MODELLING OF CUTTING TEMPERATURE DURING MILLING OPERATION OF ZIRCONIUM ALLOY

ILESANMI DANIYAN[1], BOITUMELO RAMATSETSE[2], MUNISH GUPTA[3], HUMBULANI SIMON PHULUWA[4]

[1]Department of Mechatronics Engineering, Bells University of Technology, P. M. B. 1015, Ota, Nigeria

[2]Department of Mechanical & Mechatronics Engineering, Stellenbosch University, Stellenbosch 7602, South Africa

[3]Faculty of Mechanical Engineering, Department of Machining, Assembly and Engineering Metrology, VSB-Technical University of Ostrava, Ostrava, Poruba, Czech Republic

[4]Industrial Engineering & Engineering Management, University of South Africa, Florida, South Africa

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Corresponding author : afolabiilesanmi@yahoo.com

ABSTRACT

Zirconium is used commercially for nuclear power generation and for increasing electricity output. However, its poor thermal conductivity may result in buildup of residual stress during machining, thereby affecting its machinability. This study investigates the temperature variation of zirconium alloy using Response Surface Methodology (RSM). Three process parameters were used during the milling operation: depth of cut (0.1-0.35 mm), feed per tooth (0.1 -0.25 mm), and cutting speed (50-200 m/min). The experimental matrix generated by RSM was validated via physical machining taking cutting temperature as the measured response. The milling operations were conducted using a DMU80 monoBLOCK DECKEL MAHO Computer Numerical Control (CNC) milling with the aid of Polycrystalline Diamond Tool (PCD) of 50 mm × 100 mm, diameter of 10 mm, with 12° positive rake angle. Findings shows that the optimal values of the process parameters that gave moderate cutting temperature (100.8 °C) were: depth of cut (0.225 mm); feed per tooth (0.175 mm) and speed of cut (125 m/min). This results suggest that there might be a tradeoff. Furthermore, the statistical analysis of the developed predictive model gave a **P-value of** 0.0021 **(less than 0.05) and F-value of 6.68 which indicate the developed model is significant.** Hence, this study may assist machinists in achieving the effective machining of zirconium alloys and prediction of cutting temperature.

KEYWORDS

CNC, Milling operation, Process parameter, RSM, Zirconium alloy

1 INTRODUCTION

Zirconium alloy (ZR4) is used commercially for nuclear power generation and for increasing electricity output. It has desirable high strength and corossion resistance ability, however, its poor thermal conductivity may result in build up of residual stress during machining, thereby affecting its machinability [Wan *et al.,* 2019]. Furthermore, excessive heat could be generated during machining operation that may result in thermal bending of the cuting tool and workpiece and cutting tool, thus affecting dimensional accuracy and tool life [Wan *et al.,* 2019]. Exisitng studies indicates that zirconim alloy possesses some important mechanical properties such as high bending strength and toughness, high resistance to wear and corrosion [Shahmiri *et al.,* 2018 ; Zhang *et al.,* 2020] amongst others, and as such it finds potential applications in the manufacturing, medical and aerospace industries etc. [Piconi & Maccauro, 1999 ; Manicone *et al.,* 2007 ; Luo *et al.,* 2018 ; Pekkan *et al.,* 2020 ; Chen *et al.,* 2024]. However, when its processing is done outside optimal range of the process parameters it may trigger high temperature and high reactivity which may further result in high surface roughness in the workpiece and reduction in the cutting tool life. Therefore, to reduce the reactivity of zirconium alloy, there is a need for effective process design such as the selction of the right cutting tool with proper orientation, effective chips removal mechanism, application of effective coolants, and optimisation of machining parameters amongst others [Manicone *et al.,* 2007].

In addition, zirconium alloy is prone to work-hardening during milling operation which may cause rapid tool wear and poor surface finish, thus, the need to optimise the machining parameters to enhance its machinability, promote tool life, and achieve the desired surface requirements. The conventional trial-and-error approaches of selecting machining parameters are time-consuming and inefficient. Conversely, design of experiment technique such as the Response Surface Methodology (RSM) offer a systematic approach to the selection of optimum process parameters and development o for developing predictive models for the optimization of machining processe. Hence, the aim of this study is to the variation in cutting temperature and time during the milling operation of zirconium alloy using the RSM in order to minimise temperature variation and enhance process performance.

2 LITERATURE REVIEW

Steyn [2021] revealed that it is possible to machine zirconium alloy to the intended surface quality although, it is prone to tool degradation and poor surface finish if the limitations of zirconium allloy such as poor thermal conductivity are not addressed.

Bian *et al.* [2014] conducted the milling operation of zirconia ceramics using Polycrystalline Diamond (PCD) tool. The result shows that the axial depth of cut can significantly influence factors such as brittleness, rate of material removal and surface quality of the material. Yan *et al.* [2022] employed the combination of the finite element and simulation and RSM for the optimisation of process parameters during the milling of zirconia ceramics using the PCD tool. The outcome of the study show that there was significant agreement between the fnite element and simulation results and the RSM results thus indicating the suitability of both technques for the optimisation of process parameters during zirconia milling. Jianxun and Quanping [2012] employed the finite element simulaton for investigating the cutting process of zirconium alloy. The results obtained indicated that the finite element and simulation approah is suitable for optimising the process parameters during zirconium machining. Deng *et al.* [2019] reported similar findings that numerical simulation is a suitable approach for investigating the machining process of zirconia ceramics. Yan *et al.* [2022] indicated the need for process parameters optimisation during the milling of operation of zirconia ceramic and to ensure that the cutting is done within the optimal range to prevent brittle fracture of the workpiece. Wang *et al.* [2018] indicated that the coated tool exhibits improved tribological behaviour during the milling of zirconium alloy while Ferraris *et al.* [2012] inicated that the PCD tools are suitable for effective turning of ZrO2 at high speed. Conversely, Rong *et al.* [2017] also reported similar findings that the use of the PCD tool is suitable for micro end milling of ZrO2 ceramics with tendency for reduction in tool wear. Pan *et al.* [2020] found that the properties of ZrO2 nanopowders could be enhanced by graphene dispersion for effective ball milling. Li *et al.* [2011] studied the temperature distribution of nano-zirconia ceramics during grinding and found that as the depth of cut increases, a local high temperature in the grinding contact zone also increases. Liu *et al.* [2020] studied the hot deformation behaviour and processing map of Zr-4 alloy and found that the flow stress increases with the increasing strain rates with decrease in the deformation temperature. Xu *et al.* [2021] found that increase in feed per tooth increases the milling forces, surface roughness and subsequently cutting temperature during the milling of zirconium alloy and that cutting speed contributes signifcantly to increase in cutting temperature although with reduction in cutting forces. The authors therefore recommended PCD for hard milling of zircoonium alloy. This finding agrees with the results of Rong *et al.* [2017] which indicates that feed per tooth can promote surface irregularity and tool wear and that PCD tool with large paartile size is feasible for zirconium alloy milling.

This study investigates the variation in cutting temperature and time during the milling operation of zirconium alloy using the RSM. It contributes to the understanding of the machinability of zirconium alloy and the outcome may assist machinists in achieving the effective machining of zirconium alloys.

3 MATERIALS AND METHOD

3.1 Method

Tab. 1-2 present the chemical composition and properties of zirconium alloy (Zr-4) respectively.

Tab. 1. Chemical properties of zirconium alloy (Zr-4)

Element	Sn	Fe	Fe+Cr	Cr
Percent weight (wt. %)	1.20	0.18	0.28	0.07

Source : Oyesola *et al.* [2021]

Tab. 2. Physical and mechanical properties of zirconium alloy (Zr-4) [21].

S/N	Properties	Value
	Physical	
1.	Density (kg/m^3)	6530
	Mechanical	
1.	Yield strength (MPa)	230
2.	Brinell's hardness	145
3.	Elasticity modulus (GPa)	94.5
4.	Tensile strength (MPa)	330
5.	Poison's ratio	0.34

Source : Oyesola *et al.* [2021]

3.2 *Design of Experiment*

This study investigates the temperature variation of zirconium alloy using RSM implemented in the Stat-ease 2021 environment. The RSM is a statistical approach useful for design of experiment to obtain a feasible and optimal values process parameters and for obtaining amodel for predicting the experimental response value [Daniyan et al., 2024]. It is also useful in studying the individual and combined effects of the process parmeters on the experimental reponse [Daramola et al., 2019 ; Daniyan *et al.,* 2023 ; Bibili Nzegue et al., 2023 ; Daniyan *et al.,* 2024]. Three process parameters varied over three levels were used during the milling operation while the measured response is the cutting temperature (Tab. 3).

Tab. 3: Design variables matrix for the machining parameters.

		LEVEL	1	2	3
DESIGN VARIABLES	A	Depth of cut (DOC) (mm)	0.1	0.225	0.35
	B	Feed per tooth (FPT) (mm)	0.1	0.175	0.25
	C	Cutting Speed (CS) (m/min)	50	125.000	200
Response		Cutting temperature (°C)			

3.3 *Physical Machining Experimentations*

The milling operation on Zr-4 was conducted with the aid of a Computer Numerical Control milling machine (DMU80 monoBLOCK DECKEL MAHO). A Polycrystalline Diamond Tool (PCD) cutting tool of dimenson 50 mm by 100 mm, diameter of 10 mm, with a 12° positive rake angle, was employed for the end milling cutting operation. The milling operation was performed under a flood coolant system comprising of a water-soluble oil lubricant so as to promote effective chips evacuation and reduce frictional activities and the heat generated. During the experimental set up, the Kistler dynamometer (9257A) and DynoWare software (KISTLER DAQ for DynoWare Type 5697A) were used for the measurement and recording of the magnitude of the cutting forces while an infrared video thermometer (IR MT696) having temperature range of -50 to 1000 °C was employed for the measurement and recording of the cutting temperature for each experimental trial during the cutting operation. The IR thermometer has a distance to spot ratio of 20:1 as well as response time of 150 ms allowing for non-contact and accurate temperature measurement during the cutting operation The average of the measurements was taken as cutting temperature value for each experimental trial. Fig. 1 shows the experimental set up. The IR thermometer is mounted close to the milling machine targeting the cutting zone targeting and the emissivity value is adjusted to 0.10.

Fig. 1. Experimental set up.

4 RESULTS AND DISCUSSION

Tab. 4 presents the values of the process parameters and their responses. The results show that the actual value of cutting temperature ranges from a minimum value of 81.4 °C to a maximum value of 134.9 °C and that increase in CS significantly influence the cutting temperature

Tab. 4. Process parameters and their responses

Trials	DOC (mm)	FPT (mm)	CS (m/mm)	Actual cutting temperature (°C)	Predicted cutting temperature (°C)
1.	0.225	0.175	125	102.8	102.223
2.	0.1	0.25	200	134.9	135.211
3.	0.445	0.175	125	128.2	17.867
4.	0.1	0.25	50	89.7	90.001
5.	0.225	0.175	125	102.8	103.020
6.	0.225	0.175	125	102.8	102.567
7.	0.225	0.3	125	111.9	111.223
8.	0.225	0.3	125	111.9	111.223
9.	0.225	0.175	250	120.7	121.321
10.	0.35	0.25	50	94.6	94.124
11.	0.225	0.175	125	100.8	100.117
12.	0.1	0.1	200	110.6	110.983
13.	0.225	0.175	50	112.9	112.235
14.	0.35	0.1	200	135.6	135.998
15.	0.1	0.1	50	81.4	81.4102
16.	0.225	0.175	125	99.87	100.134
17.	0.225	0.175	125	99.87	99.004
18.	0.15	0.175	125	97.7	97.215
19.	0.35	0.25	200	146.5	146.546
20.	0.35	0.1	50	85.2	85.297

Tab. 5 and 6 show analysis of variance (ANOVA) and fit statistics respectively for cutting temperature. P-value of 0.0021 ($<$0.05) and F-value of 6.68 indicate the developed model is significant. Furthermore, model terms A (DOC), and C (CS) are significant with their respective p-values being less than 0.05. In addition, the fact that the "lack of fit" is insignificant implies that the model fit properly with insignificant variations.

Tab. 5. ANOVA for the 2FI model (Cutting temperature)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4308.50	6	718.08	6.68	0.0021	significant
A-DOC	670.72	1	670.72	6.24	0.0267	
B-FPT	349.07	1	349.07	3.25	0.0947	
C-CS	3176.88	1	3176.88	29.56	0.0001	
AB	18.91	1	18.91	0.1760	0.6817	
AC	97.30	1	97.30	0.9055	0.3587	
BC	38.28	1	38.28	0.3562	0.5609	
Residual	1396.96	13	107.46			
Lack of Fit	1386.09	7	198.01	1.45	0.564	Not significant
Pure Error	10.87	6	1.81			
Cor Total	5705.47	19				

Tab. 6: Fit statistics (Cutting temperature).

Metrics	Value	Metrics	Value
Std. Dev.	10.37	R^2	0.7552
Mean	108.54	Adj. R^2	0.6421
C.V. %	9.55	Adeq Precision	9.5721

The R^2 value of 0.7552 agrees closely with the Adjusted R^2 value of 0.642. Besides, both values are slightly close 1. The closer the values of the R^2 and Adjusted R^2 to 1, the better the model and vice versa. Also, the Adeq. Precision gave a value of 9.572 and values greater than 4 are deemed appropriate as it indicates an adequate signal. Hence, the model can be employed for predictive purpose within the design space. Tab. 7 presents the coefficient estimates and the Variance Inflation Factors (VIFs) for the process parameters. The coefficient estimate signifies the changes in the value of the response for a unit change in the value of a process parameters when other parameters are assumed to be constant. The VIF indicates the variance in the coefficient estimates as a result of collinearity of the process parameters. Usually, VIFs greater than 1 denotes multi-collinearity and the higher the correlation of factors and vice versa. The VIFs obtained in the cutting temperature model is 1 which indicates the absence of multi-collinearity among the process parameters thus, making the model suitable for predictive purpose.

Tab. 7. Coefficients estimates and VIFs of process parameters (Cutting temperature).

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	106.69	1	2.38	101.56	111.83	
A-DOC	7.76	1	3.11	1.05	14.48	1.00
B-FPT	5.18	1	2.88	-1.03	11.39	1.00
C-CS	16.41	1	3.02	9.89	22.92	1.00
AB	-1.54	1	3.67	-9.46	6.38	1.0000
AC	3.49	1	3.67	-4.43	11.41	1.0000
BC	2.19	1	3.67	-5.73	10.11	1.0000

Equation 1 presents the coded model equation generated from the statistical analysis carried out in the RSM for cutting temperature temperature. The equation can be used to predict the cutting temperature value and the impact of the process parameters on cutting temperature.

$$Cutting\ temperature = +106.69 + 7.76A + 5.185B + 16.41C - 1.54AB + 3.49AC + +2.19BC \quad (1)$$

Where A denotes the CS in m/min while B represents the DOC in mm, and C is the FPT in mm/tooth.

Figures 2 and 3 show the graph of residual errors and externally studentized residuals for the cutting temperature model. For Figure 2, the results do not show any significant outliers outside 10% of the diagonal line, thus, indicating that the error in the model is insignificant. For Figure 3, the data points were onserved to fall within the lower and upper boundaries. The plot shows that the model is fit as evidenced is the randomly scattered trends of the residuals. The difference between the actual and predicted values for the experimental trials. Thus, the trend indicates that that there is no significant correlation between the residuals and run order and that the developed model is unlikely to be influenced by other factors outside the independent variables.

Figure 4 shows that with small values of the DOC and FPT, the cutting temperature was low and increases with an increase in the value of DOC and FPT. At the optimum range of values for the DOC (0.225 mm) and FPT (0.175 mm), the cutting temperature was 100.8 ᵒC. Beyond these optimum values, the values of the cutting temperature increases when the values of DOC and FPT increases which makes the cutting process less sustainable. For Figure 5, initially the cutting temperature was low with small values of FPT and CS but increases gradually up to the optimal value of 100.8 ᵒC when the FPT was 0.175 mm and CS of 125 m/min.

Beyond these optimal values the magnitude of cutting temperature was found to increase. According to Figure 6, the opimum values of the DOC and CS that produced an optimum value of temperature (100.8 ᵒC) were 0.225 mm and 125 m/min respectively. Beyond these values, the cutting temperature increases due to friction and increase in cutting energy which makes the process less sustainable. Hence, the results obtained in this study shows as the CS increases, moderate the cutting temperature was obtained. Increasing CS may reduce the time of engagement of the cutting tool and workpiece as well as the overall cutting time thereby reducing the amount of heat generated. The results further show that when the process parameters were increased beyond the optimal range, the temperatre increases significantly. This may be due to increase in energy requirements and fricitional activities that characterise the increase in the values of the process parameters. Xu *et al.* [20] indicated FPT can contribte signficantly to increase in the milling forces and temperature during the milling of zirconium alloy and that increase in cutting speed can trigger significant increase in cutting temperature during milling operation of zircoonium alloy. Thus, the findings in this study indicates that there is a relationship between the process parameters and cutting temperature. Existing study also found that increase in the values of the process parameters may increase the energy consumption and ultimately the cutting temperature [Daniyan *et al.,* 2023 ; Nieslon *et al.,* 2023]. This findings is further supported by the work of AlKawaz *et al.* [2018] who obtained improvement in product finish with increase in CS during ziconium alloy milling. Hood *et al.* [2015] also demonstrated the feasibility of achieving low tool wear and improved suface finish during high speed machining of zirconium alloy.

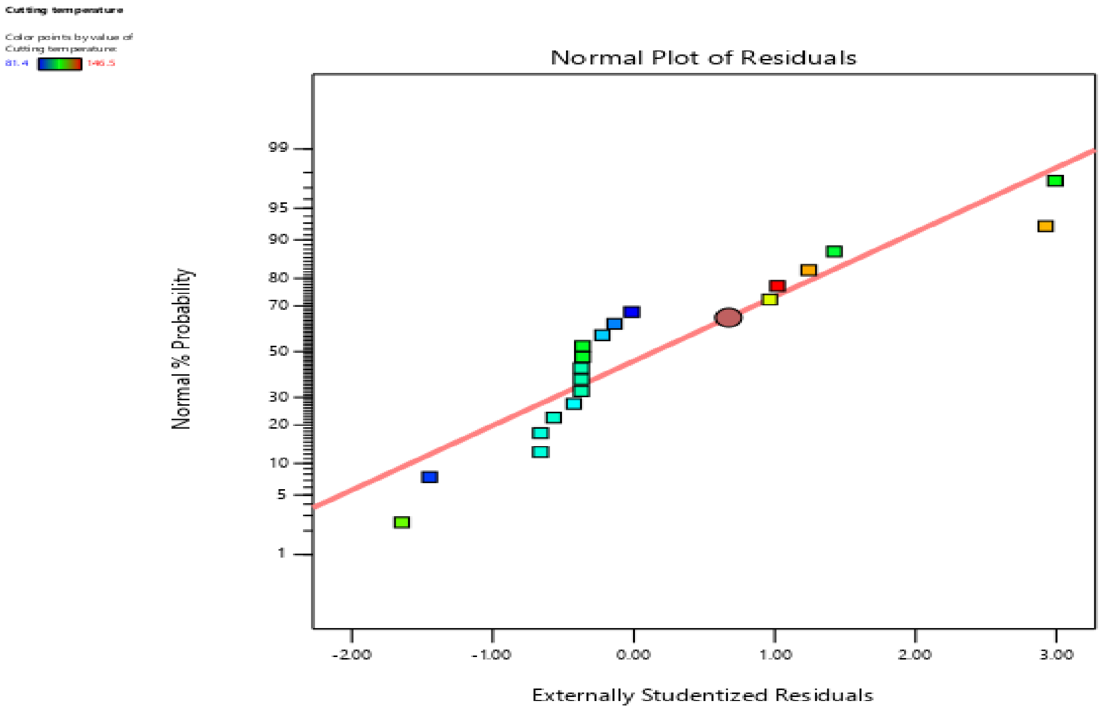

Fig. 2. Normal plots of residuals (Cutting temperature)

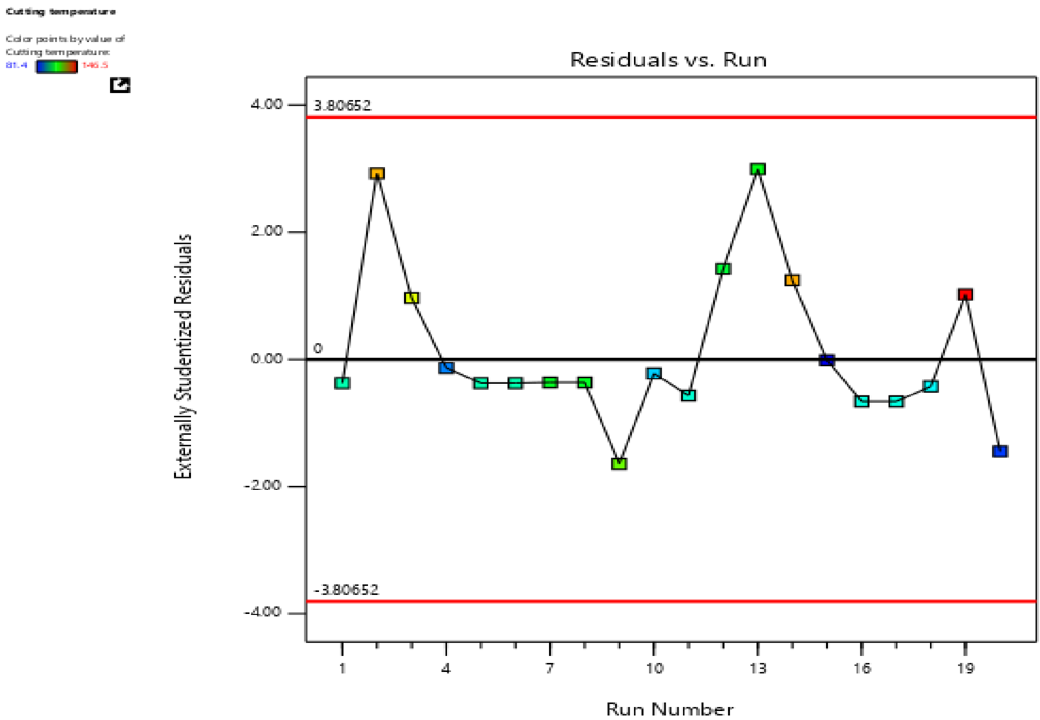

Fig. 3. Graph of externally studentized residuals (Cutting temperature)

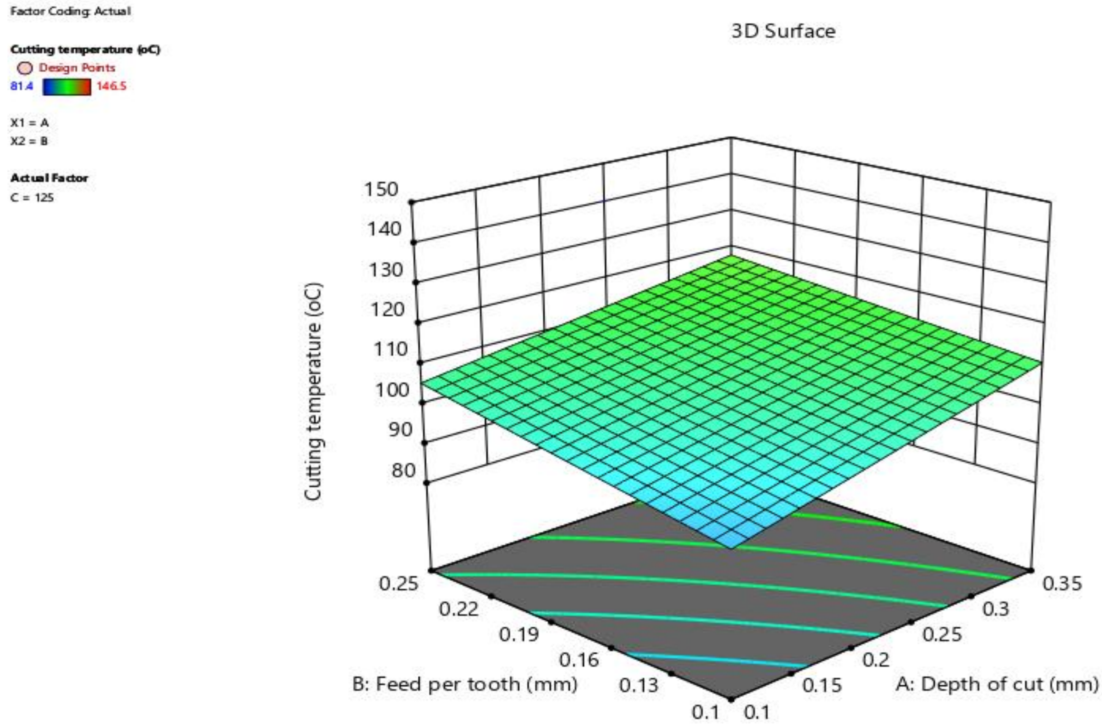

Fig. 4. Effect of DOC and FPT on cutting temperature

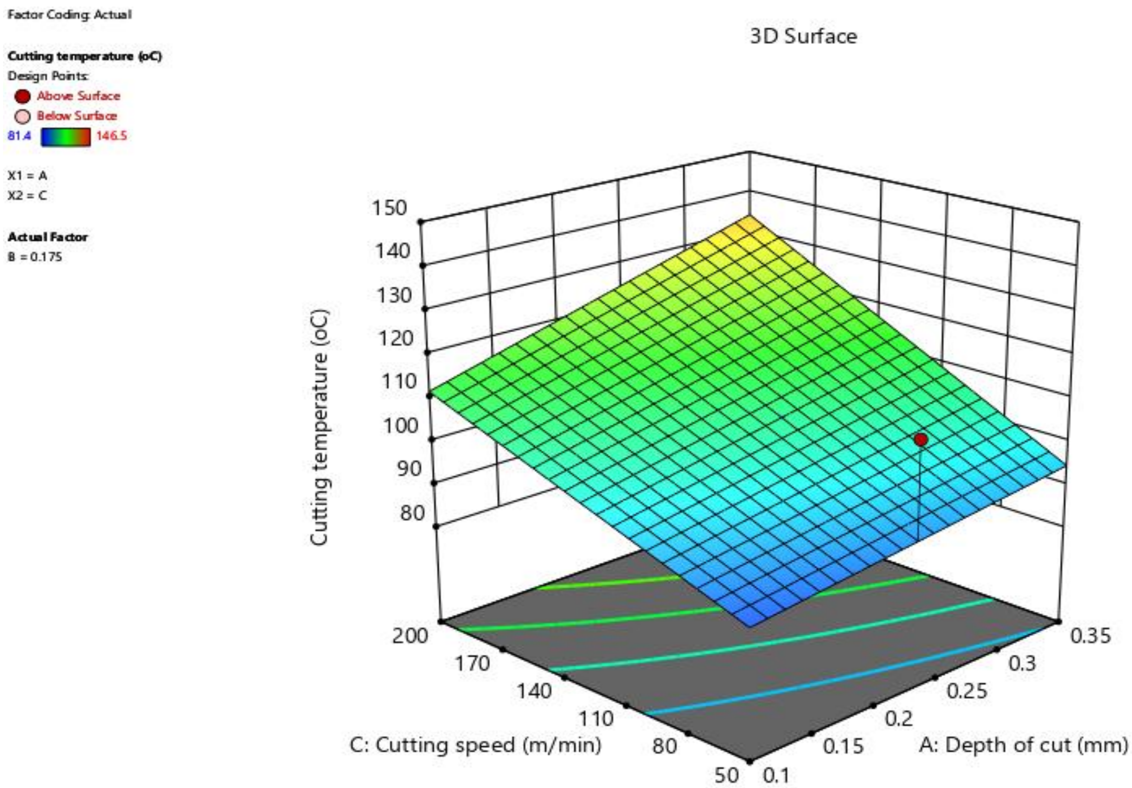

Fig. 5. Effect of FPT and CS on cutting temperature

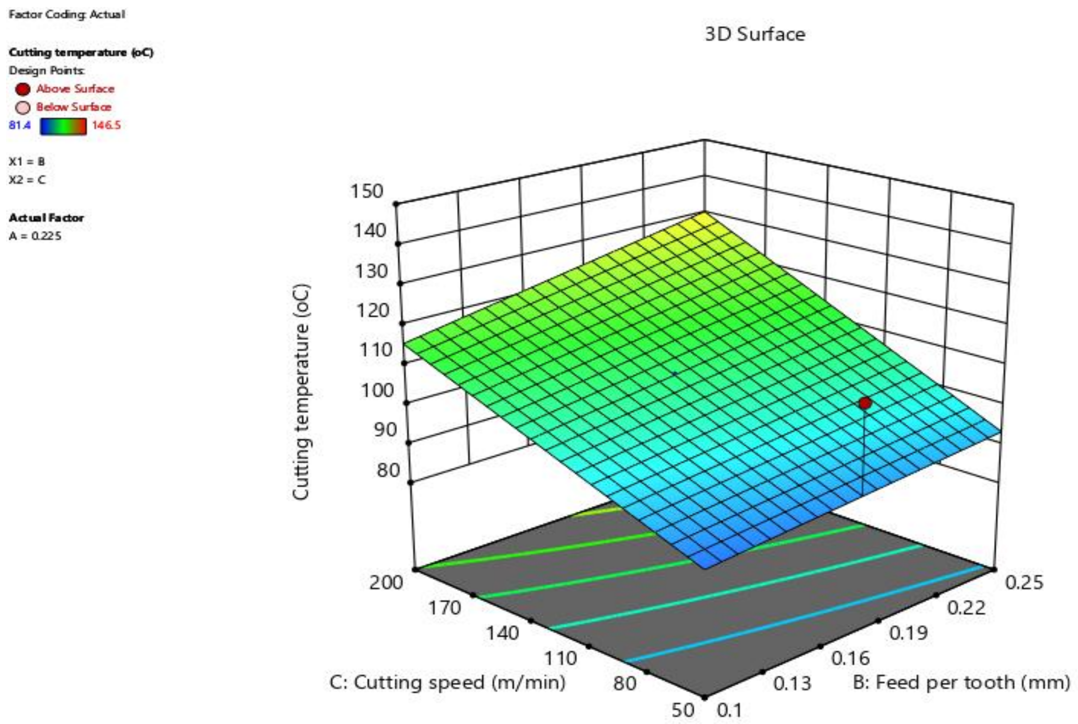

Figure 6. Effect of DOC and CS on cutting temperature.

5 CONCLUSIONS

This study investigated the temperature variation of zirconium alloy using the RSM. The design of experiment matrix generated by the RSM was validated via physical machining experimentations. Three process parameters were used during the milling operation: DOC (0.1-0.35 mm), FPT (0.1 -0.25 mm), and CS (50-200 m/min). The results show that the optimum values of the process parameters that gave moderate cutting temperature of 100.8 ^{o}C were: DOC (0.225 mm); FPT (0.175 mm) and CS (125 m/min). This results suggest that there might be a tradeoff. Furthermore, the statistical analysis of the developed predictive model gave a P-value of 0.0021 (<0.05) and F-value of 6.68 which indicate the developed model is significant. Hence, this study may assist machinists in achieving the effective machining of zirconium alloys and prediction of cutting temperature. There are other factors that could influence the machinability of zirconium alloy which were not considered in this study but could be considered as part of future studies. These include the cooling conditions, cutting tool geometry or orientation, effect of tool wear, cutting force and energy consumed amongst others.

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