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Evaluating alloy-718 machinability values modelling by using response surface methodology

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With the development of the manufacturing industry, machining parameters and material processing efficiency are important due to cost, sustainability, and other parameters, which are determining factors for usage width, material choice, and production rate. Machinability and optimization are among the scientists' and industry workers' timely objectives, guiding the manufacturing industries. Thus, the study and analysis of parameters such as surface roughness, tool wear, and force application in superalloy machining would be beneficial in various fields of the manufacturing industry. In this work, RSM (surface response method) modelling and analysis of relationship Fx, Fy, Fz forces between surface roughness of Inconel-718 material, which is a very unique alloy in terms of corrosion resistance, high-temperature elevation, and fatigue values, is examined. From this work, it was found that an experimental design was prepared using the Taguchi method, and the required number of measurements and parameter values were determined with a small number of experiments. Then, the most ideal values were determined using the Response Surface Methodology and ANOVA method to determine the best parameter levels after the surface roughness and cutting forces measurements.

Keywords: Alloy-718, Machinability, Taguchi method, Surface roughness, Cutting performance

Superalloys are commonly used in sectors where high-strength parts are required, such as the aerospace industry. One such material, Inconel 718 (2.4668), one of the nickel-iron-based superalloys, is involved in many important applications. Although the elements added to the Inconel 718 alloy have properties such as high heat, corrosion, crack, and fatigue resistance, these elements cause Inconel to be more difficult to machine and increase its cost. The problems we encountered in machining Inconel 718 can be attributed to the rapid wear of the tool when machining the hard surface, the short tool life, and the low thermal conductivity and high heat generation in the cutting zone[1-4]. Therefore, it is important to optimize and report parameters such as various cutting tools, lubrication techniques, machining methods, etc., to facilitate the machinability of Inconel 718 (chemical expansion of NiCr19Fe19Nb5Mo3) and reduce the cost[5-8]. As Mahesh and Cleverson have mentioned in their work, it can be said that rotational speed and optimum lubrication are one of the most important factors for reducing tool wear and surface roughness (R_a) in the machining of Alloy 718 (Ref. 9-10).

In recent years, many experimental studies have been carried out to investigate the effects of cutting parameters on cutting forces and surface roughness when machining Inconel 718. It can be said that the main problem in machining IN718 is the high temperature, wear of the cutting tool, and susceptibility to chemical reactions between the cutting tool and the material[11-14]. It has been shown that the different cooling methods used to reduce the heat generated in the cutting zone between tool-chip-workpiece-chip affect the cutting tool wear and surface quality by up to 55%[15]. Hansong et al. showed that the MQL technique improved the surface roughness (R_a) of Inconel 718 by an average of 32%. In another study by Mufrisah *et al.*, it was found that the surface roughness of Inconel 718 could be reduced by 88% and cutting forces by 22% with the MQL technique[16,17]. In addition to the cooling methods used in the machining of Inconel 718, the cutting speed and depth of cut are also important parameters that affect the quality of the product. Arunachalam and Peng *et al.* reported that lower cutting speeds and cut depths are beneficial for improving residual stress and surface quality when machining Inconel 718[18,19].

Imran *et al*. focused on the surface integrity and wear mechanisms associated with the mechanics of the microstructures of nickel-based superalloy Inconel 718 under dry and coolant/lubricant assisted cutting conditions. Their study provides a good basis for selecting cutting conditions for acceptable surface integrity[20]. Kumar *et al*. studied the effects of turning Inconel 718 with carbide tools under different cutting conditions on surface quality. They emphasized the superior performance of machining under minimum quantity lubrication (MMY) conditions[21]. Ibrahim *et al*. conducted experimental studies to investigate cutting parameters and machining effects on surface integrity under three different cutting conditions. As a result of the experiments, they concluded that a severe deformation occurs in the microstructure causing changes in the microstructure of a few micrometers below the surface, and that minimum quantity lubrication can improve the surface integrity properties[22].

Optimizing the cutting parameters and finding the best values is important because it improves the product quality, cutting tool life, and cutting time. Moreover, the agreement between the results of theoretical calculations and experimental results also benefits the machining industry. Lalwani *et al.* showed that their theoretical calculations agreed more than 90% with the ANOVA and RSM techniques they used in their studies. Ogunbiyi *et al*. made theoretical estimates with a low error rate of 0.12(Ref.23).

Many different methods such as CCD, RSM, ANN, and GA have optimized the cutting parameters. Wu and Lin have shown that by optimizing the cutting parameters while machining the material, the energy consumption, surface roughness, and machining time can be reduced between 4% and 40%(Ref. 24).

This study analyzed the effects of these factors on surface roughness using RSM, CCD, and ANOVA methods. Inconel 718 was machined with different cutting speeds (100-220 rpm) and two different cooling methods (dry cut and MQL).

Experimental Section

In the experimental study, the superalloy Inconel 718 with a diameter of 50 mm and a length of 200 mm was chosen as the material. The chemical properties of the material used in our study are given in Table 1. As seen from the composition of Inconel 718, nickel, iron, and chromium are the primary components, so it is a hard, heat-resistant alloy with a low conductivity coefficient. In evaluating the effects of machining parameters (feed rate, cutting speed, tool type, and lubrication type), the influence on quality indicators (i.e., roughness and tool wear) was considered by the data collected during the tests, which followed an RSM array (32 × X) experimental design[25].

CNMG 12 04 08 MM SUMITOMO cutting tips, Johnford TC 35 CNC Fanuc OT an x-z axis CNC, and MahrPerhometer/M1 type surface roughness meter were used in the experiments. In addition, Kistler 9121 dynamometer system together with a Kistler 5019 charge amplifier and DynoWare software were utilized for the force determination.

Table 1 — Machining input process parameters

Workpiece material	Inconel 718 (Chemical composition %)					
	Cr	17 - 21	Mn	0.35 max.	S	0.015 max
	C	0.08 max.	Si	0.35 max.	Al	0.2-0.8
	Fe	19.03	Mo	2.8-3.3	Cu	0.30 max
	Co	1 max	P	0.015 max	Nb+Ta	4.75-5.5
	Ni	50-55			Ti	0.65-1.15
Cutting tool	CNMG 12 04 08 MM SUMITOMO					
Cutting speed (vc)	100-220m/min					
Feed (fr)	0,1					
Workpiece dimensions	50mm dia*200mm					
Drilling environment	Dry,MQL,CO2					
Response considered	R_a (Surface rougness), F_x-F_y-F_z (Forces)					

Table 2 — Process parameters with the experimental design and their results

Experiment No	Cutting parameters (m/min)	Cooling
1	100	Dry Cutting
2	140	Dry Cutting
3	180	Dry Cutting
4	100	MQL 20 mL
5	140	MQL 20 mL
6	180	MQL 20 mL
7	100	MQL 40 mL
8	140	MQL 40 mL
9	180	MQL 40 mL

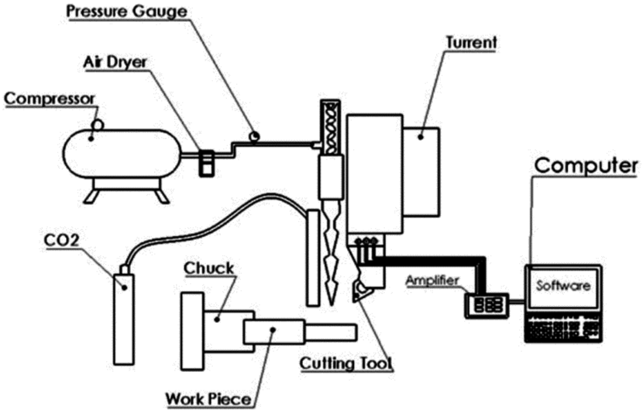

Fig. 1 — Experimental setup

Table 2 shows the cutting parameters for the CNC milled Inconel 718 material. Nine experiments were performed using the cutting speed and cooling methods we applied. These experiments obtained the measured force values (F_x, $F_y$veF_z) and Z axes and the surface roughness values (R_a).

The tools and experimental setup used in our experimental study are schematically shown in Figure 1.

Response Surface Methodology

Response Surface Methodology can be defined as statistical and mathematical techniques used to develop, improve and optimize processes. This technique is commonly used in industry when considering multiple input variables that potentially affect the performance measurement or quality attribute of a product or process. While this performance measure or quality characteristic is referred to as the response variable, the independent variables that engineers or researchers can control and are considered to affect the response variable are referred to as input variables[26].

Table 3 — Levels and coded symbols of input parameters

Factors	Unit	Coded Symbols	Levels		
			-1	0	+1
Cutting Speed	rpm	X_1	100	140	180
MQL	mL	X_2	0	20	40

RSM analyzes the approximate relationship between a dependent variable (R_a) and independent variables (v, f, d) by combining mathematical and statistical methods[27]. RSM establishes a relationship between input and output variables and shows it visually or in writing by linking it with mathematical formulas. The relationship can be first-order, second-order, or cubic, and appropriate statistical evaluation is required to evaluate the most appropriate model[28]. It is unlikely that a linear first-order model exists in a complex system such as processing, where nonlinearities dominate the relationship between parameters. Therefore, a quadratic model is formulated by regression analysis (Equation 1)[29]. When,

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_{ii}^2 + \sum_{i<j}^{k} b_{ij} X_i X_j \quad \ldots(1)$$

$b_0$is a constant term, b_i linear coefficients, b_{ii} quadratic coefficients, b_{ij} interaction coefficients, X_i and X_j are input parameters (v, f, d) and Y is the predicted response (R_a)[Ref. 30].

Results and Discussion

In the present research, response surface methodology (RSM) was used for statistical analysis of cutting speed and amount of MQL by using Design Expert 11 software. Central Composite Design (CCD), was used to determine the optimum input parameters. Experimental optimization was performed with ANOVA (analysis of variance). The levels of input parameters are shown in Table 3.

As shown in Table 3, Cutting speed and MQL was selected as an input parameter and varied from 100 to 180 rpm and 0 to 40 ml, respectively. Fx, Fy, Fz, and Ra were selected as responses. The response parameters were correlated to the input parameters using cubic model. The general cubic model equation is shown in Eq.2.

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \beta_{iii} x_i^3 + \sum_{i=1}^{k} \sum_{j=1, i<j}^{k} \beta_{ij} x_i x_j \quad \ldots(2)$$

Where $\hat{y}$ is the response; β_0 is a constant; β_i , β_{ii} , β_{iii} , and β_{iiii} are the regression coefficients; β_{ij} is the quartic coefficient; and x_i is input variable.**F_x**

The importance of each input parameter was analyzed by using F-value and the p-value obtained

Table 4 — ANOVA table for Fx

Source	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	2.656E+05	37947.81	143.90	< 0.0001	significant
A-Cutting Speed	92622.08	92622.08	351.23	< 0.0001	significant
B-MQL	41673.85	41673.85	158.03	< 0.0001	significant
Cor Total	2.670E+05				

Table 5 — ANOVA table for Fy

Source	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	56817.45	8116.78	22.92	0.0016	significant
A-Cutting Speed	33982.25	33982.25	95.94	0.0002	significant
B-MQL	2613.65	2613.65	7.38	0.0420	significant
Cor Total	58588.46				

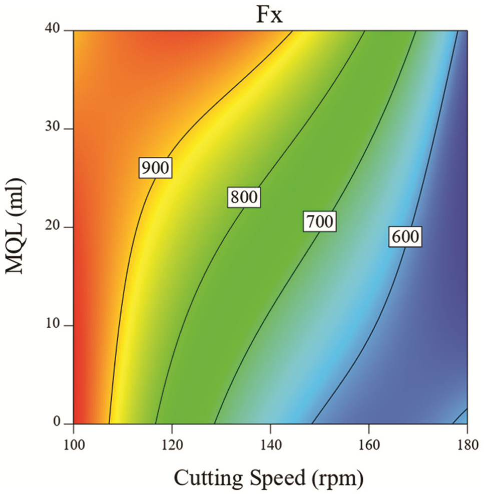

Fig. 2 — Effects of MQL and Cutting speed on Fx

with RSM. In general, the lowest p-value and the highest F-value indicate the highest importance of the created model. Statistical analysis for Fx is shown in Table 4. According to the p- value, it is found that created model and input parameters have a significant effect on Fx (less than 0.05). According to the F-value, Cutting speed has the highest F-value (351,23). These results show that the Cutting speed is the most significant parameter than the amount of MQL.

Fx was correlated with input parameters by using the cubic model given in Eq 2.

$$F_x = 757{,}169 - 215{,}2X_1 + 144{,}35X_2 - 173{,}725X_1^2X_2 + 37{,}525X_1X_2^2 \quad \text{...(3)}$$

According to the regression equation, the coefficient's sign of the parameters indicates an effect on Fx whether positive or negative. Therefore, the Cutting speed has a positive effect, while MQL has a negative effect on Fx. This means that increasing the Cutting speed decrease the Fx, whereas increasing the MQL increase the Fx. Correlation coefficient R^2 was found to be 99.5%. This shows that model is a 99.5% variation in experimental data.

Figure 2 indicate the variation of Fx according to the input parameters. Cutting speed is the most important parameter in turning operations. It is reported in the literature as the most effective parameter that directly affects surface quality, cutting forces, heat generation, and cutting tool life[19,20]. Increasing the cutting speed while maintaining the feed rate, may lead to a decrease in the cutting force. In addition, the low MQL ratio may have contributed to the decrease in cutting force as the MQL could not fully develop its cooling and lubricating properties at high cutting speeds.

Fy

ANOVA table for Fy is given Table 5. It is seen the fitted model was significant at the %1 level. As seen in ANOVA table, all input parameters have significant effect on Fy. However, it is seen that the Cutting speed(95,94) has a more significant effect on Fy than the amount of MQL(7,38) according to the F-value. A correlation coefficient R^2 was also obtained for the evaluation of the model. R^2 was found to be 96.9% and this means that the created model was excellent fitted with the experimental data.

The regression equation for Fy is given Eq 3. In this regression equation, it is seen that the Cutting speed has a negative effect, while the amount of MQL has a positive effect on Fy. Fy is the most important force expressing the main cutting force. It can be seen from Equation 4 that this is the most important parameter affecting the Fy force. This result is consistent with the literature[8-10].

$$F_y = 422{,}49 - 130{,}35X_1 + 36{,}15X_2 + 37{,}7862X_1^2 - 34{,}9138X_2^2 - 87{,}775X_1^2X_2 + 98{,}375X_1X_2^2$$

Figure 3.represent the variation of Fy according to the input parameters. As can be seen from the figure, the most important parameter affecting the Fy force is the cutting speed.

Fz

Statistical analysis for Fz is shown in Table 6. According to the ANOVA table, it is seen that all input parameters have significant effect on Fz. However, Cutting speed(2677,24) has a more significant effect on Fz than the amount of

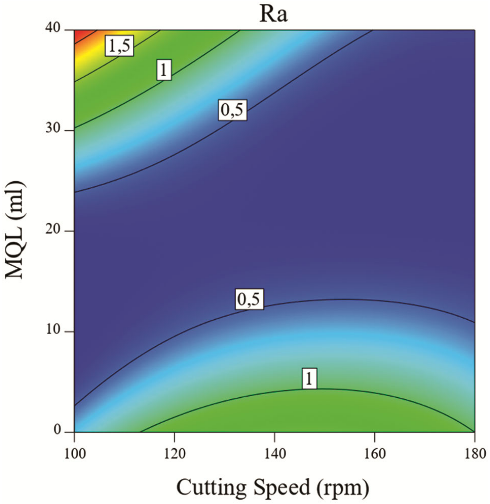

Fig. 3 — Effects of MQL and Cutting speed on Fy

Table 6 — ANOVA table for Fz

Source	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	2.100E+05	30006.28	1364.86	< 0.0001	significant
A-Cutting Speed	58858.81	58858.81	2677.24	< 0.0001	significant
B-MQL	9646.61	9646.61	438.78	< 0.0001	significant
Cor Total	2.102E+05				

MQL(438,78) according to the F-value. The correlation coefficient R^2 showed an excellent correlation between input parameters. The correlation coefficient was found to be 99.9%.

The regression equation of the Fz is given Eq. 5. As seen, the cutting speed has a negative effect, whereas the amount of MQL has a positive effect on Fz. This means, increasing the cutting speed and decreasing the amount of MQL, decrease the Fz. Increasing the cutting speed while maintaining the feed rate may lead to a decrease in the cutting force. In addition, the low MQL ratio may have contributed to the decrease in cutting force because the MQL could not fully develop its cooling and lubricating properties at high cutting speeds.

$$F_z = 390,459 - 171,55X_1 + 69,45X_2 + 48,7448X_1^2 + 121,045X_2^2 - 109,975X_1^2X_2 + 43,775X_1X_2^2 \qquad \text{...(4)}$$

Fig 4. shows the variation of Fz according to the cutting speed and the amount of MQL. It is well known that cutting forces decrease at high cutting speeds. This situation is confirmed in the graph below. It is also worth noting that the MQL rate is 20-30 ml/hr. A low use of the MQL rate is a good result for sustainable machining.

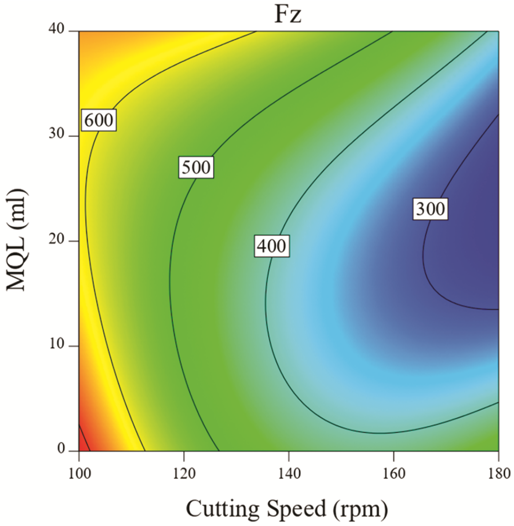

Fig. 4 — Effects of MQL and Cutting speed on Fz

Table 7 — ANOVA table for Ra

Source	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	3.96	0.5655	2915.61	< 0.0001	significant
A-Cutting Speed	0.0006	0.0006	3.16	0.1357	Not significant
B-MQL	0.1255	0.1255	647.02	< 0.0001	significant
Cor Total	3.96				

Ra

Table 7 shows the ANOVA results for Ra for different cutting speed and the amount of MQL. It is seen that the created model was significant at 1% level. It is seen that the amount of MQL has a significant effect on Ra, while Cutting speed has not a significant effect. Progress is cited in the literature as the most important machining parameter affecting surface roughness. In addition, the cooling lubrication system is also effective. The present results show that MQL i.e., the cooling lubrication system is effective. This is also consistent with the literature. The correlation coefficient was found to be 99.9%, and this means that the input parameters have an excellent correlation with each other.

Using RSM based on regression analysis, a cubic model was obtained for the Ra and given in Eq 5.

$$Ra = 0,304172 - 0,2505X_1 - 0,533X_1X_2 + 0,777397X_2^2 + 0,4815X_1^2X_2 - 0,354X_1X_2^2 \qquad \text{...(5)}$$

According to the regression equation, both input parameters have a negative effect on Ra. The effect of feed rate on surface quality is well known. Therefore, cutting speed is not a directly effective parameter, but it does have an effect. The MQL cooling lubrication system also loses its effectiveness at high speeds.

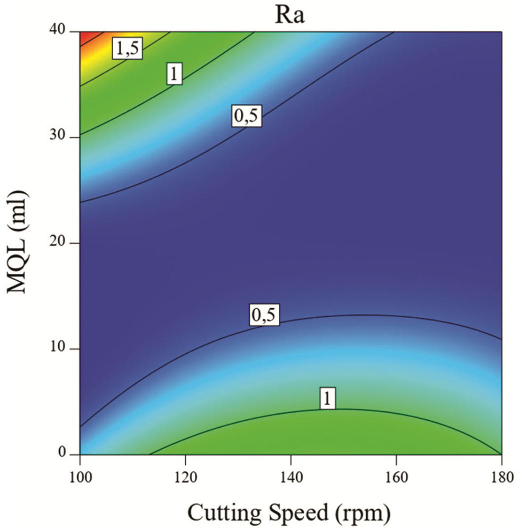

Fig. 5 — Effects of MQL and Cutting speed on Ra

Table 8 — Optimization criteria

Parameter	Approach	Limits Lower	Limits Upper	Importance
X_1-Cutting Speed	In range	100	180	3
X_2 -MQL	In range	0	40	3
Fx	Minimize	520.3	996.5	3
Fy	Minimize	339.5	608.1	3
Fz	Minimize	263.3	725.1	3
Ra	Minimize	0.288	2.199	3

Therefore, it can be considered normal that the cutting speed and the MQL ratio have little effect on the surface quality.

Figure 5.indicates the variation of Ra according to the cutting speed and the amount of MQL.As can be seen from the figure, the MQL ratio of 10-30 ml positively affects the surface quality, while the small amount of oil contributes to sustained machining.

Optimization and validation

The multi-criteria decision analysis was applied to determine the optimal input variables. The Design Expert 11 software was used to generate the CCD design matrix. In the optimization process Fx, Fy, Fz and Ra were considered to be optimized based on the defined criteria seen in Table 8. The importance of the all parameters was defined as equal.

The optimum cutting speed and the amount of MQL were found to be 180 rpm and 22,87 mL, respectively. At this condition, the optimal value of Fx, Fy, Fz and Ra were found as 534,027, 324.75, 264.42 and 0.24, respectively.

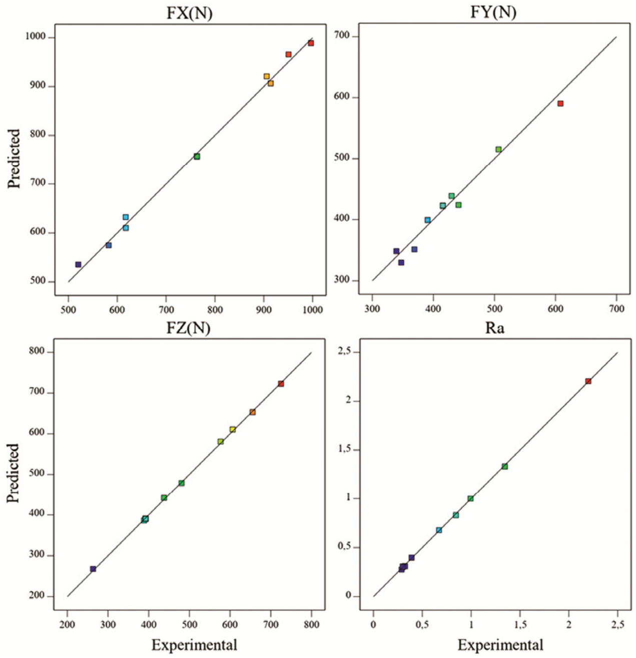

Fig. 6 — Predicted and experimental parameters for Fx, Fy, Fz and Ra

An experimental validation was carried out to validate Fx, Fy, Fz and Ra after the optimization process. At this condition, Fx, Fy, Fz and Ra was found as 520, 3, 347,4, 263,3, 0,28, respectively. The predicted and experimental values of responses are shown in Fig. 6.

Conclusion

In this study, the superalloy material Inconel 718, widely used in defence and aerospace industries, is machined on a CNC lathe. The cutting speed and the machining parameters of the cooling system and the cutting forces and the values of surface roughness throughout machining were measured, and statistical methods and their effect values determined the main parameters affecting these values.

First, an experimental design was prepared using the Taguchi method, and the required number of measurements and parameter values were determined with a small number of experiments. Then, the most ideal values were determined using the Response Surface Methodology and ANOVA method to determine the best parameter levels after the surface roughness and cutting forces measurements.

- Cutting speed is the most significant parameter on Fx than the amount of MQL,
- Cutting speed has a more significant effect on Fy than the amount of MQL,
- Cutting speed has a more significant effect on Fz than the amount of MQL,

- MQL has a more significant effect on Ra than the amount of cutting speed.

Declarations Conflict of interest

The authors declare that they have no confict of interest.

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