Response Surface Methodology (RSM) based analysis for tool life optimization in cryogenic CO2 milling of Inconel 718

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Abstract. This study presents the tool life optimization of carbide coated ball nose milling inserts using high-speed milling Inconel 718 under cryogenic CO2 environment. A total of 29 experiments were conducted based on Box-Behnken Response Surface Methodology using the 4 factors; cutting speed (Vc: 120-140 m/min), feed rate (Fz: 0.15-0.25 mm/tooth), axial depth of cut (ap: 0.3-0.7 mm), and radial depth of cut (ae: 0.2-0.6 mm) at three levels each. By using ANOVA, it was found that all factors have significant effects on tool life. However, the feed rate shows its highest influence on the tool performance where the tool life can be lengthened by reducing the feed rate values. After that, the relevant influencing parameters on tool life were derived in the form of mathematical model which was then used to predict the response within the predetermined parameters. With an average error of 8.2% between the predicted and actual tool life, it confirms the adequacy of the model in this research. ANOVA also suggests a tool life of 23.40 min could be obtained at optimized parameters of; Vc: 120.06 m/min, Fz: 0.15 mm/tooth, ap: 0.66 mm and ae: 0.53 mm under cryogenic CO2 condition.

1. Introduction
Inconel 718 is a nickel-based alloy and it is the most widely used super-alloy for fabricating components operating in an aggressive service environment in heavy industries such as aerospace, marine and petrochemical plant. Inconel 718 is selected to apply because it has advanced mechanical and chemical properties that allow it to withstand its properties at stringent operating conditions. In aerospace industry, it is specifically used to produce the hottest components of turbine engine such as turbine blades which operates up to 520°C of service temperature. It is well performed at such elevated temperature due to its high heat and corrosion resistance and high hot hardness and strength [1]. Moreover, this difficult-to-cut material also has good tensile, creep and rupture strength that upsurges its demands in industries [2]. However, those superior properties develop more challenges in terms of its machinability, particularly when machined in high speed. For Inconel 718, its high-speed machining begins at speed approximately over 50 m/min. Rapid tool wears that shorten the tool life is among the most difficulties that need to be tackled when machining Inconel 718 in high speed. As reported by researchers such as Patil et al.[3], Aramcharoen et al. [4], Nalbant et al. [5] and Hadi et al. [6], the major cause of short tool life is due to the advanced mechanical and chemical properties of Inconel 718 that increase mechanical and thermal
loads on the cutting tool. As consequences, the tool lost its hardness, leading to severe plastic deformation and wear acceleration. Therefore, proper selections of cutting parameters such as cutting speed, feed rate and depth of cut as well as cutting coolant are important as they have significant influences on tool performances. For instance, Kasim et al. [7] asserted that cutting speed, feed rate, and depth of cut provided significant effect on tool life during high-speed milling Inconel 718 in Minimum Quantity Lubrication (MQL) condition. They also found that longer tool life can be achieved at lower values of those parameters. This finding was supported by Abdul Hadi [8] who also milled Inconel 718 at high speed but in cryogenic machining using liquid nitrogen (LN$_2$). According to their report, higher cutting speed increased the cutting temperature and resulted in severe tool wear. It is because, at high cutting temperature, Inconel 718 tends to harden rapidly that increases its hardness as well as its difficulty to be machined. It happens when its poor thermal conductivity which causes heat which is generated during the shearing of material fails to dissipate through the workpiece and the chips but accumulates at the cutting edges [9]. The heat builds up to the extreme values and then softens the cutting tool materials and accelerates wear. Besides that, Badroush et al. [10] conducted high speed turning Inconel 718 in cryogenic LN$_2$ condition and found cutting speed and feed rate as the most significant factors affecting the tool life.

To reduce the cutting temperature, the application of cutting fluids in the machining processes is very important. It is used to remove the heat as early as possible and at the same time, to reduce the cutting friction between the cutting tool and the workpiece. The conventional cutting fluid has been proven to be less effective in terms of decreasing the cutting temperature and increasing tool life. Apparently, the application of gasses as a cooling agent in cryogenic machining is seen to be the best option available to counter those limitations. The one that has attracted researchers’ attention nowadays is the application of cryogenic machining using carbon dioxide (CO$_2$). The effects of CO$_2$ as a coolant agent in machining have shown a lot of benefits to the users as revealed by Machai et al. [11]; decrease notch and flank wear of the tools while machining of titanium alloys, Supakar et al. [12]; provide better lubrication, and Dilip et al. [13]; reduced cutting temperature around 5% to 22% compared to wet machining of turning AISI 1045 steel. Another benefit of CO$_2$ as reported by Dilip et al. [14] is that it offered a better resistance to rake and flank wear due to the efficient temperature control and the increase of the tool’s hardness. Cryogenic CO$_2$ also has a greater impact on the environment and health and safety issues with major reduction of environmental pollution and workplace hazard.

In this study, the high-speed milling experiments were conducted to cut Inconel 718 in cryogenic condition according to machine parameters designed by Box-Behnken Response Surface Methodology (RSM) method. Then, statistical analysis using ANOVA was conducted to identify the relationship between controlled factors (cutting speed, feed rate, axial depth of cut (DOC) and radial DOC) on tool life. At the same time, a predictive model for the tool life was developed to predict the variation of tool life within the predetermined parameters. The RSM is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes [15]. This technique is more accurate, economical and faster than the traditional method such as ‘trial and error’, ‘listen to noise’ or ‘based on vibration’ practices [16]. Researchers such as Kasim et al. [7], Badroush et al. [10] and Aruna et al. [17] are among RSM users who have applied this technique for optimizing and predicting machining performance.

2. Methodology
In this study, the workpiece used for conducting the experiment is Inconel 718, grade AMS 5663 at measured hardness of 42 ± 2 HRC on its top surface. It underwent double aged heat treatment from its raw grade of AMS 5662 with the hardness of 92 HRB according to the material supplier. The dimension of the workpiece is 170 mm x 100 mm x 50 mm (length x width x height) in the form of a solid block. The chemical composition by weight percentage of this commercially available Inconel 718 contains; Ni (53%), Cr (18.3%), Fe (18.7 %), Nb (5.05%), Mo (3.05%), Ti (1.05%), Al (0.49%),
Co (0.3%), Mn (0.23%), Si (0.08%), C (0.051%), Cu (0.04%), B (0.004%), P (<0.005%) and S (<0.002%).

For the cutting tool, Sumitomo carbide coated ball nose milling inserts with grade ACK 300 were used. It is a multi-coated tool by the alternate layers of TiAlN and AlCrN until it achieves 3 µm of coating thickness. The radial rake angle, axial rake angle, and approach angle are 0°, -3°, and 90° respectively. The insert is 10 mm diameter attached to a 16 mm diameter tool holder at an overhang of 60 mm. The down-end milling experiments were performed on a CNC milling machine model DMG 635, V Eco having a maximum spindle speed of 80,000 rpm. The independent factors for the experiment were cutting speed (Vc), feed rate (Fz), axial DOC (ap) and radial DOC (ae) controlled at three levels as listed in Table 1. A total of 29 experiments were conducted in cryogenic CO₂ condition as in Figure 1. The experimental layout was designed using Box-Behnken RSM where all parameters were arranged without combining their highest and lowest value of each factor at the same time. This is to avoid cutting the material under extreme conditions which would probably produce inadequate results [18].

For the cryogenic system, the coolant is the mixture of liquid and gas CO₂ and compressed air which were mixed together in an in-house designed of CO₂ regulator system. Each of them was controlled at pressure 11 bar, 6 bar, and 4 bar for liquid CO₂, gaseous CO₂, and compressed air, respectively. The minimum temperature of the cryogen existed from the nozzle was controlled at approximately -55 °C. The coolant was supplied through a copper nozzle directed to the tool-chip interface in the cutting zone. The CO₂ regulation system was employed to control the pressure that can influence the liquid-gas-snow phase changes which occur along the flow of the coolants in the insulated hose and the nozzle.

The experiment focused on measuring the progress of tool wear and the total cutting time required to complete all pass in order to identify the tool life. Due to that, the cutting process was interrupted after every specific pass interval to observe and measure the growth of wear on the flank face of the insert. The average (VB) and maximum flank wear (VBmax) were measured and recorded by using a three-axis Mitutoyo toolmaker's microscope at 30x of magnification as shown in Figure 2. This microscope was attached with a digital micrometre that can measure in x-axis and y-axis in 0.001 mm resolution. A custom holding jig was used to tightly hold the insert along the measurement process so that the measurement can be accurately performed. The cutting process then was continued using the same insert until the VBmax reached 0.2 mm. Once it reached the limit, the cutting was stopped and the insert was isolated.

Table 1. Cutting parameters and their levels of control

| Control parameters      | Level of control parameters |
|-------------------------|----------------------------|
|                         | -1  | 0   | 1   |
| Cutting speed, Vc (m/min)| 170 | 190 | 210 |
| Feed rate, Fz (mm/tooth) | 0.15| 0.2 | 0.25|
| Axial depth of cut, ap (mm)| 0.3 | 0.5 | 0.7 |
| Radial depth of cut, ae (mm) | 0.2 | 0.4 | 0.6 |
Figure 1. Experimental setup with cryogenic CO$_2$ delivery, and the insert attached to the clamping chuck

Figure 2. The three-axis Mitutoyo toolmaker's microscope with the insert held by a holding jig

3. Results and optimization

3.1. Tool life from experimental results

Table 2 shows 29 experimental layouts based on Box-Behnken RSM with the experimental and predicted tool life results. Based on the experimental results, the longest tool life was 22.77 min which was recorded at $V_c$: 120 m/min, $F_z$: 0.2 mm/tooth, $a_p$: 0.5 mm and $a_e$: 0.2 mm. Meanwhile, the shortest tool life was 3.17 min, obtained at $V_c$: 130 m/min, $F_z$: 0.25 mm/tooth, $a_p$: 0.5 and $a_e$: 0.6 mm.

| No | $V_c$ (m/min) | $F_z$ (mm/tooth) | $a_p$ (mm) | $a_e$ (mm) | Tool life (min) | Error Actual | Error Predicted | Error % |
|----|--------------|-----------------|------------|------------|----------------|--------------|----------------|--------|
| 1  | 120          | 0.15            | 0.50       | 0.40       | 20.91          | 20.57        | 1.62           |        |
| 2  | 140          | 0.15            | 0.50       | 0.40       | 10.26          | 11.31        | 10.24          |        |
| 3  | 120          | 0.25            | 0.50       | 0.40       | 11.39          | 11.11        | 2.48           |        |
| 4  | 140          | 0.25            | 0.50       | 0.40       | 6.00           | 7.11         | 18.43          |        |
| 5  | 130          | 0.20            | 0.70       | 0.20       | 17.63          | 19.30        | 9.47           |        |
| 6  | 130          | 0.20            | 0.70       | 0.20       | 13.47          | 13.36        | 0.82           |        |
| 7  | 130          | 0.20            | 0.70       | 0.40       | 12.8           | 12.63        | 1.36           |        |
| 8  | 130          | 0.20            | 0.70       | 0.40       | 7.05           | 6.69         | 5.16           |        |
| 9  | 120          | 0.20            | 0.70       | 0.40       | 22.77          | 22.44        | 1.46           |        |
| 10 | 140          | 0.20            | 0.70       | 0.40       | 16.9           | 15.81        | 6.48           |        |
| 11 | 120          | 0.20            | 0.50       | 0.60       | 14.15          | 15.76        | 11.40          |        |
| 12 | 140          | 0.20            | 0.50       | 0.60       | 7.85           | 9.13         | 16.33          |        |
| 13 | 130          | 0.15            | 0.30       | 0.40       | 17.58          | 16.12        | 8.31           |        |
| 14 | 130          | 0.15            | 0.30       | 0.40       | 9.41           | 9.28         | 1.33           |        |
| 15 | 130          | 0.15            | 0.70       | 0.40       | 9.43           | 10.18        | 7.95           |        |
| 16 | 130          | 0.15            | 0.70       | 0.40       | 3.77           | 3.34         | 11.28          |        |
| 17 | 120          | 0.20            | 0.30       | 0.40       | 15.09          | 14.74        | 2.29           |        |
| 18 | 140          | 0.20            | 0.30       | 0.40       | 17.43          | 16.24        | 6.81           |        |
3.2. Statistical analysis using ANOVA

Statistical analysis using ANOVA was conducted on the experimental results to identify the significant influence on the tool life by the control factors. A second-order statistical equation model was also developed by using the experimental tool life results and is shown in Equation (1). Based on the ANOVA results as in Table 3, the F-Value of the model is 72.72 and the Prob>F is obviously smaller than 0.05. These imply that the second-order polynomial model generated is significant. By arranging the F values in a descending order, the Box-Behnken quadratic model reveals that factors B, D, A, C, BD, D^2, AC, A^2, and AB are the significant model terms in the model. All of them have a significant effect on the performance of the multi-coated tool life with the major influence coming from feed rate. In this research, the tool life can be lengthened by reducing the feed rate values. Table 3 also shows that the lack of fit is 0.0717 which indicates it is not significant. Thus, the model is adequate and fit for predicting the variation of tool life within the predetermined cutting parameters. It can also be noticed that the determination coefficient (R^2) of the model is 0.9668, which specifies that the model adequately represents the real relationship between the control factors. An adequate precision of 32.183 which is greater than 4 indicates an adequate signal, which is considered desirable.

The interaction effect between control factors on the tool life was analysed using 3D surface model graph as shown in Figures 3, 4 and 5. Figure 3 shows the interaction between feed rate and radial DOC. Both approaches which are by increasing the radial DOC at minimum feed rate (0.15 mm/tooth) or by increasing the feed rate at minimum radial DOC (0.2 mm) could be applied to extend the tool life. Based on the interaction between cutting speed and axial DOC as shown in Figure 4, the longest tool life could be achieved either by increasing the cutting speed at the lowest axial DOC (0.3 mm) or increasing the axial DOC when cutting speed is at the minimum value (170 m/min). For interaction between cutting speed and feed rate as in Figure 5, it recommends that the lowest cutting speed (170 m/min) and feed rate (0.15 mm/tooth) should be applied to lengthen the tool life to the longest. However, increasing the feed rate at any value of cutting speed will reduce the tool life. The steepest skewness of feed rate shows its higher influence on the tool performance. This result was similar with the finding of Kasim [7] which investigated high-speed milling Inconel 718 in MQL condition.

Table 3. ANOVA table for tool life

| Source      | Sum of squares | DF | Mean square | F Value | Prob > F  |
|-------------|----------------|----|-------------|---------|-----------|
| Model       | 771.07         | 9  | 85.67       | 72.72   | < 0.0001  |
| A-Cutting speed | 131.94         | 1  | 131.94      | 111.98  | < 0.0001  |
| B-Feed rate  | 140.15         | 1  | 140.15      | 118.95  | < 0.0001  |
| C-Axial DOC  | 105.85         | 1  | 105.85      | 89.84   | < 0.0001  |
| D-Radial DOC | 133.60         | 1  | 133.60      | 113.39  | < 0.0001  |
| A^2          | 53.80          | 1  | 53.80       | 45.66   | < 0.0001  |
TL: 1.973 min  TL: 17.28min  TL: 15.48 min  TL: 16.42 min

**Figure 3.** Interaction between Fz and ae at Vc: 130 m/min and ap: 0.50 mm

TL: 14.92 min

**Figure 4.** Interaction between Vc and ap at Fz: 0.2 mm/tooth and ae: 0.40 mm

TL: 7.155 min  TL: 20.62 min  TL: 11.36 min

**Figure 5.** Interaction between Vc and Fz at ap: 0.5 mm and ae: 0.40 mm

3.3. **Development and validation of the Second-Order Model using RSM**

Second order model equation for the tool life of carbide coated ball nose milling inserts was established using Box-Behnken RSM design as:

|          | TL: 73.38 | TL: 62.28 | < 0.0001 |
|----------|-----------|-----------|----------|
| D²       | 73.38     | 1         | 73.38    | 62.28    | < 0.0001 |
| AB       | 6.92      | 1         | 6.92     | 5.87     | 0.0256   |
| AC       | 66.10     | 1         | 66.10    | 56.10    | < 0.0001 |
| BD       | 74.48     | 1         | 74.48    | 63.21    | < 0.0001 |
| Residual | 22.39     | 19        | 1.18     |          |          |
| Lack of Fit | 21.19     | 15        | 1.41     | 4.74     | 0.0717   | not significant |
| R-Squared| 0.9718    |           |          |          |          |
| Adj. R-Squared| 0.9584   |           |          |          |          |
| Pred. R-Squared | 0.9228 |           |          |          |          |
| Adeq. Precision | 32.183 |           |          |          |          |

**Figure 3.** Interaction between Fz and ae at Vc: 130 m/min and ap: 0.50 mm

**Figure 4.** Interaction between Vc and ap at Fz: 0.2 mm/tooth and ae: 0.40 mm

**Figure 5.** Interaction between Vc and Fz at ap: 0.5 mm and ae: 0.40 mm
Tool Life, TL =
252.91894 - 2.57297Vc - 145.60000Fz + 178.23750ap + 4.40360ae + 6.97976E-003Vc^2 + 81.51634ae^2 + 1.31500Vc.Fz - 1.01625Vc.ap - 431.50000Fz.ae

(1)

The model was then used to calculate the predicted tool life. The results were compared with the actual experimental results to determine the accuracy of the model. Based on comparison results shown in Table 2 and Figure 6, the errors ranged from 0.01% to 39.32% and the average error was 8.2%. Based on the common practice, the optimization model can be considered valid and acceptable when the error is less than 15%. Moreover, most of the measured tool life was obtained experimentally and the predicted value from equation (1) generated close results.

To validate the adequacy of the mathematical model, the diagnostic plots of the predicted vs. actual and the outlier T as per Figure 7a and 7b were analysed. Both plots proved that the residuals followed a normal distribution and fit the data well. As per Figure 7 (a), all actual and predicted points fall close to the straight line, which means that the errors are distributed normally. Meanwhile, in Figure 7 (b), all data are within the limits, which show no obvious pattern and unusual structure in the model.

Figure 6. Comparison between actual and predicted tool life of multi-coated carbide inserts

Figure 7. a) The diagnostic plots of the predicted vs. actual, b) Outlier T

3.4. Optimization of tool life

The main objective of the optimization is to determine a combination of optimum processing parameters within the predetermined parameters that can lengthen the tool life to the maximum. ANOVA suggests it can be reached at Vc: 120.06 m/min, Fz: 0.15 mm/tooth, ap: 0.66 mm and ae: 0.53 mm to obtain a tool life of 23.4 min. The ramp view in Figure 8 clearly indicates the point of optimum parameter and the longest tool life in the set parameters. This predicted tool life is longer than the longest tool life that was achieved through the experimental works.
4. Conclusion

In this study, the Box Behnken RSM was systematically applied to improve the tool life of carbide coated ball nose milling inserts in high-speed milling of Inconel 718 under cryogenic CO$_2$ condition. Results from the experimental found that the longest tool life of 22.77 min was achieved at Vc: 120 m/min, Fz: 0.2 mm/tooth, ap: 0.5 mm and ae: 0.2 mm. However, ANOVA suggests the tool life of 23.4 min can be reached at Vc: 120.06 m/min, Fz: 0.15 mm/tooth, ap: 0.66 mm and ae: 0.53 mm. All four controlled factors have influenced on the tool life with the feed rate and radial DOC as the major contributors. For interaction between factors, the main influencer is the interaction between feed rate and radial DOC followed by the interaction between cutting speed and axial DOC. It was also found that the developed mathematical model accurately represented the tool life at an average error of 8.2% when compared to the actual and predicted tool life. This shows that the model is adequate for predicting the tool life values within the range of predetermined parameters in the cryogenic CO$_2$ environment.

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