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# Optimisation of CNC Turning Parameters using RSM for Inconel 718 in Dry Cutting Conditions, Focusing on Surface Roughness

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ABSTRACT

Inconel 718 is widely utilised in machining applications due to its exceptional mechanical properties, particularly in high-temperature environments, making it a preferred material in industries such as aerospace and automotive. However, the machining of Inconel 718 material presents significant challenges, particularly in achieving an optimal surface finish under dry-cutting conditions using a CNC turning machine. This study addresses the critical issue of improper cutting parameters involving cutting speed (*Vc*) and feed rate (*fz*), which can adversely affect the surface quality of machined components. This research aims to determine the optimal cutting parameters that minimise surface roughness (*Ra*) on Inconel 718 in dry-cutting conditions. A systematic methodology was employed, wherein various *Vc* from 30 to 100 m/min, *fz* was adjusted between 0.03 to 0.07 mm/rev, and a constant depth of cut was set at 0.5 mm. The Response Surface Methodology (RSM) was utilised to analyse the effects of these parameters on *Ra*, allowing for the identification of optimal machining conditions. The results show that *Vc* 100 m/min and *fz* 0.0696 mm/rev significantly improve surface finish by producing the lowest *Ra* of 0.4416 µm, which is 51% better than *Vc* 65 m/min and *fz* 0.03 mm/rev. This study contributes to the body of knowledge on CNC turning machining of superalloys in dry-cutting conditions. It provides valuable insights for machine operators aiming to enhance machining efficiency and product quality in industrial applications.

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## INTRODUCTION

Computer numerical control (CNC) lathe machining is a precise and automated manufacturing process that uses computer-controlled tools to rotate workpieces while cutting, shaping, and finishing them into custom designs and components. Dry machining was selected in this study to promote environmentally friendly and sustainable manufacturing by eliminating cutting fluids, which are costly and pose health and disposal concerns. While it is acknowledged that the absence of coolant can lead to poor surface quality due to increased heat and friction (Yang et al., 2023). The study aimed to evaluate tool performance and surface finish under dry conditions to identify parameters that could mitigate these effects. This approach aligns with green manufacturing practices and provides insights into optimising dry machining processes for industrial applications.

However, there is a weakness in CNC lathe machining, as improper cutting parameters such as feed rate (*fz*) and cutting speed (*Vc*) can lead to surface finish issues that indirectly affect dimensional inaccuracies, especially when working with harder materials in dry cutting conditions. A significant weakness when machining Inconel 718 in dry-cutting conditions is the potential for increased surface roughness (*Ra*) due to elevated tool wear and thermal stresses. As noted by Wassila et al. (2020), higher cutting velocities in dry machining led to a deterioration in surface quality, as the absence of lubrication exacerbates tool wear mechanisms, resulting in a rougher surface finish. Furthermore, studies have shown that the lack of coolant can cause thermal expansion and residual stresses in the material, which negatively impact the surface integrity (Norfauzi et al., 2024; Siddique et al., 2023). This interplay between cutting parameters and *Ra* highlights the necessity for careful optimisation of machining conditions to mitigate adverse effects and improve the overall quality of the machined surface (Huynh et al., 2025). Without a cutting fluid, this can lead to poor surface quality. The investigation should focus on analysing the effects of cutting parameters such as *Vc* and *fz* on *Ra* during dry machining of Inconel 718 to determine optimal conditions for improving surface finish.

This paper aims to determine the optimal cutting parameters using Response Surface Methodology (RSM) to minimise *Ra* during the dry cutting conditions on Inconel 718. These tests involve systematically varying critical cutting parameters, namely *Vc* and *fz*, with a constant depth of cut (*ap*), to evaluate their individual and combined effects on the machining process. The application of RSM allows for systematically exploring the relationships between cutting parameters such as *Vc*, *fz*, and *ap* and their effects on *Ra* (Wassila et al., 2020). Previous studies have demonstrated that optimising these parameters can significantly improve surface quality, as evidenced by the work by Tayisepi et al. (2024) and Kurşuncu (2024), who successfully utilised RSM to enhance machining performance in similar contexts. Furthermore, Eskandari et al. (2022) indicate that employing RSM not only aids in identifying optimal conditions but also provides insights into the interactions between multiple factors, ultimately leading to more efficient machining processes for Inconel 718. A series of controlled experimental tests should be conducted to accomplish the study's objective by determining optimal cutting parameters for minimising *Ra* during dry machining on Inconel 718. Each test will be carefully monitored, with measurements taken to assess *Ra* evaluated using surface profiling equipment. Data collected will be analysed to establish correlations between the cutting parameters and surface quality outcomes, ultimately identifying optimal machining conditions that enhance performance and longevity in machining Inconel 718 without cutting fluid. Fig 1 shows a pipeline for the overall study.

A future study could focus on the effects of titanium aluminium nitride (TiAlN) coatings during dry machining on Inconel 718. TiAlN is known for its superior thermal stability and oxidation resistance compared to titanium nitride (TiN) (Zhang et al., 2021). Investigating the performance differences between these coatings could provide valuable insights into improving machining efficiency. These render them particularly suitable for high-temperature applications such as the dry cutting of challenging superalloys that indirectly affect the final surface finish, or *Ra* (Wassila et al., 2020). The inherent high hardness of TiAlN contributes to a significant reduction in abrasive wear. At the same time, its low-friction

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characteristics help to decrease cutting temperatures, thereby minimising tool wear and promoting smoother cutting operations. By investigating the influence of TiAlN coatings on critical parameters such as cutting forces, temperature distribution, and tool wear, this research would yield valuable insights into the potential of this coating to enhance tool life and improve surface finish during the dry machining of Inconel 718. Ultimately, such findings could facilitate the optimisation of machining processes, balancing efficiency and quality in manufacturing components from this demanding material.

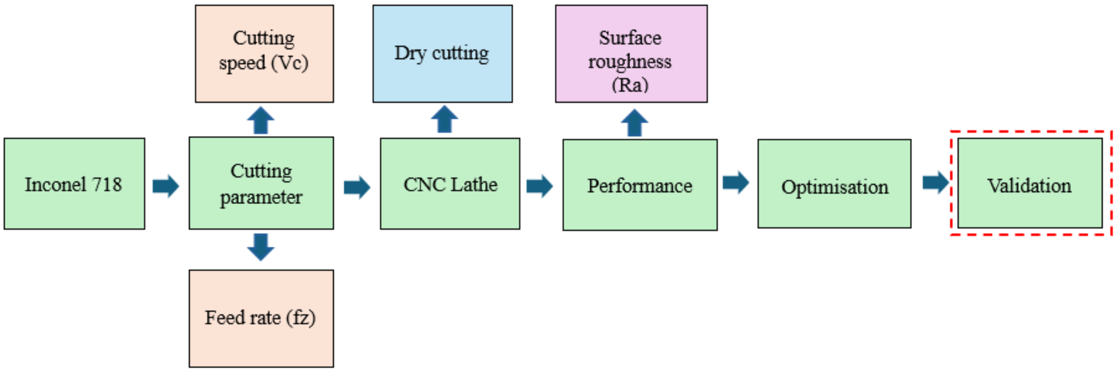


Fig. 1. Pipeline for the overall study.

## EXPERIMENTAL PROCEDURE

The workpiece material used for the turning operation study was Inconel 718, a high-performance nickel-based superalloy characterised by its excellent mechanical properties and resistance to extreme environments, particularly at elevated temperatures. Inconel 718 is composed primarily of nickel (50-55%), chromium (17-21%), and iron (bal.), along with significant additions of niobium (4.75-5.5%) and molybdenum (2.8-3.3%), which contribute to its high strength and corrosion resistance. This alloy is particularly suited for turning operations due to its ability to maintain structural integrity under thermal stress and its favourable machinability when subjected to appropriate cutting conditions. Table 1 shows the physical properties of Inconel 718, and Fig 2 shows Inconel 718 with specific dimensions used in this study.

Table 1. Physical properties of Inconel 718

| Hardness (HRc) | Melting point (Co) | Yield strength (MPa) | Tension strength (MPa) |
|---|---|---|---|
| 48 | 1350 | 490 | 820 |

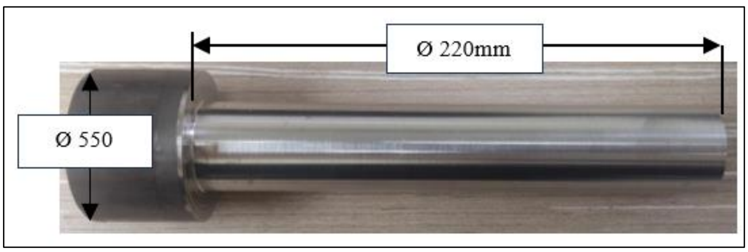


Fig. 2. Inconel 718.

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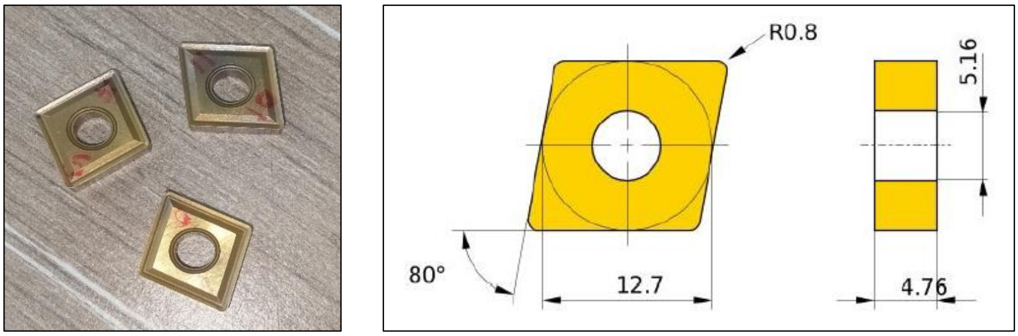
## Turning Process

The turning process using a CNC turning machine, as shown in Fig 3, was conducted to investigate the effects of various cutting parameters, namely *Vc* and *fz*, with constant *ap*, on the surface finish of Inconel 718. Given the increasing demand for precision components in aerospace and other high-tech industries, understanding the machining characteristics of Inconel 718 is critical for optimising manufacturing processes and enhancing product reliability.


Fig. 3. Doosan Lynx 220L lathe CNC.

## Cutting Tool

Fig 4(a) shows the usage of a TiN (titanium nitride) coated carbide cutting tool with CNMG specification type CNMG120408. Three cutting tools can be used for experiments, each capable of preparing 11 tests. The cutting tool specifications are shown in Fig 4(b).




(a) (b)

Fig. 4. (a) Carbide cutting tool and (b) specification of CNMG120408.

## Range of Cutting Parameters

An extensive experimental design was established to investigate the impact of cutting parameters on *Ra*. The primary cutting parameters examined in this study are *Vc* (m/min) and *fz* (mm/rev), while *ap* (mm) is in a constant condition. The parameters obtained are referred to from the box (manufacturer) of the LAMINA-type cutting tool, and the parameter range is expanded, as shown in Table 2. Each parameter was allocated several levels to assess its potential influence on *Ra* effectively.

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Table 2. The range of parameters

| Name | Unit | Level | |
|---|---|---|---|
| | | Low | High |
| *Vc* | m/min | 30 | 100 |
| *fz* | mm/rev | 0.03 | 0.07 |

## Response Surface Methodology (RSM) Method

Table 3 shows Vc and fz generated by RSM using Design Expert 13 software, following the range of parameters from Table 2 with a constant cutting depth and *Ra* result based on the experiment. In this study, RSM is a statistical approach investigating the relationships between independent (explanatory) and dependent (response) variables. This study uses the Central Composite Design (CCD) method in a face-centered option as a second-degree polynomial model involving two factors (*Vc* and *fz*), with three center points to enhance the accuracy and reliability of the model, which subsequently produced 11 runs for machining tests. To analyse the statistical significance of the developed RSM model, an analysis of variance (ANOVA) was conducted to help determine the contribution of each machining parameter.

Table 3. Generated machining parameters from RSM

| Run | *Vc* (m/min) | *fz* (mm/rev) | *ap* (mm) | *R*a (µm) |
|---|---|---|---|---|
| 1 | 65 | 0.05 | | 0.6712 |
| 2 | 30 | 0.07 | | 0.4953 |
| 3 | 65 | 0.03 | | 0.861 |
| 4 | 30 | 0.03 | | 0.81 |
| 5 | 65 | 0.05 | | 0.6872 |
| 6 | 30 | 0.05 | 0.5 | 0.623 |
| 7 | 100 | 0.05 | | 0.546 |
| 8 | 100 | 0.03 | | 0.712 |
| 9 | 65 | 0.05 | | 0.6732 |
| 10 | 65 | 0.07 | | 0.5389 |
| 11 | 100 | 0.07 | | 0.442 |

Lowest *Ra* based on experiment

## RESULTS AND DISCUSSION

Fig 5 shows the *Ra* test results from machining parameters generated by RSM based on the provided range. The results indicate that a 100 m/min *Vc* and a 0.07 mm/rev *fz* achieved the lowest *Ra* in dry-cutting conditions, which is 0.442 µm, equal to 51% better than 65 m/min *Vc* and 0.03 mm/rev *fz*. This outcome is attributed to the effective chip formation and material removal facilitated by the high *Vc*, which minimises heat generation and tool wear. The suitable combination of *fz* allows for finer cuts, enhancing surface quality by reducing the depth of engagement per revolution (Faiz et al., 2019; Azhar et al., 2020). Overall, the combination of these parameters optimises machining performance, as supported by previous literature on dry-cutting practices. However, at the lowest *fz* of 0.03 mm/rev across all *Vc*, the *Ra* of Inconel 718 is high due to the increased friction and heat generation at the cutting interface, which is particularly problematic in dry-cutting conditions. Inconel 718, known for its high strength and work-hardening characteristics, exhibits significant challenges during machining. Low *fz* can lead to prolonged tool engagement with the material, exacerbating wear and promoting the formation of a built-up edge (Song et al., 2023). This built-up edge can further deteriorate surface integrity, resulting in a rougher finish as the tool struggles to remove material without lubrication effectively (Zhu et al., 2022; Azhar et al., 2023). Consequently, while lower feed rates are often associated with improved surface finishes (Khandey et al., 2023), the unique properties of Inconel 718 necessitate a careful balance of cutting parameters to mitigate adverse effects on surface quality during dry machining operations.

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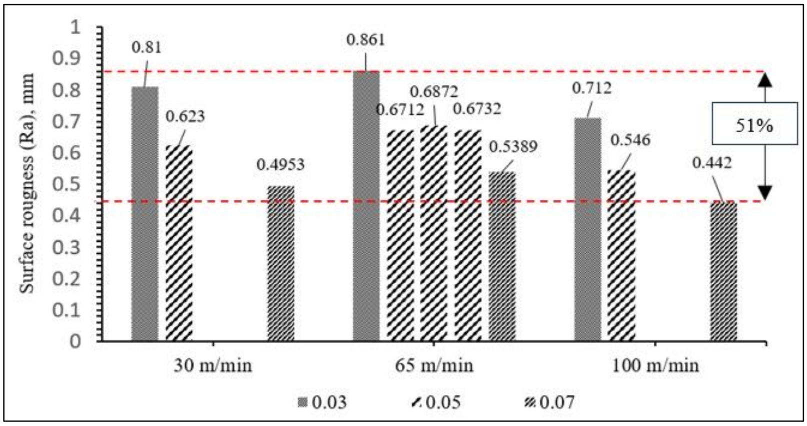


Fig. 5. Surface roughness result.

## ANOVA Results for Responses

Eliminating insignificant terms is crucial to constructing a precise model. Table 4 verifies that only pure error is associated with the model, indicating that it is acceptable to remove these terms. The results of the ANOVA demonstrate a 43.20% chance that the lack of fit is insignificant despite the presence of a considerable model. The turning experiments aimed to investigate the impact of cutting parameters, namely *Vc*, *fz*, and the constant of *ap*, on surface *Ra* during the machining of Inconel 718. The predicted $R^2$ value of 0.9780 indicates a relatively low proportion of variance in the response variable that is explained by the model when using new data.

Table 4. ANOVA for the *Ra* – quadratic model

| Source | Sum of squares | df | Mean square | F-value | p-value | Contribution % |
|---|---|---|---|---|---|---|
| Model | 0.1662 | 5 | 0.0332 | 343.48 | <0.0001 | Significant |
| *A-Vc* | 0.0087 | 1 | 0.0087 | 89.76 | 0.0002 | |
| *B-fz* | 0.1370 | 1 | 0.1370 | 1416.17 | <0.0001 | |
| *AB* | 0.0005 | 1 | 0.0005 | 5.16 | 0.0723 | |
| $A^2$ | 0.0199 | 1 | 0.0199 | 206.02 | <0.0001 | |
| $B^2$ | 0.0018 | 1 | 0.0018 | 18.71 | 0.0075 | |
| Residual | 0.0005 | 5 | 0.0001 | | | |
| Lack of fit | 0.0003 | 3 | 0.0001 | 1.46 | 0.4320 | Not significant |
| Pure error | 0.0002 | 2 | 0.0001 | | | |
| Cor total | 0.1667 | 10 | | | | |
| $R^2$ | | | | | | 0.9971 |
| Adjusted $R^2$ | | | | | | 0.9942 |
| Predicted $R^2$ | | | | | | 0.9780 |
| Adeq. Precision | | | | | | 57.5132 |

Independent variable really affects the output.

The model is good enough to explain the relationship between variables ($p > 0.05$).

In contrast, the Adjusted $R^2$ value of 0.9942 suggests that the model accounts for approximately 99.42% of the variability in the response variable when adjusted for the number of predictors included. The difference of less than 0.2 between these two metrics implies a reasonable degree of model reliability, as a close alignment between predicted and adjusted $R^2$ values typically indicates that the model is not overfitting the data and that the predictors included are relevant to the response variable. In addition, Adeq. Precision is an important measure of the signal-to-noise ratio in statistical models, with a desirable threshold of greater than 4. The current analysis reveals an Adeq. Precision ratio of 57.5, indicating a strong signal and suggesting that the model can effectively differentiate between significant factors and noise. This

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favourable ratio enhances the model's applicability in navigating the design space, facilitating informed decision-making for optimising process parameters.

*Regression mathematical model*

Equation 2 provides the mathematical expression utilised in Equation 1, derived using regression coefficients for *Ra* responses. Coded Equation 2 can forecast the outcome for each factor's specified amounts. By default, the variables' high and low levels are coded as +1 and -1, respectively. The coded Equation 2 can ascertain the influence of the relative factors by comparing the factor coefficients.

$$Y = \beta 0 + \beta 1A + \beta 2B + \beta 3C + \beta 4AB + \beta 5AC + \beta 6BC + \beta 7A2 + \beta 8B2 + \beta 9C2 \quad (1)$$

$$Ra = +0.6756 - 0.0380A - 0.1511B + 0.0112AB - 0.0887A + 0.0267B2 \quad (2)$$

Regarding actual factors in the original units, the response for each factor specified values can be predicted using the actual Equation 3. The regression coefficients are adjusted to correspond to the original units of each parameter, allowing for the utilization of the actual factors to estimate the response based on the specified values of each factor, as delineated in the actual Equation 3.

$$\mathrm{R}a = 1.03712 + 0.007529Vc - 15.27856fz + 0.015964fz - 0.000072Vc^2 + 66.84211\,fz^2 \quad (3)$$

*Predicted vs actual*

The predicted value compared to the actual value in Fig 6 shows a significant degree of correlation, indicating that the model effectively captures the underlying relationships between the independent variables and the response variable. The analysis reveals that the predicted *Ra* values closely align with the observed data points, indicating a strong correlation between the modelled parameters and the actual surface roughness measurements obtained during the machining process. This consistency validates the predictive model employed in this study and underscores its potential utility for optimising cutting conditions in future machining operations, particularly for challenging materials such as Inconel 718. Statistical metrics such as the coefficient of determination ($R^2$) and root mean square error further substantiate this finding, as they demonstrate a high level of explanatory power and minimal deviation from the actual values. Additionally, residual analysis indicates that the errors are randomly distributed, reinforcing the model's validity.

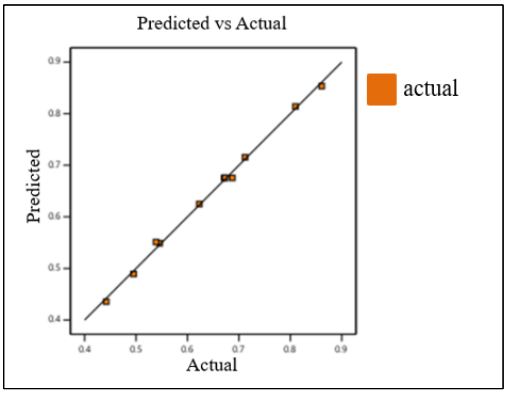


Fig. 6. Effect of cutting parameters on surface roughness *Ra*.

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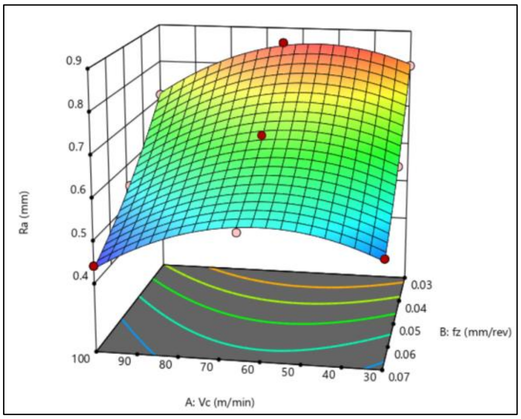
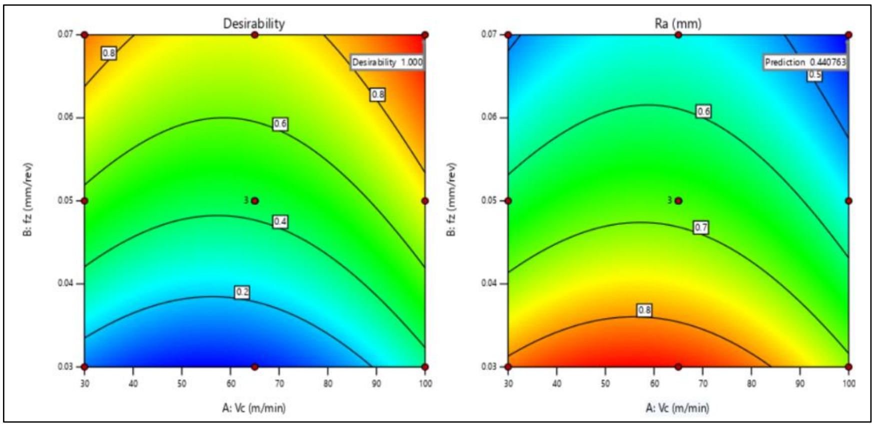
Fig 7(a) shows a 3D surface; *Ra* increases due to a decrease of *Vc* and *fz* at dry cutting on Inconel 718. This trend can be attributed to the heightened friction and thermal effects at lower *Vc*, which exacerbate tool wear and produce poorer surface finishes. Additionally, insufficient material removal at lower fz results in longer tool engagement with the workpiece, further contributing to surface irregularities (Song and Ihara, 2023). The findings align with previous studies that indicate a direct relationship between cutting parameters and surface integrity, emphasising the need for careful optimisation in machining operations involving Inconel 718 (Kiswanto et al., 2020; Ji et al., 2021; Zhang et al., 2025). Consequently, the application of RSM in this context not only aids in understanding the complex interactions between machining parameters but also serves as a valuable tool for predicting and enhancing surface quality in challenging materials (Faiz et al., 2019; Kumar et al., 2021).




(a)




(b)

Fig. 7. (a) The interaction effect *Vc* and *Ra* and (b) optimization results based on the desirability function approach.

In the context of factor coding in contour observation, a desirability value of 1 indicates that the predicted response variable is at its optimal level, which is the target for the optimisation process, as shown in Fig 7(b). In this study, the desirability of 1 signifies that the combination of cutting parameters of *Vc* and *fz* has been effectively optimised to achieve the minimum *Ra*, which is a critical quality metric in machining operations (Kumar et al., 2021 & Mukri et al., 2023). The predicted *Ra* value through the polynomial model is 0.440763 µm, which quantifies the relationship between the input factors and the output response. However, the references used to support this claim do not directly address the specific prediction

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(Shivakumar et al., 2020). In this study, achieving a low *Ra* value is particularly significant when machining Inconel 718 at dry cutting conditions, where surface integrity directly impacts the performance of components in high-stress environments (Maddamasetty et al., 2021). Thus, both the desirability score and the predicted *Ra* serve as critical indicators of the success of the optimisation efforts in RSM.

*Confirmation*

In the present investigation, the optimisation objective is defined as "in range," while the solution criterion is established as "minimise." The anticipated output of the desirability function exhibits characteristics consistent with a "smaller is better" paradigm. As illustrated in Fig 8, the optimal process parameters are identified as *Vc* = 100 m/min and *fz* = 0.0696 mm/rev, which correspond to a minimum surface roughness (*Ra*) value of 0.4416 µm, achieved under a desirability index of 1.000. These optimal parameters are subsequently applied in a real-time machining environment to conduct a validation test.

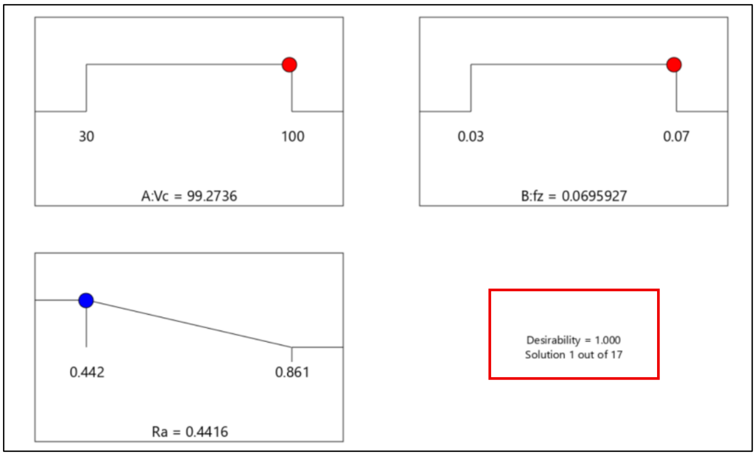


Fig. 8. Optimal process parameters using RSM.

Table 5 shows the result of the validation of the *Ra* model. The process is done by re-experimenting with the machining and analysis processes using the optimal process parameter value in Fig 5 and comparing the actual and predicted values for an average three-time *Ra* reading. The table shows that the *Ra* measured varies in the optimum range of over 98% confidence in the verification test. The percentage of overall experimental error lies in the minimum *Ra* that was tested at 100 m/min *Vc* and 0.0696 mm/rev *fz*, which obtained -0.7640%.

Table 5. Confirmation results

| Machining parameter | | Actual value, | Experimental value | | | Mean | Error |
|---|---|---|---|---|---|---|---|
| *Vc* | *fz* | *Ra* | 1 | 2 | 3 | | |
| 100 | 0.0696 | 0.442 | 0.454 | 0.4387 | 0.442 | 0.4450 | -0.7640 |

## CONCLUSION

In conclusion, this study successfully identified optimal cutting parameters for turning CNC machining on Inconel 718 under dry cutting conditions through the *Ra* evaluation. By systematically varying *Vc* and *fz* while employing the statistical RSM method, the research demonstrated that a 100 m/min *Vc* and a 0.0696 mm/rev *fz* significantly reduced *Ra* to 0.4416 µm, which is 51% better than the highest *Ra* value. However,

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the study has its research limitations, namely, the absence of a cutting fluid causes *Ra* to increase and affects the overall machinability of Inconel 718. In addition, the machining range is limited to specific parameters, as this study is a preliminary study that requires further exploration of a broader spectrum of parameters. This research can serve as a foundation for further studies exploring the effects of additional variables, such as tool geometry, coating, and environmental conditions, on the machinability of Inconel 718. For practitioners in the aerospace and automotive industries, the insights gained from this study can inform better machining practices, leading to improved product quality and reduced manufacturing costs. Identifying optimal cutting parameters in dry-cutting conditions can contribute to more sustainable manufacturing processes by eliminating cutting fluid consumption. In summary, while this study has significantly contributed to understanding machining Inconel 718, ongoing research is essential to address its limitations and explore the broader implications for academia and industry.

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## CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

## AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: **data collection**: Muhammad Dzulzikri Suhaimey; **study conception and design**: Norfauzi Tamin, Kahirol Mohd Salleh; **analysis and interpretation of results**: Norfauzi Tamin, Ahmad Arif Hakimi, Iqmal Farhan Rashidi; **Resources:** Umar Al Amani Azlan, Norfariza Ab Wahab. **validation**: Wan Abdul Hafiz Wan Abdul Malik. All authors reviewed the results and approved the final version of the manuscript.

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