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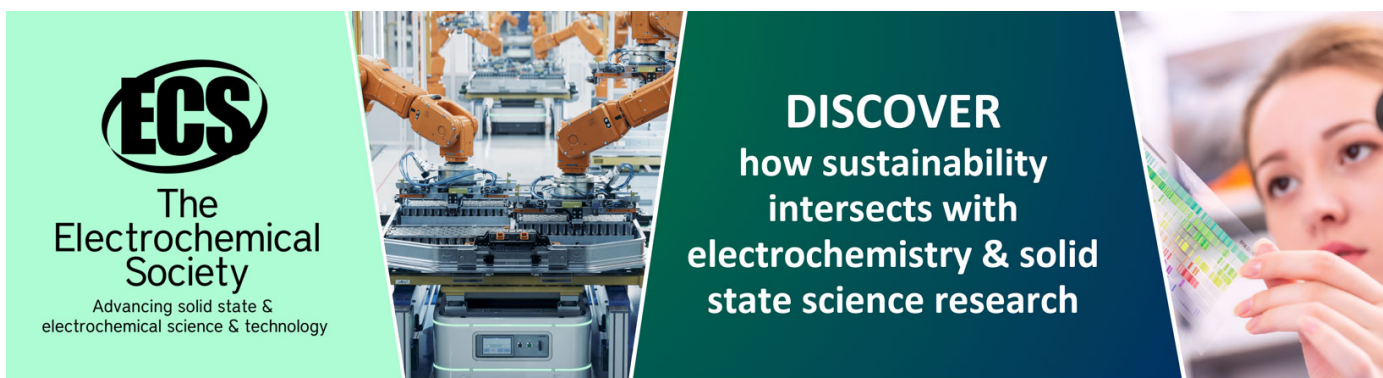
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Analysis of face milling performance on Inconel 718 using FEM and historical data of RSM

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Abstract. This study involves conducting finite element (FE) analysis on face milling of Inconel 718 and investigating the effect of cutting parameters to resultant force and tool temperature. The cutting parameters considered include cutting speed in the range of 20 to 40 m/min, feed rate in the range of 0.10 to 0.20 mm/tooth and depth of cut in the range of 0.1 to 0.2 mm. The experimental approach is carried out using Analysis of Variance (ANOVA) and Response Surface Methodology (RSM). According to the results, the significant factors that affect the resultant force are feed rate and depth of cut. On the other hand, cutting speed has no significant impact on the resultant force. The interaction between feed rate and depth of cut has the most influence on the resultant force. Meanwhile, all cutting parameters considered significantly affect the tool temperature. Through the RSM method, the obtained optimal setting of the parameters is 23.13 m/min, 0.10 mm/tooth and 0.10 mm for cutting speed, feed rate and depth of cut, respectively. The simulated results are then validated by an experiment. It is found that the percentage of relative error between the FE simulation and the actual experiment for resultant force and tool temperature is 10% and 31%, respectively. Considering all possible errors, the overall trend of the simulated results is reasonably in a good agreement with the experimental results.

1. Introduction

Inconel 718 is a nickel-based alloy that exhibits good mechanical and chemical properties, and possesses special features such as corrosion resistance, high temperature resistance, creep resistance and also high strength to weight ratio [1, 2]. It can be applied in a temperature range of -217°C to 700°C [3]. Due to its remarkable characteristics, this material has been selected as one of the main components in the aerospace industry. More than 50% of the structural material in various modern aircraft jet engines and space shuttle main engines (SSMEs) are made of Inconel 718, especially in combustion section that undergoes extreme temperatures and pressures [4, 5]. Nevertheless, the drawback of this material is that it is hard to machine. The machinability rating of Inconel and titanium is 0.09-0.3 as compared to 0.4, 1.2 and 1.9 of stainless steel 304, 6061 and 7075 aluminium alloy, respectively [6]. Abrasiveness, gummy property, poor thermal conductivity and work hardening are the main issues reported in the body of literatures. Premature failure



of the cutting tool occurs due to hardening surface layer, attributable to stress at tool-workpiece interface, thermal softening, adhesion, diffusion, notching and thermal cracking [7,8]. Other problems reported are the undesirable alteration of machined surfaces to increase the hardened layer as a grain structure and the workpiece easily deforms in response to the machining induced strain loading on the sub-surface [9]. In addition, the cutting tool is prone to chipping, abrasion, adhesion and attrition on cutting edge, flank face and rake surface [10]. Inconel 718 is widely used as a critical component of turbine engine components and the material is required to meet the following criteria: surface finish less than $0.8\mu\text{m}$, material strain less than 0.01mm , no formation of white layer, amorphous or recast layer, no redeposit material and no non-parent material [11].

Face milling is among the machining strategies to form a flat surface from the component. It has been indicated that the type of coating is more significant as compared to cutting speed [8]. The CBN tool has shown severe wear pattern and higher wear value compared to ceramic and carbide tools. The application of coated cutting tool of TiAlN-TiN has been shown to over perform the TiAlN and double the tool life time [12]. Several studies associated with the cutting force have reported that it increases as the feed rate and depth of cut increases. Bhatt et al. (2006) measured the cutting force in an investigation of Inconel 718 under dry cutting conditions [13]. The researchers observed that the cutting force increases as the feed rate and the axial depth of cut increase, which contributes to the increase of the resultant force. This is due to the increase in volume of cut per tooth. Higher forces are required during the shearing process of the work material [14]. A similar result is found by another study that highlights the increase of chip load per tooth as the feed rate increases is the reason for the increase of the resultant force in the machining process [15]. The temperature also increases due to friction and adiabatic processes. However, the depth of cut is found to be more significant on heat being generated rather than feed rate and cutting speed [16].

There are numerous works claiming the success of employing finite element method (FEM) to model the machining process. FEM can eliminate shop floor trials that are often very costly and labour intensive [17]. However, the big issue involved in modelling machining process with FEM is long computational analysis time. Depending on the complexity of the problem, the computational analysis time can be days or even weeks. This is due to the nature of FEM calculation that analyses all over the workpiece at every feed step and angular increment of the cutter. This long computational analysis time limits its application for industry practice that needs to manufacture parts in a few days. Therefore, there exists an opportunity to improve the modelling efficiency. This paper proposes a new modelling methodology by taking the advantages of FEM and combining them with statistical analysis that can increase the analysis time for it to become practical and feasible for industry use. In this study, the finite element package AdvantEdge is combined with statistical Response Surface Methodology (RSM) historical data to simulate face milling of Inconel 718. The simulation aims to investigate the magnitude of the cutting forces and the effect of the tool temperature for different machining parameters.

2. Methodology

In this study, the face milling of Inconel 718 is modelled as orthogonal cutting using FEM AdvantEdge software. The boundary conditions are defined by assigning the cutting process, cutting parameter and the process kinematics. During this study, face milling process is modelled and analysed to evaluate on the magnitude of cutting force and cutting temperature. The Lagrangian method is adopted in the machining simulation, in which each individual node of the mesh follows the corresponding material particle during the motion. The cutting tool and workpiece are modelled with six-nodes triangular elements. Considering performance and accuracy of simulation, the minimum element edge length for chip bulk and cutting edge are set to $36\mu\text{m}$ and $28\mu\text{m}$, respectively. Due to large deformation on the machining simulation, adaptive re-meshing method is employed to avoid any extreme element distortions. The re-meshing takes place whenever elements from the cutting edge area are changed from their initial shape. The radius of refined region is set 0.137mm . The mesh refinement factor, mesh coarsening factor and chip refinement factor of adaptive re-meshing are all set to 1, 5 and 1, respectively. The result is set with 30 output frames.

Inconel 718 is used as the workpiece material. The length, width and height of the workpiece used are 10mm , 15mm and 2mm , respectively. The diameter of the face cutter tool is set at 50mm . Round inserts of

10mm in diameter are used. The cutting parameters such as cutting speed, feed rate and depth of cut are set for the machining process. Table 1 shows the cutting conditions applied in this study while Figure 1 depicts the geometry of the indexable inserts.

Table 1: Cutting conditions

Cutting Condition	Details
Cutting type	Face milling
Workpiece material	Inconel 718
Type of insert	PVD coated with TiAlN
Coolant condition	Dry with chilled air

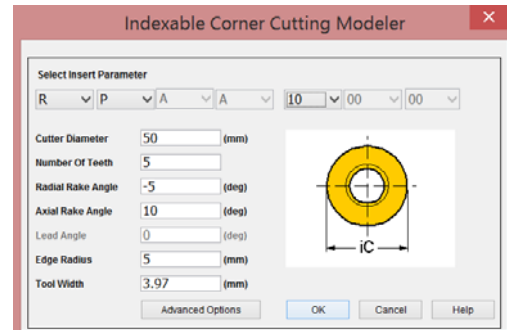


Figure 1: Geometry of the indexable inserts

A total of 18 runs are simulated with a combination of various parameter ranges for the cutting speed (V_c), feed rate (f_z) and depth of cut (DOC) as shown in Table 2. An angle of rotation of 360° is applied, which represents one turn of the face cutter. The initial default temperature is set at 24°C . The simulation results are collected to determine the best combination of parameters that produce the lowest resultant force and temperature of the cutting tool. Next, the simulated results obtained are validated with the actual experimental results.

Table 2: Design of experiment matrix for simulation

Level	Cutting speed (m/min)	Feed rate (mm/tooth)	Depth of Cut (mm)
1	20	0.10	0.10
2	300	0.15	0.2
3	40	0.20	

In the FE simulations, the force values are obtained by comparing the before and after tool-workpiece engagement. The force values of feed force (F_x), cutting force (F_y) and thrust force (F_z) can be calculated by using Equation 1 to Equation 3, respectively. The total of these forces is combined into the resultant force (F_r), which is obtained by Equation 4 [18]. Equation 5 is used to measure the tool temperature, T .

$$F_x = F_{x\max} - F_{x\min} \quad (1)$$

$$F_y = F_{y\max} - F_{y\min} \quad (2)$$

$$F_z = F_{z\max} - F_{z\min} \quad (3)$$

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (4)$$

$$T = T_{\max} - T_{\min} \quad (5)$$

The data is analysed by analysis of variance (ANOVA) to evaluate the significance of the model and the parameters. The significant terms can be identified when their p -value is less than 0.05. A historical data of RSM is used to find the optimum response, which yields the lowest resultant force and cutting temperature. Validation experiments are conducted to investigate the simulation results with the actual machining process. The experiment is set up using CNC milling machine shown in Figure 2. The Kistler dynamometer is used to measure the feed force (F_x), cutting force (F_y) and thrust force (F_z). A thermal imager Fluke Ti400 is employed to measure the temperature of the cutting tool during machining. The emissivity is set at 0.19 for Inconel 718. Image of the temperature is analysed by InsideIR 4.0 software.

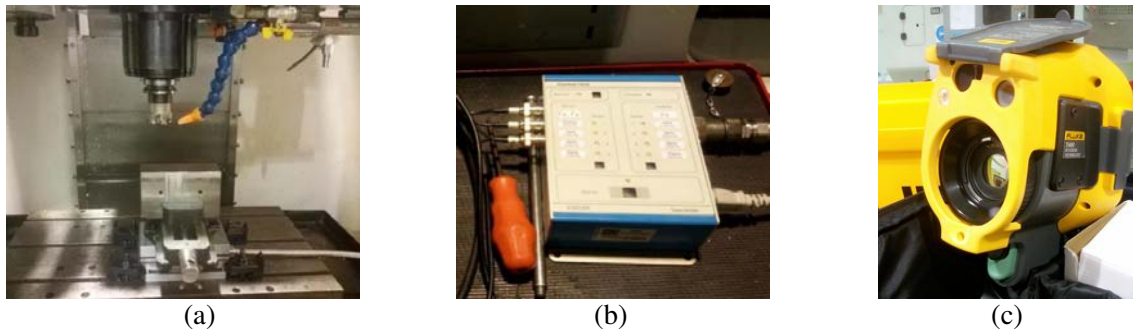


Figure 2: Experiment set-up during validation: (a) Inconel 718 on the CNC milling, (b) Kistler dynamometer set for force measurement, (c) Fluke thermal imager to capture cutting temperature

3. Result and Discussion

Based on the results of FE simulation, Figure 3 to Figure 5 show the profile forces exerted on the cutting tool in different axes. The graph profile manifests the force exerted onto the rake face of the cutting tool during the circumferential tool motion. Because the number of inserts is five, one rotation generates five waveforms. The waveform increases when the cutter removes maximum material and equally decreases when minimum.

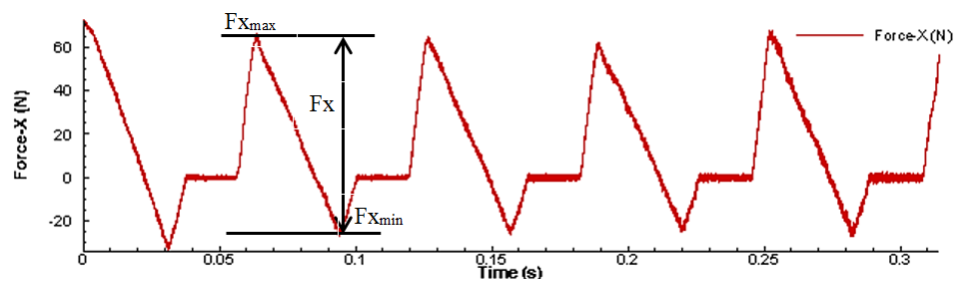


Figure 3: Graph of feed force (F_x)

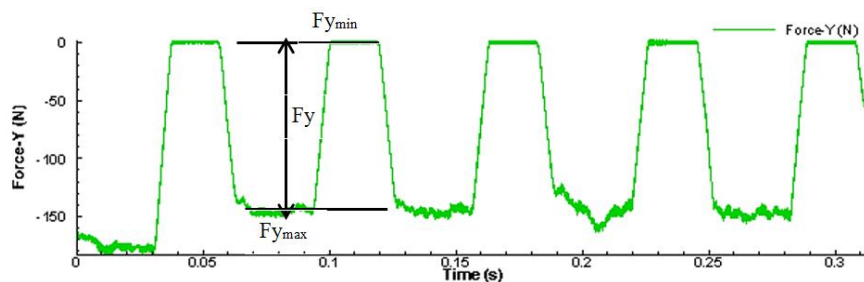


Figure 4: Graph of cutting force (F_y)

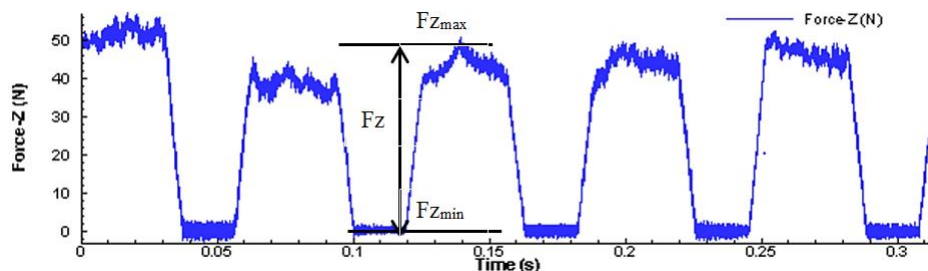


Figure 5: Graph of thrust force (F_z)

Figure 6 depicts the simulation results of the cutting temperature. It shows that the heat is localized at the tool tip due to friction between the chip and the cutting tool. The simulation also shows that most of the temperature is dissipated through the chip formation and the cutting temperature during the face mill is relatively low. Figure 7 depicts the time history of the tool temperature during one cycle of tool rotation. Table 3 tabulates the collected data after all simulations are done. Each run corresponds to a different combination of cutting parameters to evaluate their effect on the resultant force and tool temperature.

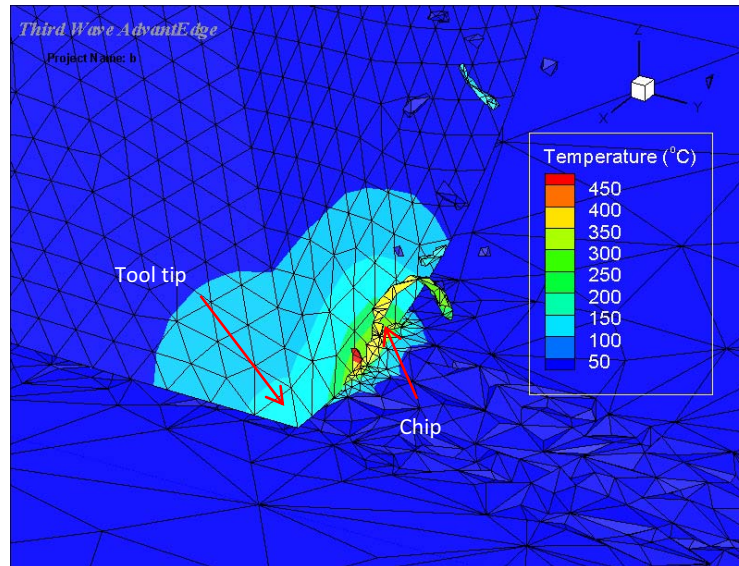


Figure 6: 3D temperature generated model by simulation

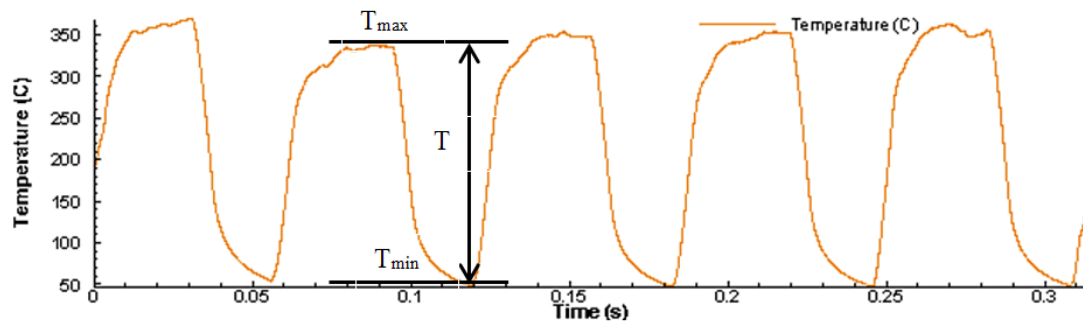


Figure 7: Graph of tool temperature

The resultant force for each of the simulation runs is calculated using Equation 4 and they are plotted in Figure 8. The graph indicates that the increasing feed rate will increase the resultant force and the depth of cut. This trend continues at various cutting speeds for each of the three runs. On the other hand, to evaluate the effect on the tool temperature, each simulation run has a different combination of cutting parameters. A graph for the tool temperature is plotted as shown in Figure 9. The graph indicates that the increasing feed rate will increase the tool temperature and the depth of cut. This trend continues at various cutting speeds for each of the three runs.

Table 3: Simulation results under different cutting conditions

No.	Cutting speed, V_c (m/min)	Feed rate, f_z (mm/tooth)	Depth of cut, a_p (mm)	Feed Force, F_x (N)	Cutting Force, F_y (N)	Thrust Force, F_z (N)	Resultant force, F_r (N)	Tool temperature ($^{\circ}\text{C}$)
1	20.00	0.10	0.10	41.00	116.43	34.59	128.19	200.35
2	20.00	0.15	0.10	65.94	179.50	62.52	201.19	257.34
3	20.00	0.20	0.10	92.91	240.19	125.31	286.40	309.48
4	30.00	0.10	0.10	39.28	111.78	36.12	123.86	253.22
5	30.00	0.15	0.10	68.33	168.09	59.18	190.85	323.35
6	30.00	0.20	0.10	82.19	228.58	109.48	266.44	377.89
7	40.00	0.10	0.10	38.85	111.10	30.49	121.58	285.98
8	40.00	0.15	0.10	73.91	168.63	61.68	194.17	379.72
9	40.00	0.20	0.10	96.58	253.59	116.74	295.40	440.86
10	20.00	0.10	0.20	65.94	150.11	47.67	170.74	278.90
11	20.00	0.15	0.20	92.56	262.08	80.48	289.36	345.27
12	20.00	0.20	0.20	124.58	322.93	130.45	369.89	396.85
13	30.00	0.10	0.20	65.63	150.76	45.13	170.51	337.39
14	30.00	0.15	0.20	90.24	250.96	84.52	279.76	411.40
15	30.00	0.20	0.20	166.00	365.73	178.29	439.43	541.86
16	40.00	0.10	0.20	67.35	162.41	48.88	182.49	402.59
17	40.00	0.15	0.20	91.94	247.09	83.17	276.45	467.49
18	40.00	0.20	0.20	129.11	358.08	133.91	403.51	551.50

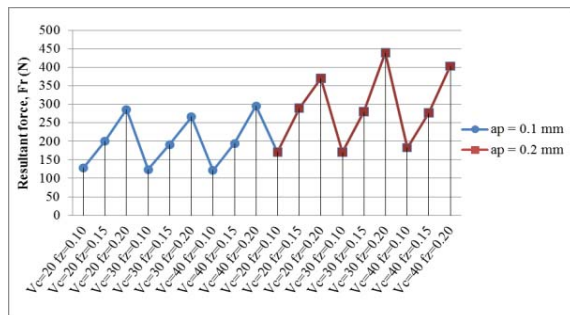


Figure 8: Graph of resultant force for 18 runs of simulation

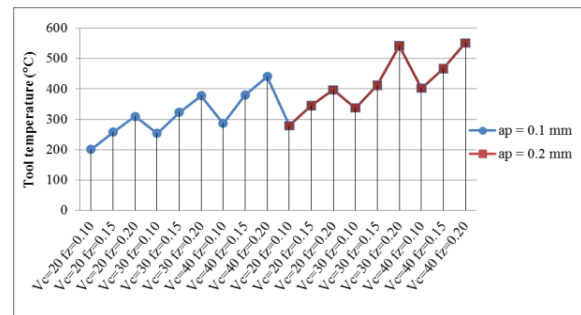


Figure 9: Graph of tool temperature for 18 runs of simulation

In order to indicate the influence of the cutting parameters on the resultant force and tool temperature, ANOVA method is used. Two-factor interaction (2FI) model is found to be significant for the resultant force. The p -value of <0.0001 and F -value of 91.38 imply that the model is significant as shown in Table 4. The value of $\text{Prob} > F$, which is less than 0.05, indicates that the model terms are significant. The ANOVA results show that the feed rate (B), depth of cut (C) and interaction between feed rate and depth of cut (BC) are significant model terms. In addition, the values greater than 0.10 indicate that the model terms are insignificant. The results show that the cutting speed (A), interaction between cutting speed and feed rate (AB), and depth of cut (AC) are insignificant model terms.

Table 4: ANOVA table for resultant force

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.503E+005	6	25054.20	91.38	<0.0001	significant
A	64.54	1	64.54	0.24	0.6371	
B	1.128E+005	1	1.128E+005	411.59	<0.0001	
C	33287.16	1	33287.16	121.41	<0.0001	
AB	175.59	1	175.59	0.64	0.4405	
AC	114.64	1	114.64	0.42	0.5311	
BC	3833.47	1	3833.47	13.98	0.0033	
Residual	3015.98	9	274.18			
Cor Total	1.533E+005	17				

Based on an analysis of the variance decomposition, the R^2 of the model is 0.98, demonstrating that the variability of the response data is around its mean. The prediction of the resultant force (F_r) is denoted by Equation 6.

$$F_r = 47.85 - 2.1V_c + 586F_z - 397.78ap + 9.37V_cF_z + 6.18V_cap + 7149.33F_zap \quad (6)$$

Figure 10 shows the effect of each cutting parameter on the resultant force. The interaction between the cutting speed and feed rate (AB) is insignificant as shown in Figure 10(a). As the feed rate increases with the increasing cutting speed, the resultant force only slightly increases. Figure 10(b) shows the same condition of the interaction between cutting speed and depth of cut (AC). The effect of the depth of cut on the resultant force is also almost constant when interacting with the cutting speed due to the insignificant effect of the cutting speed on the resultant force. The interaction between the feed rate and depth of cut is significant on the resultant force as shown in Figure 10(c).

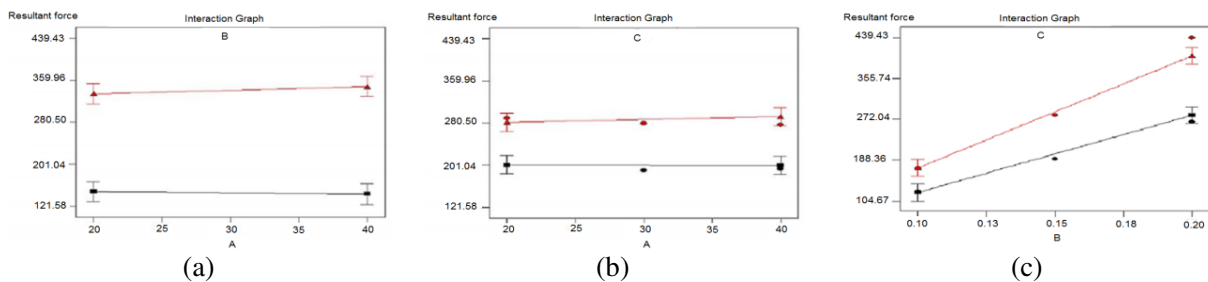


Figure 10: Interaction analysis response to resultant force between: (a) cutting speed and feed rate (AB), (b) cutting speed and depth of cut (AC), (c) feed rate and depth of cut (BC)

Meanwhile, linear model is suggested for the tool temperature in the software. It implies that the linear model is significant with p -value of <0.0001 and F -value of 133.72. The value of Prob > F, which is less than 0.05, indicates that the model terms are significant. The ANOVA results in Table 5 show that the cutting speed (A), feed rate (B) and depth of cut (C) are all significant model terms.

Table 5: ANOVA table for tool temperature

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.528E+005	3	50923.12	133.72	<0.0001	Significant
A	45627.17	1	45627.17	119.81	<0.0001	
B	61634.77	1	61634.77	161.84	<0.0001	
C	45507.42	1	45507.42	119.49	<0.0001	
Residual	5351.32	14	382.24			
Cor Total	1.581E+005	17				

Based on the ANOVA, the R^2 of the model is 0.96, showing that the model fits the data. The prediction of the tool temperature (T) is given by Equation 7.

$$T = -186.31 + 6.17V_c + 1433.35F_z + 1005.62ap \quad (7)$$

The graph of the tool temperature against the cutting speed is plotted in Figure 11. The temperature increases as the cutting speed increases since the heat generated per unit time increases with the cutting speed. This is in line with findings by other researchers [14]. The reduction in force is due to an increase in the cutting speed, which can be attributed to the tool mean face temperature. As cutting speed increases, the temperature increases, making the material softer. The shear plane temperature and the temperature rise are mainly due to friction. Meanwhile, the plot of the tool temperature against the feed rate is shown in Figure 12. It can be observed that the temperature increases as the feed rate increases, and the graph linearly increases. One of the reasons for this is the tool-chip contact length and heat distributed off by the chip increases at the mean time. Besides this, the chip deformation coefficient decreases and the material removal rate increases, which leads to a higher temperature. The feed rate is among the dominant factors to generate a high temperature. Last but not least, the graph of the tool temperature against the depth of cut is depicted in Figure 13. With the increase of the cutting depth, both the cutting force and the cutting heat generated also increase. This is because area of cut per tooth increases as the depth of cut increases. The greater the contact area and the friction between the workpiece and the cutting tool, the higher the temperature will be.

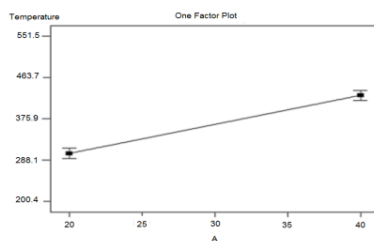


Figure 11: Graph of tool temperature versus cutting speed

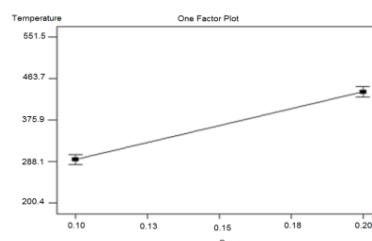


Figure 12: Graph of tool temperature versus feed rate

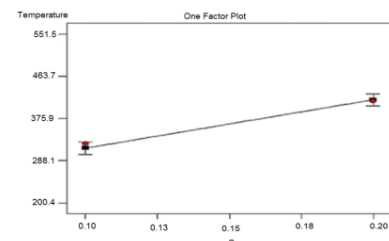


Figure 13: Graph of tool temperature versus depth of cut

The RSM method is used for optimization of the parameters to determine the lowest resultant force and tool temperature. The criteria for cutting speed (V_c), feed rate (f_z), depth of cut (ap), resultant force and tool temperature are set according to the goals to be achieved shown in Table 6. The lowest resultant force and tool temperature to be obtained during machining is the main goal of this study.

Table 6: Criteria for obtaining the optimum response

Constraints		Lower Limit	Upper Limit
Name	Goal		
Cutting speed, V_c	is in range	20.0	40.0
Feed rate, f_z	is in range	0.10	0.20
Depth of cut, ap	is in range	0.10	0.20
Resultant force	minimize	121.58	439.43
Temperature	minimize	200.35	551.50

The minimum value of cutting force and temperature can be obtained by the following combination: cutting speed of 23.13 m/min, feed rate of 0.10 mm/tooth and depth of cut of 0.10 mm, which has the highest desirability of 0.994 as shown in Figure 14. The ramp function shows the optimization parameters

are set within parameter range. Predicted value of the resultant force is 125.67N and the tool temperature is 200.34°C.

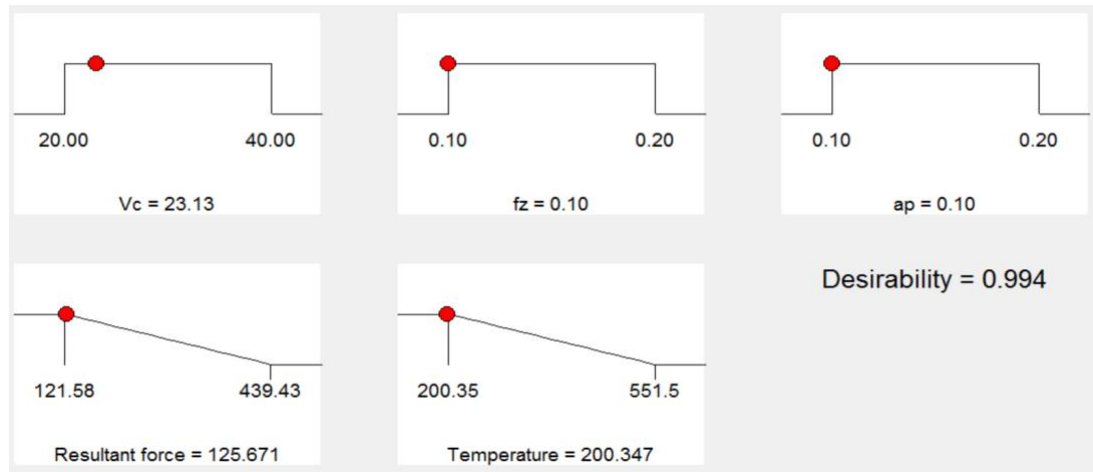


Figure 14: Ramp function graph

Figure 15 shows the result of all the forces recorded by the dynamometer during one path of 100mm tool travel length. Due to the orientation dynamometer during the actual cutting process, the cutting force, feed force and thrust force were labelled as F_x , F_y and F_z , respectively. The details of the forces can be clearly seen when the graph is zoomed in into one cycle. Figure 16 shows the force within one rotation of the cutting tool. There are five waveforms that indicate the number of inserts used for the cutting tool. It took 0.4 seconds to complete one cycle. The graph shows that the cutting force (F_x) dominates the feed force (F_y) and thrust force (F_z). Based on this observation, the located cutter rotation angle affects the magnitude of the forces. This is evidenced by the direction of the F_x axis being perpendicular to the feed direction. In contrast, F_y is minimum due to the force axis being parallel to the feed direction. The thrust force is also minimum due to minimum of rake angle to push the material downwards. It is also reported that the first waveform has higher force values compared to subsequent waveforms. This is because the insert initiates to cut the fresh uncut work piece. Higher cutting forces are required during the beginning of the machining because the surface area and volume of material removed are greater. The subsequent force is slightly lower due to the reduction in the amount of material to be cut.

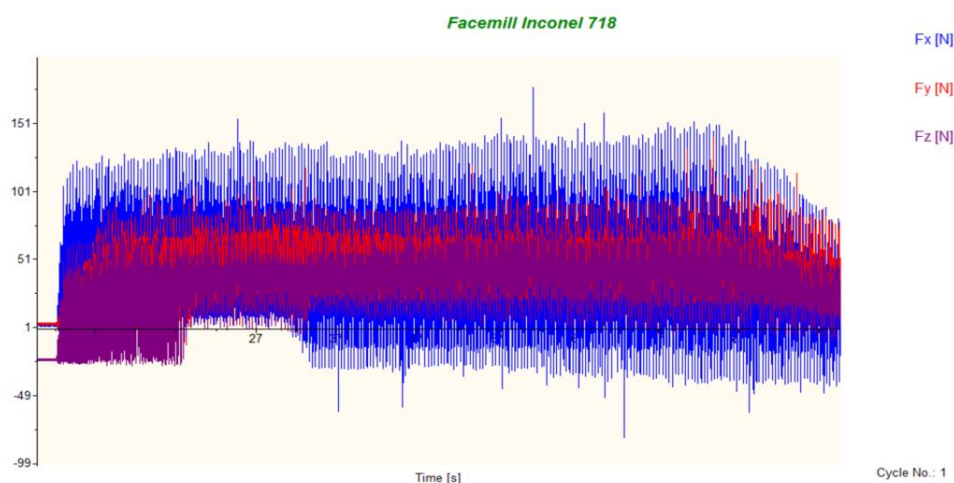


Figure 15: Full machining process with cutting forces

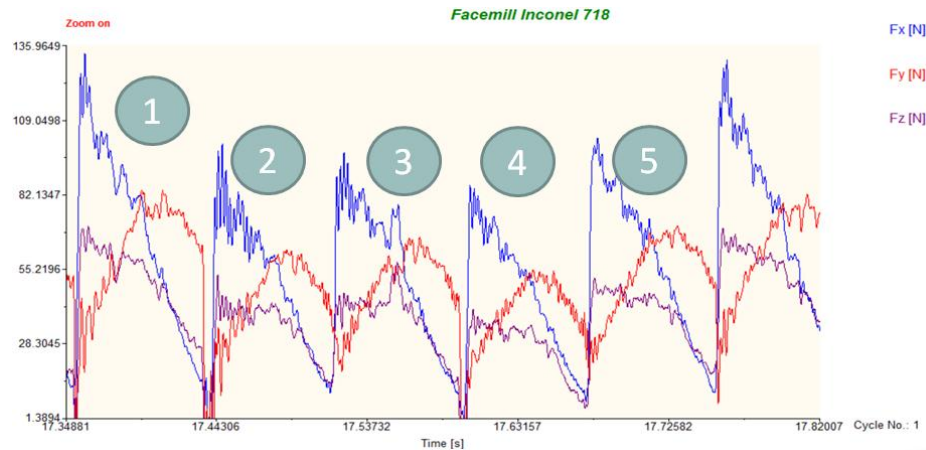


Figure 16: Machining process with cutting forces, feed force and thrust force of one cycle from the Kistler dynamometer

After the experiments, post recording process is required to identify the maximum temperature. The temperature analysis is done with the help of the thermal imager software. Figure 17 shows the spectrum image of the cutting tool and workpiece. The measured temperature of the cutting tool is highlighted with a small rectangle box in the tool area of Figure 17(b).

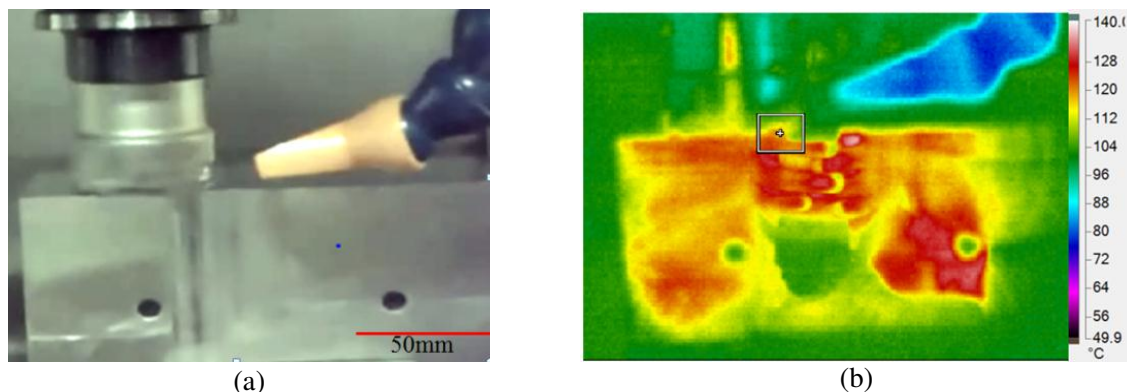


Figure 17: Infrared image of the sample: (a) actual picture, (b) temperature spectrum

Table 7 shows the comparison between simulation and experimental runs for the resultant force and tool temperature. Generally, the actual experimental results are lower than the FE simulations. The error for cutting force is acceptable since the value is less than 10%. However, further investigation is required for the tool temperature. The influence of high error is likely due to the small traceable cutting region to be captured by the thermal camera. Inaccurate results could be due to the material property being based on a software database that requires appropriate customization via subroutines.

Table 7: Measurement between simulation and experimental run

Parameter	Simulation	Experiment	Error, R_e (%)
Resultant force	121.32 N	109.22 N	9.97
Tool temperature	186.53°C	128.55°C	31.08

4. Conclusion

In this study, AdvantEdge software is used as a simulation tool for face milling of Inconel 718. The effect of cutting speed, feed rate and depth of cut on resultant force and tool temperature are evaluated. Based on 18 simulation runs, the resultant force recorded ranges from 121N to 439N while the tool temperature ranges from 200°C to 551°C. The most dominating factor is found to be the feed rate, followed by depth of cut, while cutting speed has no significant difference on the resultant force. On the other hand, the cutting speed, feed rate and depth of cut are the dominating factors that affect the tool temperature during machining. According to the validation, the resultant force, which is composed of cutting force, feed force and thrust force, is accurately modelled with a percentage of relative error of less than 10% between FEM simulation and actual experiments. However, the temperature model error is 31%.

Acknowledgement

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