Turning of Inconel 718 using liquid nitrogen: multi-objective optimization of cutting parameters using RSM

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Received: 21 November 2021 / Accepted: 10 February 2022 / Published online: 1 March 2022
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Abstract
The objective of this research was to investigate the effectiveness of application of liquid nitrogen (LN₂) in turning of Inconel 718 compared to flooded cutting and select suitable LN₂ cutting parameters using response surface methodology (RSM). The results of turning experiments conducted by spraying LN₂ to the cutting area of Inconel 718 bar showed that using either low or high cutting parameters, cutting performance of Inconel 718 under the cryogenic condition was generally worse than the flooded cutting. However, using the medium cutting parameters, the LN₂ cutting performance was as good as that of the flooded cutting both showing a cutting force of 90 N, 60 µm of flank wear and 0.5–0.6 µm of surface roughness (Ra). These parameters were further optimized using desirability function of RSM to determine the set of parameters that provided the lowest cutting force, flank wear and Ra values and the highest material removal rate (MRR) under cryogenic cutting. Analysis of variance (ANOVA) performed on the regression models developed showed that cutting speed was the only significant factor on the cutting force. Feed rate was the most influential parameter on the flank wear. Feed rate and depth of cut were significant factors both affecting Ra. Multi-objective optimization showed that a cutting speed of 87 m/min, a feed rate of 0.06 mm/rev and a depth of cut of 0.37 mm constituted the optimum cutting parameters for achieving a cutting force of 78 N, flank wear of 58 µm, Ra of 0.49 µm and the MRR of 1.97 cm³/min under the cryogenic cutting condition.

Keywords Inconel 718 · Cryogenic cutting · Multi-objective optimization · Response surface methodology (RSM) · Wear mechanisms · Surface quality

Abbreviations
LN₂ Liquid nitrogen
RSM Response surface methodology
Vc Cutting speed
ANOVA Analysis of variance
ap Depth of cut
CCD Central composite design
f Feed rate
SS Sum of squares
Fc Cutting force

1 Introduction
Inconel 718 is a widely used nickel-based superalloy with high corrosion and creep resistance for elevated temperature applications. Machining of this precipitation hardenable alloy provides challenges due to retention of strength at elevated temperatures, high strain hardening, low thermal conductivity and presence of hard carbide
particles in its microstructure [1]. As a result, generally, tool wear [2–4] and cutting forces are high and the machined surfaces have low quality [5, 6]. Various methods have been proposed to facilitate machining of nickel-based superalloys including high-pressure machining [7], utilization of nano-fluids [8], laser-assisted machining [9], heat-assisted machining [10, 11] and hybrid machining (application of two or more of the cutting methods mentioned above simultaneously) [12]. Another effective method is the application of a cryogen (liquefied gas such as liquid nitrogen or CO$_2$) during the cutting process. The cutting parameters for cryogenic machining are yet to be defined. Response surface methodology (RSM) is an effective statistical analysis method which is used for designing the experiments and optimizing the process parameters [13–15]. It has been employed for optimization of manufacturing processes of various engineering alloys including superalloys [16–18]. The use of RSM could determine the set of machining parameters under which these new cutting methods could provide high machining efficiency and low tool wear. The literature survey presented in the following paragraphs of this section summarizes the previous experimental work on cryogenic machining of nickel-based superalloys and also reviews the statistical analyses methods for the optimization of machining parameters.

Cryogenic cutting is considered as a clean machining method since liquid nitrogen (LN$_2$) evaporates instantly, leaving the machined workpiece dry and free of cutting fluid films and contaminants. Although the cost of LN$_2$ cutting is higher than flooded cutting, it has the advantage of eliminating post-cutting cleaning and need for recycling. Operating the machining process using cryogens increases the rate of heat dissipation and alleviate manufacturing issues related to generation of high temperatures at the tool-workpiece interface. Machining practices in which cryogens were applied to the cutting area date back to 1919. Some researchers have applied the cryogen on the workpiece material by immersing the material into the liquid cryogen container [19] while others have sprayed it onto the cutting area [20] or used the combination of these two techniques [21]. Cryogenic cooling during the machining process has several beneficial effects on machining performance including (1) changing the mechanical properties of the workpiece and tool materials (increase in hardness, modulus of elasticity and strength of materials) and (2) removing the heat generated during the machining process and (3) change in frictional characteristics of the tool-chip and tool-workpiece interfaces [22, 23].

Cryogenic machining of difficult-to-cut materials has been studied in comparison with other machining methods using minimum quantity lubrication (MQL), flooded and dry cutting [24, 25]. Kaynak [26] conducted a study of cryogenic cutting of Inconel 718 and observed that flank wear was the lowest compared to MQL and dry turning — the difference increased as the cutting speed increased. The surface roughness generated during cryogenic machining was lower than MQL and dry cutting. Some researchers observed that cryogenic machining can lead to improvements of certain machining parameters but cause deterioration of others when compared to flooded cutting of Inconel 718. Stephenson et al. [27] conducted rough turning tests on Inconel 750 using carbide tools under cryogenic machining with CO$_2$-MQL coolant and compared the results with aqueous flooded cutting. Cryogenic machining resulted in smaller amount of flank and notch wear; however, it increased the crater wear. Additionally, material removal rate increased up to 40% during cryogenic machining. Iturbe et al. [28] reported that tool life in flooded cutting of Inconel 718 was 3 times lower compared to cryogenic cooling. The results also showed that Ra surface roughness values were doubled for cryogenic machining (2 μm) compared to flooded cutting. Moreover, the depth of subsurface microstructural damage in cryogenic cutting was four times higher than the conventional flooded cutting. Tebaldo et al. [29] conducted turning experiments on Inconel 718 under different cooling conditions namely dry, flooded, MQL and minimum quantity cooling (MQC) at different cutting speeds using cemented carbide tools. Taylor wear curves showed that at a constant tool life (15 min), the maximum cutting speed used under flooded cooling was 51 m/min, 47 m/min and 49 m/min for MQC, MQL and MQC. Additionally, the cemented carbide tool subjected to cryogenic temperatures was subjected to thermal shock causing fracture.

Response surface methodology (RSM) is a powerful tool for the investigation of effect of process parameters on the response factors [30]. However, there are few studies on optimization of parameters under cryogenic machining of superalloys using RSM. Most of the previous reports on cryogenic machining of Inconel 718 were based on experiments that were conducted at cutting parameters that were either randomly selected or were conceived to be the most important ones according to the researchers. Although the parameters used in these experiments were generally consistent with those recommended by the manufacturers, the selection of the cutting parameters used in the laboratory experiments can be improved using RSM. Thus, a systematic approach using
RSM has been adopted in the current research to determine an optimum set of machining parameters [31]. Although cryogenic machining has several advantages, the above literature survey shows that it does not always improve the machining quality. Consequently, it has not been implemented as a viable practice in machining industries. The question of which set of parameters should be used during the cryogenic machining to obtain an overall favourable performance comparable to conventional flooded cutting is yet to be answered. Pusavec et al. [32] have attempted to address this question by optimizing the cutting parameters using RSM. They compared cryogenic cooling with MQL and Cryo/MQL. According to their results, cryo-MQL showed better results in terms of tool wear and cutting force. A cutting speed of 42.3 m/min, a feed of 0.05 mm/rev and a depth of cut of 0.88 mm were found to be the most suitable set of cutting parameters. There are a few papers on the comparison of conventional flooded and cryogenic machining of Inconel 718; however, in these studies, fixed cutting parameters were used for conducting the experiments.

The novelty of the current work is investigation of the machining behaviour of Inconel 718 under cryogenic cutting under a broad range of machining parameters, namely low, medium and high cutting speeds and feed rates in comparison to the conventional flooded cutting. This research aims to compare the results from cutting of Inconel 718 obtained by continuously pouring LN2 to the cutting area with those of the conventional flooded and dry cutting processes. Comparison were made in terms of cutting force, flank wear and Ra surface roughness at different cutting speeds and feed rates. Based on the experimental results, it was observed that cryogenic cutting performed as good as flooded cutting at medium cutting parameters. In order to find a set of optimum cutting parameters, central composite design (CCD) of response surface methodology (RSM) was employed. Optimum cutting parameters were determined by using the desirability function of RSM. Statistical analyses were employed in order to investigate the effect of cutting parameters on the response factors, namely flank wear, cutting force, Ra surface roughness and material removal rate (MRR). Cutting speed, feed rate and depth of cut were selected as cutting parameters each in five levels (Sect. 2).

| Table 1 | Mechanical properties of Inconel 718 at 25°C |
|----------|-----------------------------------------------|
| 2% yield strength (MPa) | Tensile strength (MPa) | Reduction of area at fracture (%) | Hardness (HRC) |
| 1081.09 | 1416.18 | 36.7 | 44 |

2 Materials and methods

Hot rolled bars of Inconel 718 alloy were used as the workpiece material (with a composition of Ni (wt.%) 53.84, Fe 18.02, Cr 17.98, (Nb + Ta) 5.39, Nb 5.38, Mo 2.92, Ti 0.96, Al 0.47, Co 0.35, Mn 0.09, Si 0.08, Cu 0.05, C 0.02, P 0.01, B 0.004, S 0.0003, Ta < 0.01, Mg < 0.01 and Ca < 10 PPM). The samples were solution-treated by heating to 955 °C and holding for 1 h and then quenching in water. The mechanical properties of the workpiece material at room temperature are listed in Table 1 and its microstructure is shown in Fig. 1.

Turning experiments were conducted on HAAS CNC Lathe using uncoated cemented carbide inserts and a tool holder with the ISO designation of DNGG150402 and PDJNR2020 manufactured by Sandvik Cormorant. The cross-sectional analysis of the cutting edge of the
tool showed that the effective rake angle was +9°. To prevent ploughing action, and consequently, lower the amount of plastic deformation during the cutting process, a tool with a small radius was selected (0.2 mm), and the depth of cut was selected to be larger than the tool radius [33].

**Fig. 2**  
(a) Dimensions of linear strain gauge,  
(b) Wheatstone bridge configuration on the tool holder,  
(c) strain gauges attached on the tool holder and  
d) calibration diagram.

**Fig. 3**  
(a) Experimental setup showing the LN₂ Dewar flask, rotary pump and wireless data acquisition system,  
(b) application of LN₂ to the cutting area.
Linear strain gauges mounted on the tool holder were used to measure the cutting force in the tangential direction. The resistance and gauge factor of the strain gauges were 3.5 kΩ and 2.08 (Fig. 2a). Since the changes in the resistance of strain gauges were very low (usually less than 0.5%) [9], a Wheatstone bridge configuration was used [34] (Fig. 2b). A ‘groove’ was machined on the surface of the tool holder to improve the sensitivity of the measurements at small deflections that the tool holder experimented during the machining process (Fig. 2c). The force measurement setup was calibrated before each cutting experiment by hanging weights. Figure 2d shows the linear relationship between the applied load and the output voltage ($V_{\text{out}}$). A data acquisition system including a wireless transmitter (V-Link 2.4 GHz Wireless Voltage Node 181) and an analogue base receiver (MicroStrain Micro TxRx wireless base station W/ analogue outputs) was used to measure the cutting forces during the turning process. More details about the data acquisition system can be found in the research by Krishnamurthy et al. [19].

Cryogenic cutting experiments were conducted using a rotating pump mounted to a flask to spray the liquid nitrogen on the cutting edge of the tool and contact surface of the workpiece (Fig. 3a, b). Flooded cutting experiments were conducted using a synthetic cutting fluid. Flank wear values were recorded according to ISO 3685:1993 standard by measuring the flank wear land [35] at least in 10 spots, and the average values are reported. After each experiment, the insert was examined using a ZEISS Axio Vert optical microscope at x 20 magnification. The microscope was fitted with a digital camera. For measuring the wear land on the images obtained, the ImageJ software was used.

Vertical scanning interferometry (VSI) mode of WYKO NT 1100 optical profilometry system was utilized for 3D measurements of the machined surface roughness values. The measurements were taken at least in five areas on each machined surface.

In the current manuscript, the results section is presented in two parts: in Sect. 3.1, the results of a comparison between cryogenic, flooded and dry cutting are presented in terms of flank wear, cutting force and Ra surface roughness. Section 3.2 aims to optimize the cutting parameters at which the lowest values of cutting force, flank wear and Ra surface roughness were achieved using desirability function of response surface methodology (RSM). Regression models were developed in order to correlate cutting parameters to the response variables, and ANOVA was employed to determine the significance of each cutting parameter using central composite design (CCD) type of the response surface methodology (RSM) by using MINITAB software. Figure 4 shows the design of experiments cube plot. Axial, factorial and centre points are illustrated in this figure along with the related test numbers. Axial points estimate the quadratic terms of the model. The factorial portion of the design contributes to the estimation of the interaction terms in the second-order model. The centre points provide an internal estimate of error and contribute to the estimation of quadratic terms [36]. Three cutting parameters, namely cutting speed, feed rate and depth of cut, each at five levels, were considered as the process parameters. Material removal rate (MRR), flank wear, cutting force and surface roughness were considered as the response factors. Moreover, statistical analyses and multi-objective optimization of parameters using analysis of variance (ANOVA) and desirability function of RSM in machining using LN$_2$ are given in this section.

3 Results and discussions

3.1 Comparison of cryogenic cutting with flooded and dry machining

The objective of this section is to determine any difference in variations of cutting force, flank wear and surface roughness with cutting speed and feed rate when LN$_2$ is
applied to the cutting edge in comparison to conventional flooded cutting. In addition, since cryogenic cutting may be considered as a type of dry cutting method, the results were also compared to dry machining.

### 3.1.1 Effect of cutting parameters on cutting force under different cutting conditions

Figure 5a, b show the variation of cutting force values in terms of cutting speed and feed rate under cryogenic, flooded and dry conditions. The minimum value of cutting force (90 N) was obtained at a cutting speed of 70 m/min (Fig. 5a). By increasing the cutting speed, the flow stress of the workpiece material may decrease if the softening due to the increase in the cutting temperature outperforms the strain hardening effect. Pawade et al. [37] investigated the turning of Inconel 718 and showed that after a critical speed (60 m/min), the effect of increase in cutting temperature on the flow stress is more significant than the strain hardening. However, further increase in the cutting speed led to higher cutting force. This could be attributed to an increase in strain rate hardening but more experimental evidence is needed to confirm it. Iturbe et al. [38] in their study on the machining behaviour of Inconel 718 showed that high strain rate hardening coupled with high cutting temperatures at higher cutting speeds results in high cutting forces.

Figure 5b shows that by increasing the feed rate, the cutting force constantly increased. An increase in uncut chip thickness with increasing the feed rate, which in turn increases the normal load on the tool rake face, may result in a higher friction force and consequently a higher cutting force [39]. Variations of cutting forces with cutting time at different feed rates under cryogenic and flooded cutting are shown in Fig. 6a–c. At a feed rate of 0.01 mm/rev under cryogenic cutting (Fig. 6a), there was a large variation in the cutting force values due to the fracture of the tool nose and occurrence of chipping in the minor cutting edge (Sect. 3.1.2), which in turn resulted in high surface roughness (Sect. 3.1.3). The cutting force value was smaller (90 N) and more stable at a feed rate of 0.05 mm/rev under cryogenic cutting (Fig. 6a) compared to feed rates of 0.01 and 0.09 rev/min. The cutting force had an increasing trend with the feed rate up to 0.09 mm/rev (Fig. 6c) After 4 s, the cutting tool started to vibrate which is shown by the fluctuations in the cutting force values in Fig. 6c. Generally, flooded cutting had higher stability and less variation of cutting force with time, and the tool vibration was less than that of cryogenic cutting.

### 3.1.2 Effect of cutting parameters on flank wear under different cutting conditions

Figure 7a, b show the variation of average flank wear values with cutting speed and feed rate under the cryogenic condition, in comparison with flooded and dry cutting conditions. The measurements were done at least in 10 spots, and the average values are reported. Flank wear increased with an increase in the cutting speed as shown in Fig. 7a. An increase in cutting temperature reduces the strength of the tool material promoting wear and facilitates the adhesion of workpiece material and formation of built-up edge (BUE) [39]. Figure 7b shows that at the feed rate of 0.01 mm/rev under the cryogenic condition, wear was high. High
Fig. 6 Variations of cutting force with time at a feed rate of a 0.01 mm/rev, b 0.05 mm/rev and c 0.09 mm/rev when LN₂ is applied to the cutting area.
amount of chipping resulted in nose fracture on the minor cutting edge (Fig. 8a, b). Under dry cutting at low feed rate of 0.01 mm/rev (Fig. 7b), high flank wear in the form of chipping could also be observed (Fig. 8e, f). Failure of the cutting edge during cryogenic cutting was also reported in previous studies. Pusavec et al. [32] observed catastrophic failure of the cutting edge during the cryogenic cutting of Inconel 718 when compared to dry, MQL and CryoMQL conditions.

By increasing the feed rate to 0.05 mm/rev, the flank wear value dropped significantly to 100 µm, which was as low as that of flooded cutting, while dry cutting still resulted in a high flank wear value of 100 µm (Fig. 7b). Chipping was still observed under cryogenic cutting, but in a smaller amount (Fig. 9b). Adhesive wear was promoted at 0.05 mm/rev feed rate under cryogenic and flooded conditions and resulted in larger BUE formations (Fig. 9a–d). However, abrasive wear was the dominant wear mechanism under dry cutting (Fig. 9e, f).

At a higher feed rate of 0.09 mm/rev, flank wear value did not change significantly compared to that of 0.05 mm/rev (Fig. 7b). When the cryogenic condition was used, the tool wear mechanism changed as chipping did not occur neither on the major nor minor cutting edge (Fig. 10a, b). However, another wear mechanism, namely depth of cut (DOC) notch, was observed both on the minor and major cutting edges (Fig. 10a, b). Under flooded and dry conditions, built-up edge (BUE) was observed at this parameter (Fig. 10c–f).

Generally, adhesion of workpiece material on the cutting edge was high under cryogenic cutting which resulted in formation of BUE at all the feed rates. Zhuang et al. [40] reported similar results in which high adhesion and BUE were observed in cryogenic cutting of Inconel 718. Flank wear values were almost similar for cryogenic and flooded conditions for all cutting parameters while dry cutting resulted in higher flank wear at all the cutting parameters.

3.1.3 Effect of cutting parameters on Ra surface roughness under different cutting conditions

Figure 11a, b show variations of arithmetic average surface roughness Ra with cutting speed and feed rate under different cutting conditions. The effect of cutting speed on surface roughness depends on the variation of the cutting force with the speed — as cutting speed increased from 20 to 70 m/min, cutting force first decreased to a minimum value (0.5–0.6 µm) and increased again at 120 m/min (Fig. 5a).

Figure 11b shows that high values of Ra (1.65 µm) were observed at low feed rate (0.01 mm/rev) when cutting was carried out using LN2 possibly due to tool failure (Fig. 8b). Flooded cutting resulted in lower Ra (0.32 µm) as the cutting force was low (Fig. 5b), and the cutting edge retained its original shape (Fig. 8c, d).

Generally, surface roughness was lower under flooded than cryogenic cutting conditions. Under cryogenic condition more vibrations were created during the cutting process (Fig. 6a–c). Similar results were reported by Tebaldo et al. [29]. They compared MQC with dry and flooded cutting and reported a lower magnitude of surface roughness for the flooded turning compared to cryogenic turning.
The workpiece surface quality generated under cryogenic and flooded cutting conditions was closely investigated by SEM (Fig. 12a, b). Figure 12a shows surface morphology produced while LN2 was applied during the cutting process at different feed rates. At a low feed rate (0.01 mm/rev), at which the tool failed, formation of cavities and high built-up layers (BUL) resulted in a high $Ra$ value (1.7 µm) and poor surface quality. Side flow and BUL were observed at high feed rate (0.09 mm/rev) in lesser extent than 0.01 mm/rev, but the $Ra$ value was still high (1.4 µm). Side flow is the result of high pressure on the workpiece material left behind on the secondary cutting edge of the tool [34]. It has been shown that side flow can be zero for brittle materials [41]. At the
medium feed rate (0.05 mm/rev), however, the surface defects such as grooves and BUL were less prominent, and the $Ra$ value dropped to 0.6 µm, resulting in good surface quality, which was comparable to the one produced under flooded cutting as shown in Fig. 12b. Under flooded cutting, the surface quality was consistent and no change in the formation of surface defects was observed at different cutting parameters. However, the surface roughness increased with the feed rate (Fig. 12b) and formation of larger feed marks. Therefore, the surface
quality and formation of surface defects when LN$_2$ was sprayed to the cutting area was highly dependent on the feed rate at which the machining process was carried out. On the opposite, there was a consistency in the formation of surface defects under flooded cutting in the range of cutting speed and feed rates studied.

### 3.2 Statistical analysis and optimization of cutting parameters using LN$_2$ by RSM

Experimental results described in Sect. 3.1 indicated that there can be a set of parameters in which the cryogenic machinability of Inconel 718 could be as good as flooded...
machining in terms of tool wear, cutting force and surface quality. In order to determine these optimum cutting parameters under the cryogenic cutting condition, response surface methodology (RSM) was utilized. Cutting speed, feed rate and depth of cut were selected as the process parameters (Table 2) and flank wear, cutting force, $Ra$ surface roughness and material removal rate (MRR) were considered as the response parameters for the multi-objective optimization process using desirability function. The material removal rate (MRR) is defined as $V_c \times f \times a_p$. Experimental results on machining of Inconel 718 using LN$_2$ according to RSM experimental design arrangement are summarized in Table 3. The effect of cutting parameters on the response parameters was investigated by 3D surface graphs and statistical analyses so as to determine the most significant parameters on each response factor.

### 3.2.1 Effect of cutting parameters on cutting force

Quadratic regression model developed for the cutting force is presented in Eq. 1. Coefficient of determination ($R^2$) and adjusted coefficient of determination ($R^2$-adjusted) values of the model were calculated as 88.17% and 82.69%.

$$F_c = -3.5 - 2.100V_c + 1310f + 174a_p + 0.01482V_c^2 + 966f^2 + 51a_p^2$$  \hspace{1cm} (1)

Examination of normal probability plot of the residuals (Fig. 13a) and histogram of standardized residuals (Fig. 13b) for cutting force show that residuals are distributed normally around zero which shows the adequacy of the developed model.

Analysis of variance (ANOVA) for cutting force is presented in Table 4. In this table, $DF$ is the degree of freedom, which is one for each parameter, SS is the sum of squares which is a statistical technique to determine the variation of data points compared to the line of best fit, MS is mean square which is defined as SS/DF, and MSE is the mean square of error. $F$-value is calculated as MS/MSE, which is used to determine whether the test is statistically significant, meaning the results are meaningful and not randomly obtained [42]. For this purpose, the probability value ($P$-value) is calculated. $P$-value is defined as the smallest level of significance ($\alpha = 0.05$) that would lead to rejection of the null hypothesis, which is the average value of the dependent variable is the same for all groups [36]. In other words, when the $P$-value of a variable is less than 0.05, it can be stated with the 95% of confidence that the variable is statistically significant, and when the $P$-value of a variable is between 0.5 and 0.1, the variable is considered marginally significant [43]. $P$-value analysis of the cutting parameters in Table 4 showed that the cutting speed with the $P$-value of 0.011 was the only statistically significant parameter and had the highest contribution percentage (CRP) to the cutting force (85%). The feed rate had a marginally significant effect ($P$-value $= 0.122$) and had about 13% contribution to the cutting force.
3D surface graphs of the interaction effects of the cutting parameters are shown in Fig. 14a, b. An increase in cutting speed first reduced the cutting force and then increased it. The cutting force constantly increased with an increase in the feed rate and the depth of cut (Fig. 14b).

![Graph showing variation of surface quality with feed rate](image)

Table 2 Cutting parameters and their levels

| Cutting Parameters | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------------------|---------|---------|---------|---------|---------|
| Cutting speed, $V_c$ (m/min) | 20  | 45  | 70  | 95  | 120  |
| Feed rate, $f$ (mm/rev) | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 |
| Depth of cut, $a_p$ (mm) | 0.3  | 0.4  | 0.5  | 0.6  | 0.7   |
| Test no | Point Type | Cutting parameters | Response parameters |
|---------|------------|--------------------|---------------------|
|         |            | Speed, \( V_c \) (m/min) | Feed, \( f \) (mm/rev) | Depth of cut, \( \alpha_p \) (mm) | Cutting force, \( F_c \) (N) | Flank wear, \( V_B \) (\( \mu \)m) | Surface roughness, \( R_a \) (\( \mu \)m) | MRR (cm³/min) |
| 1       | C          | 70                 | 0.05               | 0.5                   | 86                 | 62           | 0.618           | 1.75       |
| 2       | C          | 70                 | 0.05               | 0.5                   | 89                 | 63           | 0.611           | 1.75       |
| 3       | C          | 70                 | 0.05               | 0.5                   | 82                 | 59           | 0.614           | 1.75       |
| 4       | C          | 70                 | 0.05               | 0.5                   | 80                 | 55           | 0.590           | 1.75       |
| 5       | C          | 70                 | 0.05               | 0.5                   | 83                 | 65           | 0.620           | 1.75       |
| 6       | C          | 70                 | 0.05               | 0.5                   | 85                 | 58           | 0.620           | 1.75       |
| 7       | A          | 120                | 0.05               | 0.5                   | 122                | 160          | 0.920           | 3.00       |
| 8       | A          | 70                 | 0.09               | 0.5                   | 140                | 67           | 1.189           | 3.15       |
| 9       | A          | 70                 | 0.05               | 0.7                   | 120                | 60           | 1.345           | 2.45       |
| 10      | A          | 20                 | 0.05               | 0.5                   | 108                | 53           | 0.805           | 0.5        |
| 11      | A          | 70                 | 0.01               | 0.5                   | 19                 | 210          | 1.199           | 0.35       |
| 12      | A          | 70                 | 0.05               | 0.3                   | 40                 | 23           | 0.634           | 1.05       |
| 13      | F          | 95                 | 0.03               | 0.6                   | 104                | 125          | 0.536           | 1.71       |
| 14      | F          | 95                 | 0.07               | 0.6                   | 153                | 97           | 1.146           | 3.99       |
| 15      | F          | 95                 | 0.03               | 0.4                   | 67                 | 100          | 0.363           | 1.14       |
| 16      | F          | 95                 | 0.07               | 0.4                   | 104                | 103          | 0.658           | 2.66       |
| 17      | F          | 45                 | 0.03               | 0.6                   | 106                | 54           | 0.851           | 0.81       |
| 18      | F          | 45                 | 0.07               | 0.6                   | 184                | 58           | 1.176           | 1.89       |
| 19      | F          | 45                 | 0.03               | 0.4                   | 66                 | 54           | 0.961           | 0.54       |
| 20      | F          | 45                 | 0.07               | 0.4                   | 110                | 27           | 0.948           | 1.26       |

*CCentral point, A axial point, F factorial point (see Fig. 4)*
Fig. 13  a Normal probability plot and b histogram of standardized residual for cutting force
3.2.2 Effect of cutting parameters on flank wear

The experimental data were used for developing a quadratic regression model in terms of flank wear using Box-Cox transformation (\(\lambda = 0\)) which as presented in Eq. 2.

\[
\ln VB = 1.78 - 0.0007V_c - 75.0 f + 14.10a_p
+ 0.000176V_c^2 + 433 f^2 - 11.72a_p^2
+ 0.099V_c \times f - 0.0301V_c \times a_p + 30.1 f \times a_p
\]

\(R^2\) and \(R^2\)-adjusted of the model were calculated as 92.17% and 85.13%. These high values confirmed the effectiveness of the model. Figure 15, a, b show the normal probability plots of the residuals for flank wear in which the data closely fall on the straight line indicating that the errors are distributed normally [36]. This also can be seen from the histogram of residuals for flank wear (Fig. 15b) showing that the distribution is around zero.

ANOVA for flank wear in Table 5 shows that all parameters had statistically significant effect on flank wear, as the \(P\)-values are less than 0.05. The feed rate with the \(P\)-value of 0.008 for \(f\) and 0.002 for \(f^2\) and CRP of 52% was the most significant variable that affected flank wear, followed by the depth of cut with a CRP of 30%.

The effect of feed rate on flank wear also can be observed in Fig. 16a, b. Flank wear increased significantly with the feed rate, especially at high cutting speeds. At a high cutting speed of 120 m/min, flank wear first decreased to a minimum value of 180 \(\mu m\) at the feed rate of 0.06 mm/rev, and then increased exponentially to 410 \(\mu m\) (Fig. 16a).

3.2.3 Effect of cutting parameters on \(Ra\) surface roughness

Regression model for predicting \(Ra\) surface roughness was developed using Box-Cox transformation (\(\lambda = 2\)) (Eq. 3). \(R^2\) and \(R^2\)-adjusted of the developed model were calculated as 82.52% and 66.72%.

\[
Ra^2 = 9.51 - 0.0486V_c - 112.4 f - 21.31a_p
+ 0.000126V_c^2 + 622 f^2 + 16.86a_p^2 + 0.174V_c
\times f + 0.0376V_c \times a_p + 88.0 f \times a_p
\]

Examination of the normal probability plot (Fig. 17a) and the histogram of standardized residual (Fig. 17b) showed that the residuals were distributed around zero which confirmed that the developed model was adequate. \(F\)-values and \(P\)-values of the feed rate and the depth of...
Fig. 14 3D surface graph showing interaction effect of a cutting speed and feed rate and b feed rate and depth of cut on cutting force
Fig. 15  
(a) Normal probability plot and (b) histogram of standardized residual for flank wear
cut presented in Table 6 showed that these parameters are statistically significant factors on $Ra$ surface roughness with CRP values of 52% and 30%.

Figure 18a shows the variation of $Ra$ surface roughness with cutting speed and feed rate. At low feed rates, $Ra$ values were high (1.4 µm) which was because of high tool wear as a result of chipping (Fig. 8). However, by increasing the feed rate, $Ra$ decreased to a minimum value and then increased again (Fig. 12). The $Ra$ surface roughness increased with increasing the depth of cut due to generation of deeper feed marks especially at a high feed rate of 0.09 mm/rev (Fig. 18b). The lowest $Ra$ was achieved at a cutting speed of 90 m/min, a feed rate of 0.04 mm/rev and a depth of cut of 0.4 mm.

### 3.2.4 Multi-objective optimization

Desirability function of RSM was used to perform the multi-objective optimization in order to determine the cutting parameters that would result in the maximum possible material removal rate, while maintaining the lowest possible flank wear, cutting force and $Ra$ surface roughness values. Each response parameter was converted to a desirability function varying from 0 to 1 in which 0 means the response is outside the acceptable region and 1 indicates that the response has reached the goal. Individual desirability functions were combined to provide a measure of composite desirability of the multi response system [16]. Constraints for optimizing flank wear, surface roughness, cutting force and material removal rate are summarized in Table 7. It was determined that a cutting speed of 87 m/min, a feed rate of 0.06 m/rev and a depth of cut of 0.37 mm were the optimum cutting parameters for achieving a flank wear of 58 µm, a cutting force of 78 N and an $Ra$ surface roughness of 0.49 µm with the MRR value of 1.97 cm³/min (Table 8). The manufacturer’s recommended values for the cutting parameters (for flooded machining) were as follows: cutting speed of 40 m/min, feed rate in the range of 0.02–0.1 mm/rev (recommended 0.04 mm/rev) and depth of cut in the range of 0.08–3 mm (recommended 0.2 mm) [44]. The optimum feed rate and the depth of cut estimated in this research are within the range of those provided by the manufacturer, but the cutting speed is twice as high as the one that manufacturer was proposed, which means that higher production rate can be possible.

### 4 Summary and Conclusions

In this work, cryogenic turning of Inconel 718 was experimentally investigated by determining the flank wear, cutting force and $Ra$ surface roughness at different cutting speeds and feed rates and comparing them with those obtained from flooded and dry conditions turning. The experimental
results showed that the machining behaviour of Inconel 718 under cryogenic cutting was highly dependent on the cutting parameters, and the cryogenic machining performance of Inconel 718, in terms of cutting force, flank wear and surface roughness, was inferior to that of the flooded cutting in most of the cases. However, it was also shown that using ‘medium cutting parameters’, the machining performance was as good as flooded machining. Low flank wear and low surface roughness (Ra) comparable to flooded machining resulted when cryogenic machining was used. Desirability function
of response surface methodology (RSM) was employed to determine the set of cryogenic cutting parameters that provided the lowest cutting force together with the lowest flank wear and \( Ra \) that can be achieved while maintaining the highest material removal rate (MRR). Analysis of variance (ANOVA) was employed to determine the significant factors affecting the response parameters. The following are the main results drawn from this research:

1. Application of liquid nitrogen spray to the cutting area lowered the flank wear compared to dry cutting, resulting in the values as low as the ones observed for flooded cutting. Abrasion of flank face of the tool and adhesion of Inconel 718 material, which resulted in high BUE formation on the cutting edge, were the main wear mechanisms in cryogenic, flooded and dry conditions. Chipping and depth-of-cut notch were observed at low (0.01 mm/rev) and high (0.09 mm/rev) feed rates under cryogenic condition.

2. \( Ra \) surface roughness was higher in cryogenic cutting than in flooded cutting at all the cutting parameters due to higher cutting tool vibrations during the cutting under cryogenic condition. Formation of surface defects such as built-up layers and cavities during cutting using LN\(_2\) was dependent on the value of cutting speed and feed rate, as opposed to flooded cutting during which there was a consistency in the surface quality. Surface morphologies produced at the medium feed rate (0.05 mm/rev) were comparable for flooded and cryogenic machining.

3. Multi-objective optimization using desirability function of RSM showed that a cutting speed of 87 m/min, a feed rate of 0.06 mm/rev and a depth of cut of 0.68 mm would constitute an optimum set of cutting parameters for achieving the lowest possible flank wear (58 \( \mu \)m), cutting force (78 N) and \( Ra \) surface roughness (0.49 \( \mu \)m) and the highest possible material removal rate, MRR (1.97 \( \text{cm}^3/\text{min} \)) in cryogenic cutting under the current test condition.
Fig. 17  

a Normal probability plot and b histogram of standardized residual for $Ra$ surface roughness
Fig. 18 3D surface graph for interaction effect of a cutting speed and feed rate and b feed rate and depth of cut on $Ra$ surface roughness.
Table 7  Constraints for optimization of flank wear, surface roughness, cutting force and material removal rate

| Response                        | Goal  | Lower | Target | Upper | Weight | Importance |
|---------------------------------|-------|-------|--------|-------|--------|------------|
| Cutting force, $F_c$(N)         | Minimum | –     | 19     | 184   | 1      | 1          |
| Flank wear, $VB_p$(µm)          | Minimum | –     | 23     | 210   | 1      | 1          |
| Surface roughness, $Ra$(µm)     | Minimum | –     | 0.363  | 1.345 | 1      | 1          |
| $MRR$(cm³/min)                  | Maximum | 0.35  | 3.99   | –     | 1      | 1          |

Table 8  Multi-objective optimization results and predicted values for response parameters

| Multi-objective optimization results | Predicted values |
|-------------------------------------|------------------|
| Cutting speed, $V_c$                  | $F_c$(N)         |
| Feed rate, $f$                        | $VB_p$(µm)       |
| Depth of cut,$a_p$                    | $Ra$ (µm)        |
| Composite Desirability               | $MRR$ (cm³/min)  |
| 87                                  | 78               | 58     | 0.49   | 1.97   |

**Funding**  This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the CANRIMT Strategic Research Network Grant NETGP 479639-15.

**Declarations**

**Competing interests**  The authors declare no competing interests.

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