid approaches, such as selective cryogenic cooling combined with minimum quantity lubrication (MQL), is highly recommended for widespread and sustainable industrial use.

Conflict of Interest

All authors declare that they have no conflicts of interest.

CRediT of Authors Contribution

T. Norfauzi: Conceptualization; Writing-original draft; Resources

K. Kamdani: Data Curation; Writing – Review and Editing

R. Izamshah: Validation; Formal Analysis

W. Hafiz: Validation; Formal Analysis

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