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Comparative Evaluation of Cryogenic and Flood Cooling for Precision and Sustainable Machining of Inconel 718

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Abstract

This study evaluates the machinability of Inconel 718—a nickel-based superalloy widely used in aerospace, defence, and high-performance applications under conventional flood cooling and cryogenic cooling with liquid nitrogen (LN_2). Its low thermal conductivity, strain-hardening tendency, and abrasive microstructure make precision machining challenging. The effects of spindle speed, feed rate, and depth of cut were investigated using Taguchi's L27 design on surface roughness (Ra), tool wear (TW), cutting forces (CF), power consumption (P), and machining noise (N). Cryogenic cooling outperformed flood cooling, reducing surface roughness and tool wear by up to 30%, lowering cutting forces and noise, and minimizing vibration and deflection. Chip morphology and economic analysis further confirmed its industrial feasibility, showing a 38% cost benefit due to reduced tool consumption and elimination of coolant disposal. Overall, cryogenic cooling enhances precision, dimensional control, energy efficiency, and sustainability, demonstrating strong potential for industrial adoption in applications demanding high accuracy and material performance.

Keywords

Inconel 718, Precision machining, Sustainability, Cryogenic cooling, Liquid nitrogen(LN2), Power consumption, Surface roughness, Cost assessment

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1. Introduction

Nickel-based superalloys are extensively employed in critical sectors due to their exceptional mechanical and thermal properties, which include high yield strength, creep resistance, fatigue resistance, and corrosion resistance at elevated temperatures [1–3]. These alloys find widespread applications in aerospace engines, gas turbines, nuclear power plants, naval systems, and automotive components where reliability under extreme environments is mandatory [4–6]. Among them, Inconel 718 has become one of the most widely used alloys owing to its superior hot hardness, thermal stability, and excellent performance in aggressive operating environments [7–9].

Despite these advantages, Inconel 718 is classified as a “difficult-to-machine material” because of its low thermal conductivity, rapid work hardening, and abrasive carbide particles that accelerate tool wear [10–12]. These characteristics lead to high cutting forces, elevated tool–workpiece interface temperatures, and poor machinability, particularly when tight dimensional tolerances and superior surface integrity are required [13–15]. Researchers have long emphasized that ensuring geometrical accuracy, tool life, and productivity while machining Inconel 718 remains a major industrial challenge [16–18].

To address these issues, several cooling and lubrication techniques have been investigated. Conventional flood cooling, the most common method, reduces cutting temperature and friction at the tool–workpiece interface [19]. However, flood cooling has significant drawbacks, including excessive use of cutting fluids, disposal costs, operator health hazards, and environmental pollution [20–22]. Moreover, mineral oil-based coolants often fail to provide adequate cooling under high-speed machining conditions, leading to thermal distortion, tool vibration, and inconsistent lubrication [23,24].

Sustainable machining approaches such as dry machining, minimum quantity lubrication (MQL), nanofluid-assisted MQL, and hybrid cooling have been explored to overcome these limitations [25,26]. Dry machining eliminates fluid use but results in excessive tool wear in superalloys [27]. MQL and nanofluid-assisted cooling improve tribological behavior, reduce cutting temperature, and enhance surface finish, but their limited cooling capacity restricts their effectiveness for machining Inconel 718 at aggressive cutting conditions [28,29]. Hybrid cooling systems, which combine MQL with cryogenic jets, have shown promise but increase process complexity [30].

Cryogenic cooling, particularly using liquid nitrogen (LN_2), has gained significant attention as an environmentally friendly and highly efficient alternative. It provides rapid heat dissipation, reduces thermal loads, and eliminates coolant disposal requirements, making it both technically and ecologically advantageous [31,32]. Studies have demonstrated that cryogenic cooling substantially lowers cutting temperature, tool wear, and residual stresses while improving surface roughness and dimensional stability [33-35]. Some studies further showed cryogenic machining enhances tool life and chip control, thereby improving process stability [36,37].

From a sustainability perspective, few studies have emphasized that cryogenic cooling not only improves machinability but also reduces energy consumption and environmental impact [38-40]. Recent review confirm that cryogenic cooling offers a transformative pathway toward precision and sustainable machining of nickel-based superalloys [41].

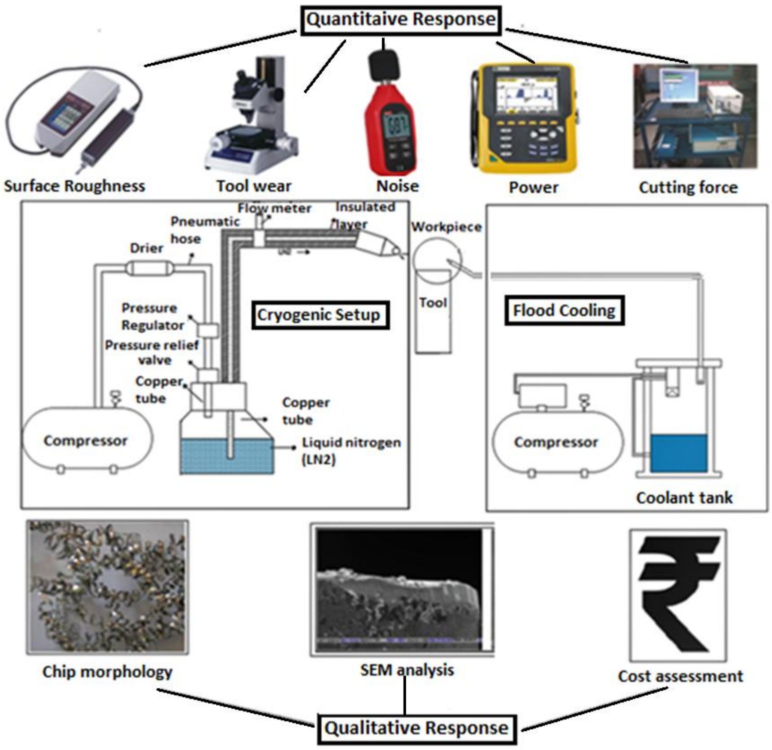

Figure 1. Schematics of the study.

Despite these advances, comprehensive studies that simultaneously consider precision machining indicators (surface roughness, tool wear, forces, and machining noise) and economic feasibility (cost, tool consumption, and coolant disposal) remain limited. This motivates the present work, which compares cryogenic cooling and flood cooling in the turning of Inconel 718, with a detailed evaluation of machining performance, cost assessment, and chip morphology to establish the industrial viability of cryogenic machining. The proposed work's schematics are shown in Figure 1.

2. Experimental Methodology

Based on a thorough assessment of the literature, three levels were chosen as the input parameters for this work: spindle speed (Vc), cutting feed (f), and depth of cut (ap). According to reports, Taguchi's experimental design offers strong, high-quality, and economical design solutions. The method can extract detailed data from the fewest experimental runs and organizing the results in a methodical manner [42]. Thus, the impact of three key process variables is observed on performance metrics like surface roughness (SR), power consumption (P), machining noise (N), tool wear (TW), and cutting forces (CF) is assessed in this work using Taguchi's L27 orthogonal array. The details of experimental setup are shown in Table 1 and Figure 2 whereas, the mechanical properties and composition of Inconel 718 are shown in Table 2.

Table 1. Experimental details of the study

Particular	Specification
Work piece	Inconel 718 alloy (Φ 40 mm X 200 mm)
Machine	MTAB Max Turn
Cutting Insert	TiN-MT-TiCN-Al_2O_3: Kennametal make, Grade- CNMG 120408-KC5010
Tool Holder	MTJNR 2525 M16
Cutting tool geometry	Cutting edge angle: 80°: rake angle: - 8°, clearance angle: - 8, Nose radius: 1 mm.
DOE	L-27 (Taguchi's array)
Input Parameters (3 levels)	Cutting speed: V_{c}- (50 m/min, 80 m/min, 110 m/min), Cutting feed: f- (0.08 mm/rev, 0.1 mm/rev, 0.12 mm/rev), Depth of cut: a_{p}- (0.4 mm, 0.6 mm, 0.8 mm)
Performance Attributes	Surface roughness, power consumption, machining noise, tool wear and cutting forces
Machining strategy and coolants used	Cryogenic: Liquid nitrogen (LN_2) as coolant, compressed air: 5 bar, Flow rate: 0.50 L/min, brass nozzle (Φ1.2 mm) positioned at 30 mm distance from the cutting tool. Flood: A neat cutting oil-137 as coolant, oil pressure: 4 bar, Flow rate: 30 L/min, nozzles (Φ 2.5 mm) positioned within 20 mm distance from the machining zone.

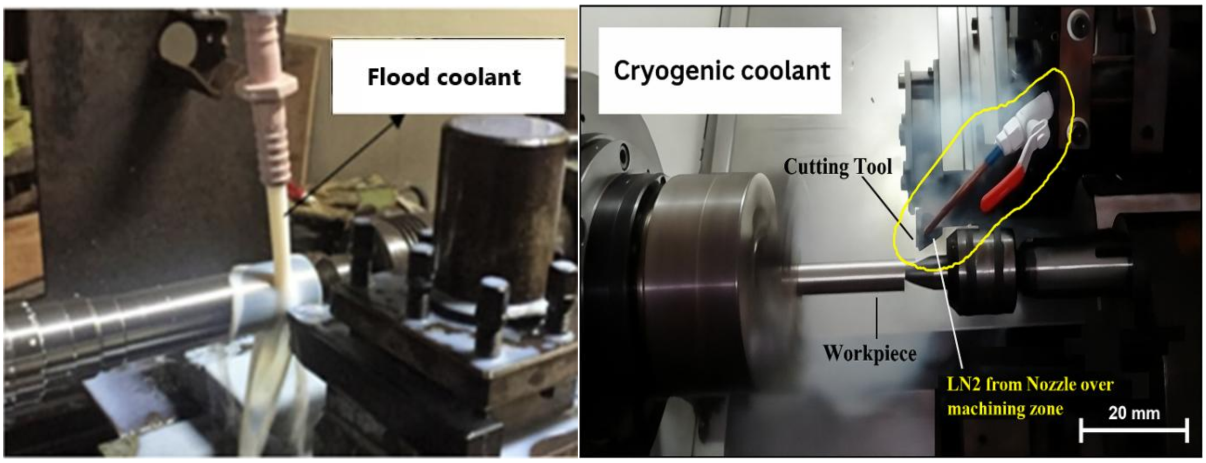

Figure 2. Experimental setup. (a) flood coolant, (b) cryogenic coolant.

Table 2. Mechanical properties of Inconel 718 [43].

Composition (%)	C- 0.10, Al- 0.40, Co- 1 max, Cr- 21.5, Fe- 5 max, Mo-9, Ti- 0.40, N- 0.015, S- 0.015 (Balanced Ni)				
Properties	Yield strength (MPa)	Hardness (HV)	Tensile strength (MPa)	Elastic Modulus (GPa)	Thermal Conductivity (W/mK)
Values	615	260	880	210	9.8

3. Measurement of Responses

To record the values of the responses such as surface roughness (SR), power consumption (P), machining noise (N), tool wear (TW), and cutting forces (CF), the tests are carried out using Taguchi's L27 orthogonal array. Every experiment is carried out twice, and for greater accuracy, the mean reading is taken for the analysis.

3.1 Measurement of surface roughness (SR)

The Talysurf surface Mitutoyo's (SJ-178) roughness machine is used to measure the surface roughness (SR) as shown in Figure 3. It was measured four times and the average value, Ra in micron, was recorded as the final result. This is done to get an accurate reading and to prevent human error.

Figure 3. Measurement of surface roughness.

3.2 Measurement of Power consumption (P)

The CNC machine's electric panel is connected to a Fluke 435 power analyzer (energy meter) equipment, which measures both active and reactive power. This provides each trial's power consumption (P) in watts (W) and recorded as final reading.

3.3 Measurement of Noise (N)

Using a Lutron SL-401 portable noise meter, the noise concentration generated during turning is measured in decibels (dB) while all other laboratory equipment is turned off in a separate workplace. To obtain the most accurate measurement of machining noise, five readings of the noise values are obtained, and the average of the readings is recorded.

3.4 Tool wear measurement (TW)

Using a Mitutoyo Toolmaker microscope, tool wear (TW) was measured and recorded in millimeters (mm) as shown in Figure 4. Under 10X magnification, the difference between the initial and final readings is recorded.

Figure 4. Measurement of tool wear.

The measurement is performed by aligning the cutting-edge perpendicular to the optical axis and using the microscope's digital or scale-based measurement system to determine the wear dimensions with micrometer precision. Multiple points along the edge are measured to calculate an average wear value. Images are captured for documentation and comparative analysis under different machining conditions. This method provides accurate and repeatable assessment of tool wear, enabling correlation with surface finish, cutting forces, and tool life.

3.5 Cutting force measurement (CF)

Using a Kistler tool dynamometer 5233A equipped with a Dyno-Ware data collection system, the cutting force (CF) was measured and expressed in newtons (N). This software plots all the force components, recording the average cutting force for each rotation.

4. Result and Discussion

The design of experiments, machining parameters, and results for two settings i.e. for flood machining and cryogenic machining are displayed in Table 3. It shows that, when compared to flood machining, the values of all attributes attained during cryogenic machining are significantly lower. This suggests that, while cutting the Inconel 718 workpiece, cryogenic machining has outperformed the flood machining.

Table 3. Comparative analysis of flood machining vs cryogenic machining.

S.N.	Vc	f	ap	Flood machining					Cryogenic machining				
				SR	P	N	TW	CF	SR	P	N	TW	CF
1	50	0.08	0.4	0.948	3134.09	90.86	0.063	267.30	0.771	2321.55	77.00	0.074	189.13
2	50	0.08	0.6	1.557	4084.34	99.14	0.094	292.31	1.266	3025.40	84.02	0.110	206.82
3	50	0.08	0.8	0.648	4669.19	96.22	0.094	292.00	0.527	3458.66	81.54	0.110	206.60
4	50	0.1	0.4	0.797	5469.00	100.04	0.110	324.05	0.659	4051.11	84.78	0.128	229.28
5	50	0.1	0.6	0.897	4024.35	95.32	0.096	315.20	0.730	2981.00	80.78	0.113	223.02
6	50	0.1	0.8	1.530	4997.61	93.31	0.089	243.91	1.244	3701.94	79.08	0.104	172.57
7	50	0.12	0.4	0.600	6317.93	100.55	0.095	290.47	0.488	4679.95	85.21	0.111	205.52
8	50	0.12	0.6	1.121	3834.14	89.47	0.086	336.57	0.912	2840.11	75.82	0.100	238.14
9	50	0.12	0.8	0.542	4669.19	98.77	0.103	385.80	0.441	3458.66	83.70	0.120	272.97
10	80	0.08	0.4	0.793	3998.85	93.33	0.077	278.26	0.645	2962.11	79.10	0.090	196.88
11	80	0.08	0.6	0.721	4951.46	102.33	0.104	313.54	0.586	3667.75	86.72	0.121	221.84
12	80	0.08	0.8	0.564	3282.52	92.08	0.070	253.56	0.458	2431.49	78.03	0.082	179.41
13	80	0.1	0.4	0.549	4151.70	95.96	0.086	264.37	0.446	3075.33	81.32	0.100	187.06
14	80	0.1	0.6	0.802	5606.24	94.68	0.068	293.83	0.652	4152.77	80.24	0.080	207.90
15	80	0.1	0.8	1.849	6362.80	97.01	0.092	339.09	1.503	4713.19	82.21	0.107	239.92
16	80	0.12	0.4	1.462	3645.98	88.57	0.077	265.29	1.189	2700.73	75.06	0.090	187.70
17	80	0.12	0.6	0.399	4269.32	100.42	0.103	274.28	0.336	3162.45	85.10	0.120	194.07
18	80	0.12	0.8	1.732	5198.44	92.33	0.081	299.94	1.408	3850.70	78.25	0.095	212.22
19	110	0.08	0.4	1.562	5382.65	98.77	0.124	321.31	1.270	3987.14	83.70	0.145	227.34
20	110	0.08	0.6	0.637	4590.13	90.49	0.077	342.53	0.519	3400.10	76.69	0.090	242.35
21	110	0.08	0.8	1.387	5022.02	97.49	0.096	351.84	1.128	3720.02	82.62	0.113	248.94
22	110	0.1	0.4	0.420	4775.76	94.50	0.069	272.46	0.341	3537.60	80.08	0.081	192.78
23	110	0.1	0.6	1.238	5913.78	99.78	0.103	272.16	1.007	4380.58	84.56	0.120	192.56
24	110	0.1	0.8	2.588	3787.93	93.54	0.100	298.10	2.104	2805.88	79.27	0.117	210.92
25	110	0.12	0.4	1.139	3134.09	88.26	0.067	267.30	0.927	2321.55	74.79	0.079	189.13
26	110	0.12	0.6	0.551	4084.34	98.77	0.084	292.31	0.448	3025.44	83.70	0.099	206.82
27	110	0.12	0.8	0.584	5469.00	101.06	0.110	324.05	0.475	4051.11	85.64	0.128	229.28

A parametric analysis was conducted to compare the effects of cryogenic machining and flood machining on the machinability of Inconel 718. The key process parameters were varied to observe their impact on all selected machining responses. Figures 5 presents the results for the effect of cutting speed and feed rate on all these attributes, respectively.

From Figure 5, it is evident that cryogenic machining yields a smoother surface compared to flood machining. The reduction in surface roughness for cryogenic machining is attributed to better lubrication, which minimizes friction during the cutting process. At lower cutting speeds, surface roughness increases. However, beyond a speed of 50 m/min, the surface finish improves. This improvement is attributed to thermal softening of the material at higher speeds, which allows for a more effective removal of material flaws. Figure 5 also shows that cryogenic machining consumes less power than flood machining. This difference arises because flood machining requires an additional pump to deliver a coolant and higher cutting forces are generated due to the excess friction in the machining zone. The power consumption increases with cutting speed and feed rate due to the higher energy demands required to maintain spindle rotation at increased cutting conditions. Previous study also supports this claim [44].

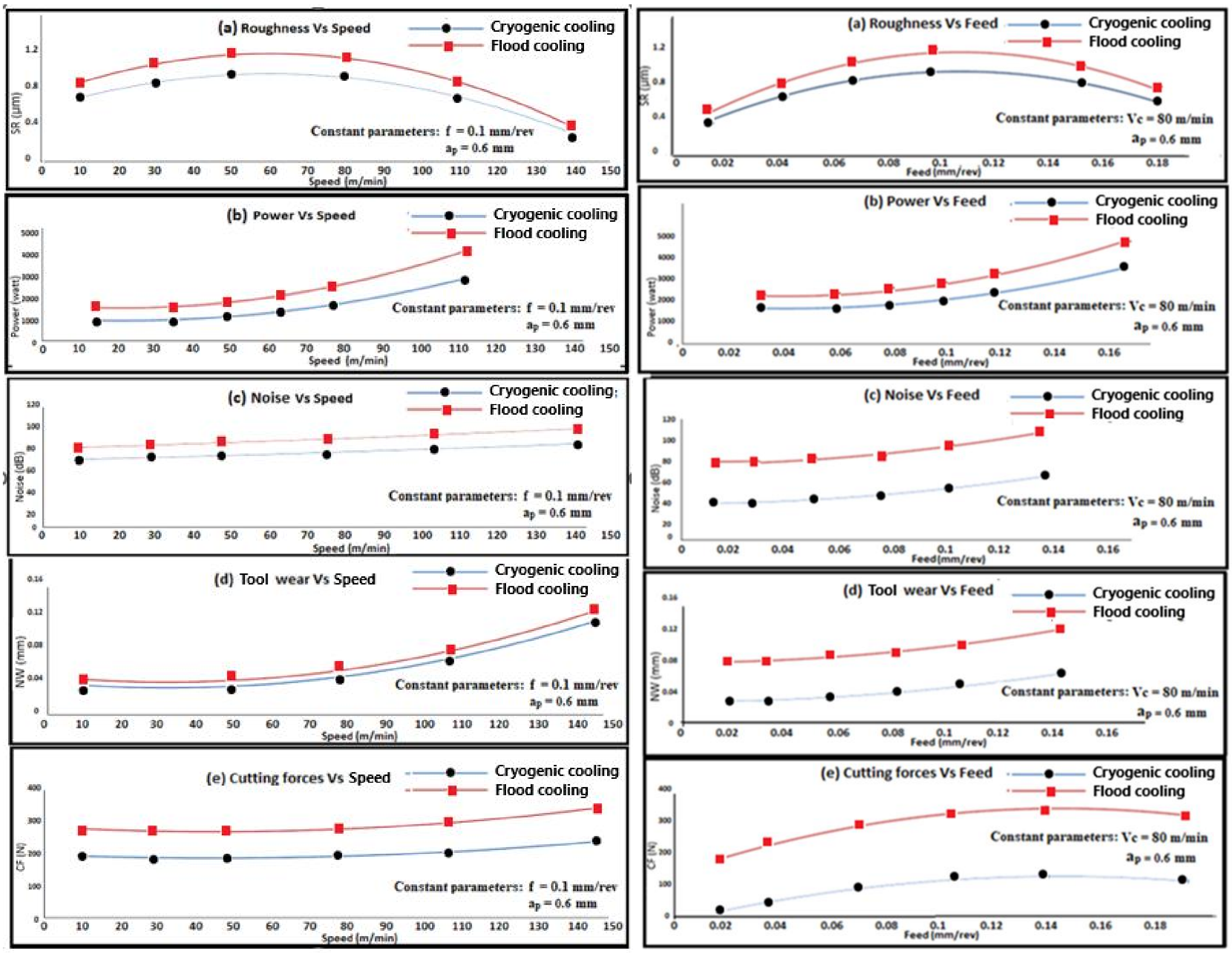

Figure 5. Effect of speed and feed on machining attributes.

Figure 5 also indicates that cryogenic machining results in lower machining noise compared to flood machining. This is because machining noise increases as cutting speed and feed rate are increased, due to higher levels of vibration and tool chatter. Figure 5 also demonstrates that tool wear is lower in cryogenic machining, as the reduced heat generation during machining results in less tool degradation. With increasing speed and feed rate, tool wear increases for both machining strategies, but cryogenic machining maintains wear levels within acceptable limits as defined by ISO standards [45]. Additionally, the cutting forces are lower for cryogenic machining due to less tool wear, maintaining sharp tool edges. Higher cutting speeds and feeds lead to an increase in cutting force due to the generation of tensile residual stresses in the workpiece. This is also supported by previous studies [46,47].

Similarly, the effect of depth of cut on the machining responses can be analysed in a similar manner, with expected trends aligning with the observed trends of cutting speed and feed. Based on the findings, cryogenic machining is shown to outperform flood machining in all key machinability characteristics when applied to Inconel 718, making it a superior choice.

4.1 Main effect Plot for responses

To understand the influence of individual machining parameters on the measured responses, main effect plots were generated from the Taguchi L_{27} design data. These plots illustrate the average response values at each level of spindle speed, feed rate, and depth of cut, thereby revealing the general trend of how each factor affects surface roughness, tool wear, cutting forces, power consumption, and machining noise. Unlike interaction plots, main effect plots focus on the independent effect of each parameter, making them a useful tool for visualizing sensitivity and identifying optimal ranges of operation. The following subsections discuss the observed trends in detail for each response parameter.

The Figure 6 shows main effect plots reveal that surface roughness decreases with increasing cutting speed. This improvement is attributed to the thermal softening of the workpiece material at higher speeds, which facilitates smoother cutting and reduces adhesion at the tool–workpiece interface. Conversely, surface roughness shows a clear increasing trend with higher feed rates. This can be explained by the fact that an increased feed imposes greater cutting loads on the tool, which in turn induces higher vibration and dynamic instability, thereby deteriorating surface finish.

Figure 6. Main effect plot for surface roughness.

The best surface finish is obtained at the combination of lowest feed rate and highest spindle speed. However, increasing the depth of cut results in a significant deterioration of surface finish. This behaviour arises from the excessive rubbing action between the tool and the workpiece, coupled with increased heat generation at higher depths of cut, which leads to a rise in surface roughness values.

Tool wear is another crucial response, as it directly influences the dimensional accuracy, surface integrity, and overall tool life, which in turn impacts the cost-effectiveness of machining. Among the various wear modes, nose wear plays a significant role as it leads to the retreat of the cutting edge and strongly affects the dimensional precision of the workpiece. Figure 7 illustrates the main effect plots for tool wear obtained under the present study, all of which remained within the acceptable limits defined by ISO 3658-1993 standards.

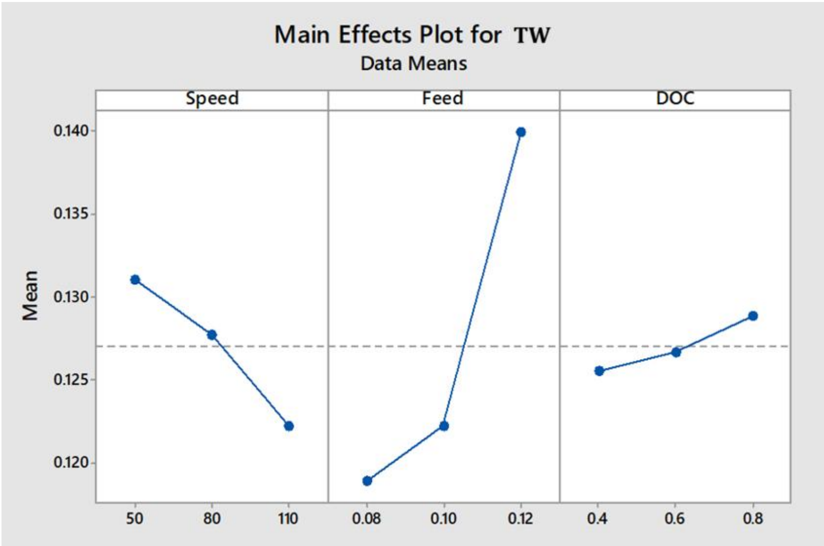

Figure 7. Main effect plot of Tool wear.

The plots indicate that tool wear decreases with increasing spindle speed. At a cutting speed of 110 m/min, the nose wear is reduced to as low as 0.122 µm. Notably, tool wear at 110 m/min shows an approximate 25% reduction compared to the lower spindle speed of 50 m/min. This behavior can be attributed to improved chip removal and reduced cutting zone temperature under higher cutting speeds, which minimizes abrasive interaction at the tool–workpiece interface.

Cutting forces play a critical role in determining the stability of the machining system. Excessive forces can deform the workpiece, promote non-uniform chip formation, and compromise dimensional accuracy. Figure 8 presents the main effect plots for cutting forces, which clearly show that higher feed rates combined with lower spindle speeds lead to peak cutting force generation.

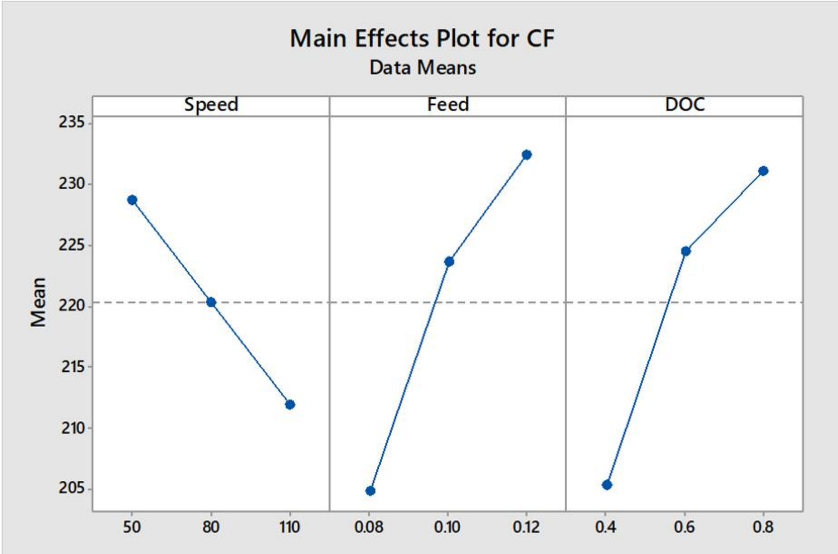

Figure 8. Main effect plot for cutting forces.

The maximum cutting force recorded was approximately 223 N at a spindle speed of 50 m/min, feed rate of 0.12 mm/rev, and depth of cut of 0.8 mm. In contrast, the lowest cutting force was observed under the cutting conditions of 110 m/min spindle speed, 0.08 mm/rev feed rate, and 0.4 mm depth of cut. This reduction at higher speeds and lower feeds can be attributed to reduced tool–workpiece contact stresses and improved chip evacuation. At lower cutting speeds, however, residual stresses induced in the workpiece tend to be tensile in nature, and with increased depth, these stresses elevate the cutting force requirements in the machining zone.

4.2 Analysis of Variance for responses

The ANOVA results for surface roughness (SR), tool wear (TW), and cutting force (CF) are presented in Table 4. The analysis indicates that feed rate (f) and depth of cut (ap) are statistically significant ($p < 0.05$) for all responses, whereas spindle speed (Vc) has no significant effect ($p > 0.05$).

This outcome is consistent with physical expectations: feed rate and depth of cut directly influence the chip load, tool–workpiece contact area, and cutting stresses, which in turn affect material removal mechanics, surface integrity, and tool wear under cryogenic machining conditions. The lack of statistical significance for spindle speed suggests that, within the tested range, it has a minor influence on heat generation and cutting dynamics compared to the dominant parameters, feed and depth of cut.

Table 4. ANOVA of machining parameters for SR, TW, and CF during cryogenic machining.

Factor	SR F-value	SR P-value	TW F-value	TW P-value	CF F-value	CF P-value
Cutting Speed (Vc)	0.22	0.802	0.75	0.483	0.84	0.448
Feed(f)	5.21	0.012	3.85	0.041	4.12	0.036
Depth of Cut (ap)	6.47	0.006	4.92	0.019	7.35	0.004
Error	–	–	–	–	–	–

The F-values indicate the relative influence of each factor on the responses. For example, depth of cut exhibits the highest F-value for cutting force (7.35, $p = 0.004$), confirming its strong impact on material removal forces. Feed rate also significantly affects SR, TW, and CF, highlighting its role in controlling tool engagement and surface finish quality. These results corroborate the observed experimental trends, where variations in feed and depth of cut caused notable changes in tool wear, cutting forces, and surface roughness, while changes in spindle speed produced comparatively minor effects.

In summary, the ANOVA analysis quantitatively validates the experimental observations, emphasizing that careful selection of feed rate and depth of cut is crucial for optimizing machining performance, precision, and sustainability in cryogenic turning of Inconel 718.

4.3 Scanning electron microscope (SEM) investigation

The post-machining modifications on the workpiece, worn-out inserts, and machined chips are examined using a scanning electron microscope (SEM) (Leica, S-430). The topography of the workpiece after machining following flood cooling and cryogenic machining is shown in Figures 9 (a) and (b), respectively. Compared to cryogenic approach, the SEM topography clearly demonstrates considerable damage to the machined surface during flood machining.

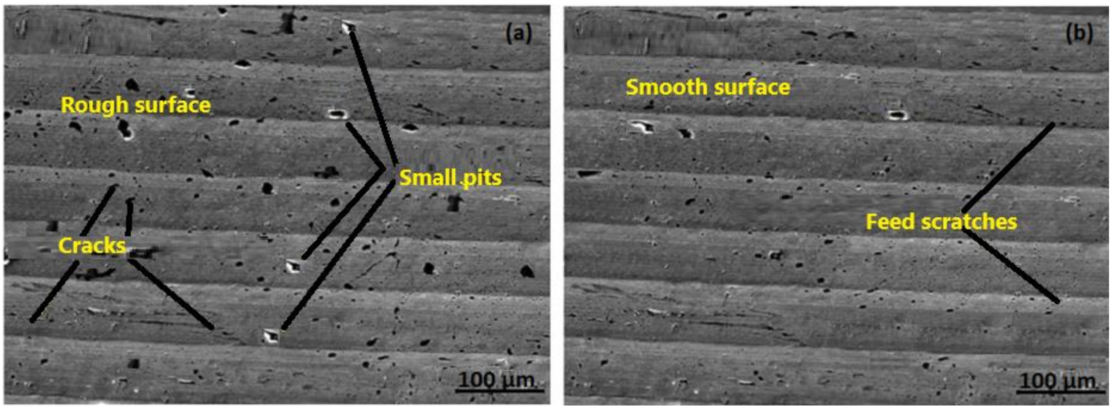

Figure 9. Surface features of Inconel 718 after: (a) flood machining, (b) cryogenic machining.

Additionally, it shows that the surface achieved by flood cooling has smaller pits and thin cracks that are far more intense than those seen on the cryogenic machined surface. Due to the higher friction at the cutting zone and inadequate lubrication, the flood cooled surface appears rough. However, surfaces that have undergone cryogenic machining have better surface quality, fewer thin cracks and pits. Previous investigations also support this claim [48].

SEM images of the worn-out tools during machining under flood cooling and cryogenic conditions are presented in Figure 10 (a) and (b), respectively. It is evident from these images that flood cooling results in more tool wear than cryogenic machining. This is because abrasion is the main cause of tool wear, which results in segment erosion as there is less lubrication during flood cooling. On the other hand, the cutting tool portion exhibits reduced erosion and abrasion in cryogenic machining. It also shows the erosion after a single trial i.e. 0.18 mm with high frittering tendency during flood cooling compared to the 0.11 mm with cryogenic cooling with no apparent wear on a cutting edge.

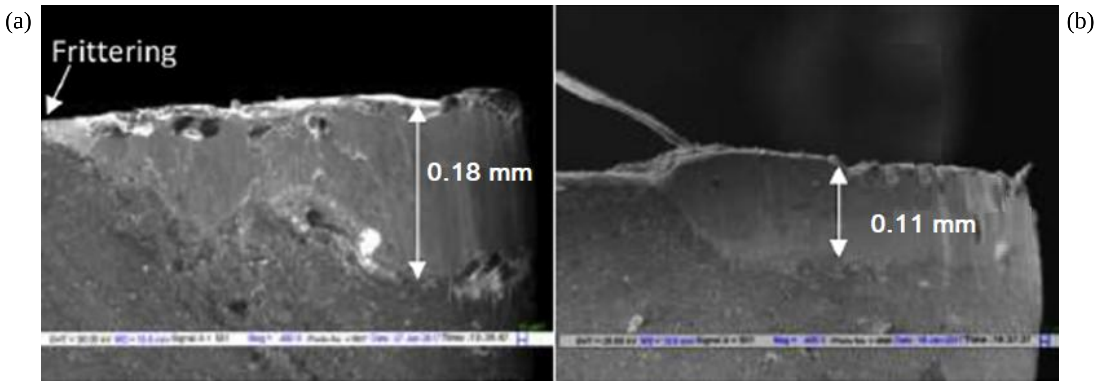

Figure 10. SEM micrographs of worn-out tools (a) flood cooled (b) cryogenic cooled.

4.4 Chip Morphology investigation

Chip morphology directly affects the surface integrity of machined part and clarifies important aspects of cutting mechanics. While maintaining constant input parameters, impacts of both machining processes on the morphologies of the chip of creation are also investigated in this work. Chips made for this purpose are examined using optical and SEM micrographs for both methods. The optical pictures of chips extracted using flood cooling and cryogenic cooling are depicted in Figure 11 (a) and (b) respectively. While the chip created during cryogenic machining is short and uniform, the chip created during flood cooling machining is shown to be twisted and wrenched. Furthermore, flood cooled chip had an uneven curvature and a rough back face due to built-up edges over the cutting plane. This clearly shows that cryogenic machining can minimize the wear of the cutting tools. Figure 12 (a) and (b) shows the micrographs of chips extracted using flood cooling and cryogenic cooling. It shows that chips generated with flood machined are distorted and non-uniformly segmented while cryogenic cooled chips are uniformly segmented. Previous studies also provided support for this claim [49,50].

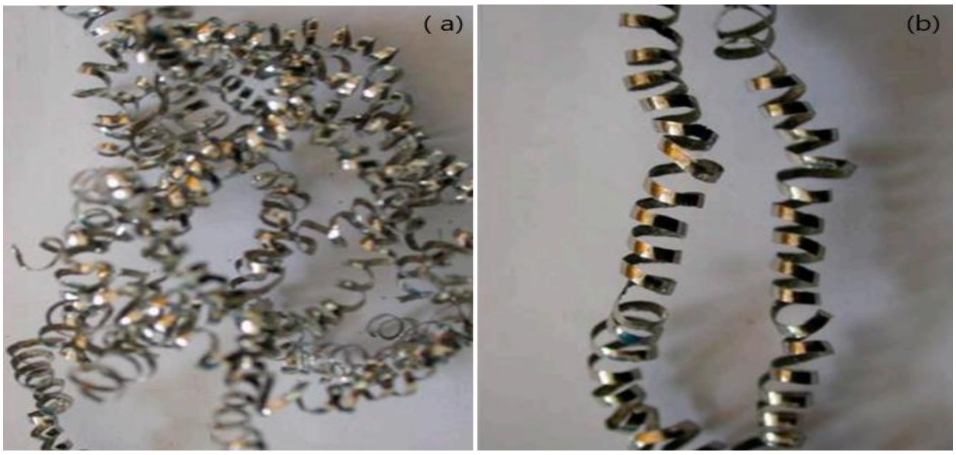

Figure 11. Optical images of chip formation. (a) MQL setup (b) cryogenic setup.

(a) (b)

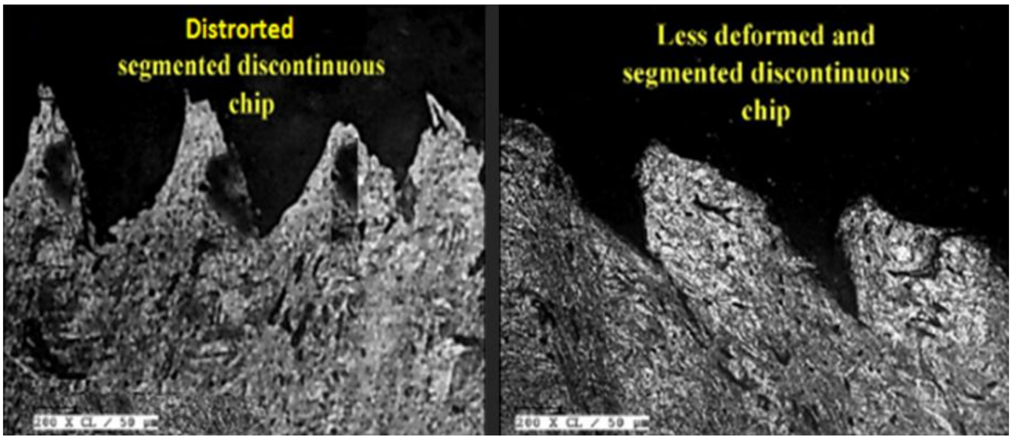

Figure 12. SEM images of chip. (a) flood machined, (b) cryogenic machined.

4.5 Cost Assessment

Table 5. Cost comparison for flood machining and cryogenic machining.

Sr. No.	Particular	Sub-category	Flood machining cost (Rs)	Cryogenic Machining cost (Rs)
1.	Materials	Cutting tool	4500 (Approx. 9 inserts; 500 Rs/ each)	2000 (Approx. 4 inserts; 500 Rs/ each)
		Coolant	3000 (Approx. 15 litres; 200 Rs/ Litre)	800 (Approx 20 litres; 40 Rs/ Litre)
2.	Energy	Machining Process	324 (27 units consumed)	252 (21 units consumed)
		Coolant circulation	Same	Same
3.	Waste	Used inserts	450 (9 inserts; Approx 50Rs/ insert or (1 Rs/gm rate)	200 (4 inserts; Approx 50Rs/ insert or (1 Rs/gm rate)
		Used coolant	1500 (Rs. 100/litre)	0
Total			**5274**	**3252**

One of the important qualitative factors in determining how sustainable the turning process [51]. This study compares the overall cost of machining for flood cooling with cryogenic turning. Some of the crucial factors considered for the cost assessment analysis are the consumption of resources and energy, creation of waste and its disposal. The computations from this section are predicated upon removal of 20 cm^3 of material using flood machining and cryogenic machining techniques after 27 trials. The comparative cost study between flood cooling and cryogenic machining is displayed in Table 5. The cost analysis for 27 trials conducted in accordance with the design of experiments highlights the primary cost components associated with flood and cryogenic machining strategies, namely materials, energy, and waste disposal. In the materials category, the cost of cutting tools for flood machining amounts to Rs. 4500, requiring approximately 9 inserts, compared to Rs. 2000 for cryogenic machining with 4 inserts. The coolant usage also shows a significant difference as flood machining consumes approximately 15 litters, costing around Rs. 3000, whereas cryogenic machining requires 20 litters of liquid nitrogen costing around Rs. 800.

The cost assumptions used in this analysis were based on a market survey and supplier quotations collected during July–August 2023 in Maharashtra, India. Cutting insert prices (Kennametal CNMG 120408-KC5010, ~Rs. 500 per insert) were obtained from a local distributor (Pune, Maharashtra). Coolant prices were sourced from certified suppliers, with neat cutting oil priced at ~Rs. 200 per litre (Kolhapur market, 2023) and liquid nitrogen at ~Rs. 40 per litre (supplier quotation, Sangli, 2023). Electricity tariffs were taken from the Maharashtra State Electricity Distribution Company Limited (MSEDCL) industrial slab rates valid during 2023. Waste disposal charges (Rs. 50 per insert or Rs. 1/gm, Rs. 100 per litre of used oil) were estimated from standard local industrial practices. These references provide transparency and industrial relevance to the cost comparison.

The energy consumption was evaluated for both machining operations and coolant circulation. The energy cost for machining with flood cooling was Rs. 324, with 27 units consumed, while cryogenic machining was more efficient, costing Rs. 252 for 21 units consumed. Coolant circulation costs remained consistent across both strategies. The waste disposal costs comprise the disposal of used cutting tools and coolant. For flood machining, 9 inserts were required, incurring a disposal cost of Rs. 450, reflecting the higher temperatures and inadequate lubrication in flood cooling (at an estimated Rs. 50 per insert or Rs. 1/gm rate, with each insert weighing approximately 50 gm as per standard disposal rates in India). In contrast, only 4 inserts were used in cryogenic machining, resulting in a lower disposal cost of Rs. 200. In terms of coolant disposal, flood machining incurs an additional cost of Rs.1500 for the disposal of 15 litters of used coolant at a rate of Rs. 100 per litter. This cost reflects the need for proper treatment and disposal due to the environmental and safety requirements associated with conventional coolants. Conversely, cryogenic machining eliminates this expense entirely, as liquid nitrogen disperses harmlessly into the atmosphere after contacting the machining zone, requiring no post-treatment or disposal. This advantage not only reduces costs but also highlights cryogenic machining as a more environmentally friendly approach, aligning with sustainable practices by avoiding hazardous waste generation and disposal. The cryogenic machining demonstrated cost efficiency, with a total expenditure of Rs. 3252 compared to Rs. 5274 for flood machining. This comparison provides valuable insights for industrial applications, supporting the shift towards advanced machining techniques that balance productivity with sustainability. This is also supported by previous research [52].

5. Conclusion

This study demonstrates that cryogenic machining offers substantial advantages over conventional flood cooling for the precision machining of Inconel 718. The approach improved tool life, reduced energy consumption, and eliminated the need for coolant disposal, thereby enhancing both machining efficiency and environmental performance.

Key outcomes include:

Up to 30% reduction in surface roughness, particularly at higher cutting speeds due to thermal softening effects.

About 10% lower machining noise, linked to reduced vibration and cutting forces.

30% decrease in tool nose wear across all parameter levels, maintaining values within ISO standards.

On average, 15% lower cutting forces, as sharper tool edges were retained under cryogenic conditions.

A 38% reduction in total machining cost, largely due to lower tool consumption and absence of coolant disposal expenses.

Beyond the immediate industrial applications, these findings also contribute to advancing research in sustainable machining practices, providing a framework for integrating precision performance with environmental responsibility in next-generation manufacturing systems These findings also highlight cryogenic machining as a viable and sustainable strategy for high-precision, high-value industries such as aerospace, defence, and energy, where dimensional accuracy and surface integrity are critical. Future work may focus on hybrid cooling strategies (e.g., LN_2-assisted MQL) and life cycle assessment (LCA) studies to comprehensively evaluate the long-term industrial and environmental benefits of cryogenic cooling.

Conflicts of Interest

The authors declare no conflicts of interest.

Generative AI Statement

The authors declare that no generative artificial intelligence (Gen AI) was used in the creation of this manuscript.

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