Numerical and Experimental Analysis of Surface Roughness of AISI D3 Alloy Steel during Pocket Milling Operation

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***Abstract*—Surface roughness is a quality index which partly determines the ability of a material to meet its service or functional requirements. In this study, the Response Surface Methodology (RSM) was used for numerical analysis of the pocket milling operation of AISI D3 alloy steel and this was validated via physical experimentations. The physical experimentations were carried with the aid of a Deckel Maho DMU80mono BLOCK 5-axis CNC milling machine. The range of the process parameters selected include; feed rate between 0.1-0.5 mm/rev, depth of cut between 1- 3 mm and speed of cut between 150-375 m/min. The RSM generated 20 possible experimental runs while their responses (surface roughness) were gotten from physical experimentations. The results of the physical experimentations serve as input into the numerical analysis carried out using the RSM. This was used to obtain a predictive model equation for determining the magnitude of surface roughness as a function of the three cutting parameters employed (feed rate, depth of cut and cutting speed). Furthermore, the optimisation of the solutions obtained generated 10 possible solutions whose desirability values were equal to 1. The findings of this study may assist machinist in achieving good surface quality during the milling operation of AISI D3 alloy steel.**

***Index Terms*—optimisation, predictive model equation, process parameters, response surface methodology, surface roughness**

I. Introduction

AISI D3 tool steel is a material which is characterised by excellent properties such as good hardenability, high compressive strength, good wear resistance, and excellent resistance to plastic deformation [1]. Its resistance to plastic deformation at elevated temperature makes it a suitable for high temperature applications [2]. The material is usually employed for making dies, development of deep drawing tools, shear knives for thin sheets, and stone processing. However, one of the major challenges which characterise its use for product development is dimensional inaccuracies and surface roughness. This defect may be traced to incorrect selection of the range of process parameters such as feed rate, cutting speed and depth of amongst others [3-4]. The selection of optimum range of these paramters, determination of effective cutting condition and cutting tool orientation represent critical decisions that can affect the degree of quality finish of the final product. To make an informed decision, sometimes machinist rely on experience but the dynamic nature of cutting operations, emerging materials and customers' requirements necessitate a more reliable approach to make an informed decision. This is because poor surface finish of a product will affect the integrity and quality of such product [5-7]. Besides, it may also affect the ability of the product to meet its service or functional requirements. Furthermore, it may increase reverse logistics with decrease in the level of customers' satisfaction. This may affect the overall profitability and reputation of the manufacturing industry. Hence, in the quest to address this challenge, this study seek to employ the combination of numerical and physical experimentations to identify the possible range of process parameters that will be effective for the pocket milling operation of AISI D3 tool steel. This may bring about the following merits: improvement of products' quality, optimisation of the time and costs of machining, as well as

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manufacturing sustainability [8-10]. Manufacturing sustainability refers to the overall sustainability of the machining process as it relates to material's machinability, amount of energy consumed and environmental friendliness. It will also assist machinists in making effective decision relating to the selection of the appropriate process conditions. Existing studies have reported on many approaches used to achieve manufacturing sustainability of materials. These include numerical experimentations, physical experimentations, analytical, Computer Aided Design modelling and simulation approaches amongst others [11-14].

Some efforts have been geared towards effective machining of tool steel to the desired surface finish. Mirzaee *et al.* [15] indicated that the addition of titanium alloy to tool steel AISI D3 (K100) at concentrations ranging from 0.7- 1.0 wt. pct. resulted in considerable alteration of the microstructure to a more uniform grain size. Furthermore, the addition of niobium at concentration ranging from 0.2 -1.0 wt pct. also resulted in a more uniform microstructure. The more uniform the microstructure, the better the mechanical properties of the material and vice versa. Mohammad *et al.* [16] and Altin [17] established that the magnitude of the process parameters such as the feed rate, depth of cut and cutting speed (as considered in this study) can significantly affect the surface finish of tool steel AISI D3 (K100). Based on this, these three process parameters were considered for investigation in this study with a view to establish their feasible range for the pocket milling operation of AISI D3 (K100) tool steel. The outcome of the literature review indicates that here are still more works to be done regarding the investigation of the machinability and surface roughness of AISI D3 alloy tool steel. For instance there is a dearth of information regarding the development of predictive model to investigate the surface roughness as well as process optimisation amongst others. Thus, this is a major focal point of this study with the aim to determine the feasible range of the cutting parameters for the pocket milling operation of AISI D3 tool steel.

II. Materials and Method

A. Numerical Analysis

The numerical analysis using RSM was implemented in the design expert software (version 8) environment. The range of the process parameters selected include; feed rate between 0.1-0.5 mm/rev, depth of cut between 1- 3 mm and speed of cut between 150-375 m/min. The RSM generated 20 possible experimental runs while their responses (surface roughness) were gotten from physical experimentations. The choice of RSM stems from the fact that it can be used to obtain a predictive model and can effectively study the interactive effect of independent cutting parameters on the response of the designed experiment [18]. The results of the physical experimentations serve as input into the numerical analysis carried out using the RSM. This was used to obtain a predictive model equation for determining the magnitude of surface roughness as a function of the three cutting parameters employed (feed rate, depth of cut and cutting speed). Furthermore, the optimisation of the solutions obtained generated 10 possible solutions whose desirability values were equal to 1. Table I presents the summary of the experimentation design with the use of RSM.

TABLE I. Numerical Experimentation Using RSM

Notation	Factors	Levels		
		-1	0	1
A	Depth of cut (mm)	1	2	3
B	Feed rate (mm)	0.1	0.3	0.5
C	Cutting speed (m/min)	150	262.5	375

The numerical analysis was validated with the aid of physical experimentations and Analysis of Variance (ANOVA). The indices for a well-developed model for predictive purpose include: the "p-value Prob > F" (< 0.050), "Lack of Fit" (which should statistically insignificant relative to the pure error) and the correlation coefficients such as the predicted R^2, R^2 and the adjusted R Squared. It is expected that the values of these correlation coefficients will be close to 1 for a model that is statistically significant model [18].

B. Physical Experimentation

The coated tungsten carbide cutting tool was selected for the milling operation [1].

The physical experiments were done out using a Deckel Maho DMU80mono BLOCK 5-axis CNC milling machine with the aid of a carbide end mill cutter of 16 mm as the cutting tool. A professional infrared video thermometer (MT 696) was used for capturing the cutting temperature during the pocket milling operation. The stationary dynamometer (KISTLER 9257A 8-Channel Summation of Type 5001A Multichannel Amplifier) with the Data Acquisition System (DAS) was also employed for capturing the magnitude of the cutting force. Figs. 1 and 2 present the physical set-up of the equipment for the pocket milling.

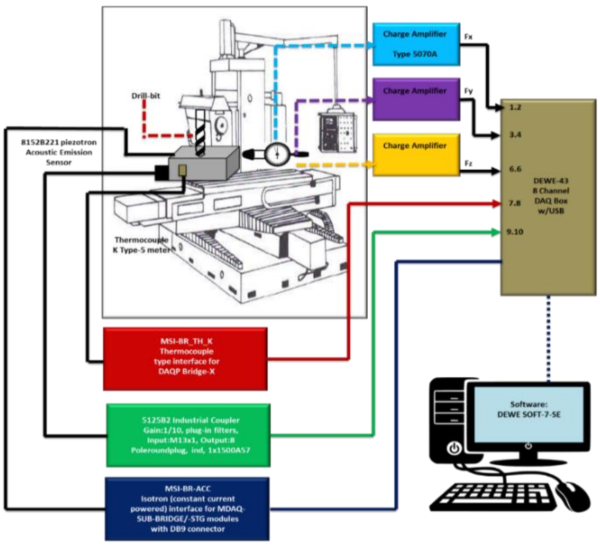

Figure 1. The integration of the equipment for milling operation

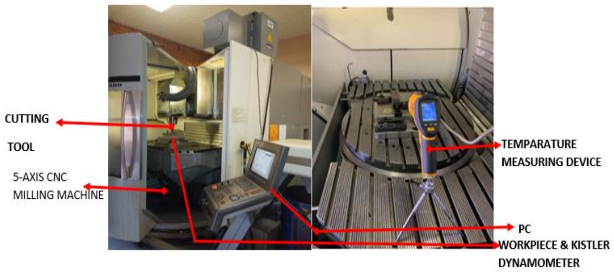

Figure 2. The experimental set-up for the pocket milling operation

The pocket milling operation involves the plunging of the cutter and subsequent movement into a marked area of the workpiece for material removal from the closed boundary of a workpiece. In the process, a cut is made to a fixed depth which ranges between 1 mm to 3 mm. The cutting operations were carried out under the soluble cooling condition involving the application of a suspension of oil in water into the cutting tool-workpiece interface through a pipe. Table II and III present the composition and mechanical properties of the AISI D3 alloy steel respectively.

TABLE II. CHEMICAL COMPOSITION (WT. %) OF ALLOY TOOL STEEL AISI D3 [1]

C	Mn	P	Si	Ni	S	Cr	Cu	Fe
2.00	0.60	0.03	0.60	0.30	0.030	12.00	0.25	84.64

TABLE III. THE PHYSICAL, THERMAL AND MECHANICAL PROPERTIES OF ALLOY TOOL STEEL AISI D3 AT 450OC TEMPERING TEMPERATURE [1]

S/N	Property	Value
	Physical	
1.	Density (kg/m^3)	7700
	Thermal	
1.	Mean coefficient of thermal expansion at 450ºC ($\mu m/m/oC$)	12.2
	Mechanical	
1.	Yield strength (MPa)	310
2.	Poisson's ratio	0.30
3.	Elastic modulus (GPa)	210
4.	Yield stress (GPa)	1.5
5.	Maximum tensile stress (GPa)	1.672
6.	Elongation	7.02
7.	Brinell's hardness (HB)	300

The pocket milling toolpath parameters and other cutting specifications are presented in Table IV while Table V presents the cutting tool geometries.

TABLE IV. CUTTING SPECIFICATIONS

Parameter	Specification
Workpiece dimension (mm)	93 by 56 by 30
Pocket diameter of the workpiece (mm)	40
Cutting pattern	Zig-zag
Cutting direction options	Uni-directional, steps sideways, and cuts in the reverse direction.
Tool path cutting angle (deg.)	90
Step Over (%)	9.6 and 12.8 for 12 mm and 16 mm cutter respectively
Tolerance for machining (%)	6.25
Tolerance for constant overlap (%)	0.5

TABLE V. THE CUTTING TOOL GEOMETRY

Symbol	Parameter	Specification
T_d	Bull nose diameter (mm)	16
n	Number of Flute	4
α	Tip Radius (mm)	4.0
φ	Helix angle (deg.)	45º
L	Overall length	120

The surface roughness of workpieces shown in Figures 3 and 4 were measured using the surface roughness testing machine (Mitutoyo SJ – 201) shown in Fig. 5.


Figure 3. Roughing cut

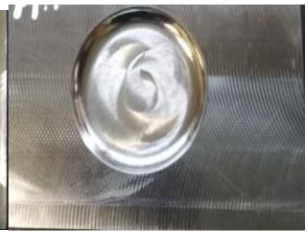
Figure 4. Finishing cut


Figure 5. Surface roughness tester

III. RESULTS AND DISCUSSION

Table VI presents the feasible combination of the process parameters and their surface roughness values obtained through physical experimentations. The feasible process parameter which produced the least surface roughness (0.476μm) include: feed rate (0.30 mm/rev), depth of cut (2.00 mm), and cutting speed (175 m/min).

The results obtained in Table VI imply that low values of feed rates, depth of cut, and cutting speed may promote surface roughness. However, when the magnitude of these process parameters are increased beyond the optimum, it may also trigger surface roughness. This means there is a need for the optimisation of the cutting parameters to keep the values within the optimum range. Amongst others factors, the requirements for an effect machining operation include: increase in tool life, good surface finish, reduction in the cutting time, and optimum energy consumption. Generally, at lower values of feed rates, depth of cut and cutting speed, depending on the hardness of the material and the cutting conditions, there may be reduction in the amount of energy consumed and cutting temperature but with tendency for friction, flank wear of the cutting tool and chattering at the work-piece-tool interface. This may increase the magnitude of the surface roughness and reduction in the useful life of the cutting tool. On the other hand, with an increase in the magnitude of the feed rates, depth of cut and cutting speed, depending on the hardness and the cutting conditions, there may be increase in the amount of energy consumed and increase in the cutting temperature but with increase in the cutting efficiency. Cutting efficiency may be measured in terms of the degree of surface finish, increase in rate of material removal, improvement in cutting tool life, or sustainability of the cutting process.

TABLE VI. PROCESS PARAMETERS AND THEIR SURFACE ROUGHNESS VALUES

Trials	Factor A: Depth of cut (mm)	Factor B: Feed rate (mm/rev)	Factor C: Cutting speed (m/min)	Actual surface roughness (micro-m)	Predicted surface roughness (micro-m)
1.	2.00	0.20	262.50	0.640	0.652
2.	2.00	0.30	265.00	0.723	0.798
3.	2.00	0.30	262.50	0.987	0.924
4.	2.00	0.30	175.00	0.476	0.499
5.	2.00	0.30	350.00	0.786	0.801
6.	2.00	0.30	300.00	0.657	0.655
7.	2.00	0.20	262.50	0.667	0.702
8.	3.00	0.30	262.50	0.880	0.862
9.	2.00	0.30	262.50	0.94	0.902
10.	2.00	0.30	150.00	0.878	0.823
11.	1.00	0.10	375.00	0.566	0.575
12.	3.00	0.10	150.00	0.785	0.798
13.	3.00	0.20	150.00	0.650	0.672
14.	3.00	0.10	375.00	0.699	0.732
15.	1.00	0.20	150.00	0.760	0.745
16.	1.00	0.10	375.00	0.734	0.750
17.	2.00	0.30	262.50	0.765	0.777
18.	3.00	0.30	262.50	0.745	0.746
19.	1.00	0.10	150.00	0.769	0.789
20.	3.00	0.20	375.00	1.47	1.5310

Fig. 6 presents the actual and the values of the surface roughness (actual and predicted) obtained for the 20 experimental trials. The results indicate a significant agreement between the actual values of surface roughness obtained from the physical experiments and the ones obtained from the numerical experimentations. This lends credence to the result obtained that the mathematical model equation is significant and suitable for predictive purpose.

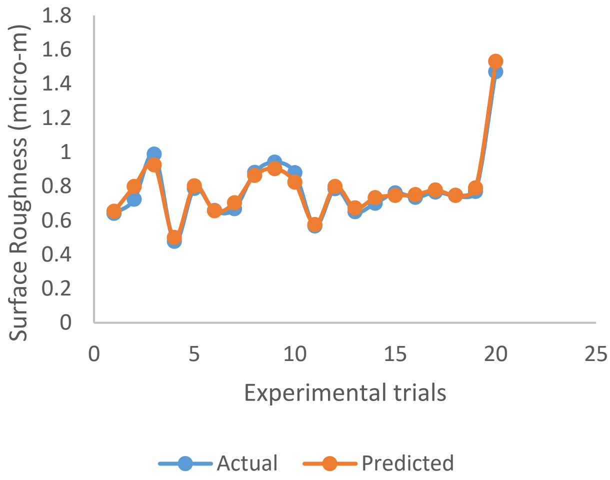

Figure 6. Actual and predicted values of surface roughness

Table VII presents the analysis of the developed 2FI model equation for determining the magnitude of surface roughness as a function of the three cutting parameters employed (feed rate, depth of cut and cutting speed). Table 8 on the other hand, highlights the Analysis of Variance (ANOVA) 2FI model.

TABLE VII. STATISTICAL ANALYSIS OF THE DEVELOPED MODEL

Statistical parameters	Sum of Squares	df	Mean square	F value	p-value Prob > F	Remarks
Model	0.039	6	0.03	0.35	0.0089	Significant
A-Depth of cut	0.28	1	0.28	0.43	0.0213	
B-Feed rate	7.976E-003	1	7.976E-003	0.41	0.0310	
C-Cutting speed	9.403E-003	1	7.976E-003	0.51	0.0486	
AB	2.485E-003	1	2.485E-003	0.14	0.0188	
AC	0.011	1	0.011	0.58	0.8399	
BC	7.801E-003	1	7.801E-003	0.043	0.011	
Residual	0.24	13	0.018			
Lack of Fit	0.16	8	0.020	1.27	0.4136	Not significant
Pure Error	0.079	5	0.016			
Corr.	0.28	19				

The model "F-value" of 0.35 implies that the model is statistically significant relative to the noise. This means that the probability that the model "F-value" this large could occur due to noise is only 89.9%. Furthermore, the value of the "p-value Prob > F" is 0.0089. Since the magnitude of the "p-value Prob > F" is less than 0.050, then there is an indication that the model terms are statistically significant. The model terms that are significant include: A (depth of cut), B (feed rate) and C (cutting speed), AB (cross effect of depth of cut and feed rate), BC (cross effect of feed rate and cutting speed). The "Lack of Fit" was found to be insignificant with a value of 0.16 relative to the pure error. It can be said that the model equation is fit for predicting the magnitude of surface roughness since the "Lack of Fit" is inconsequential. There is also a good agreement among the values of the Adjusted R-square (0.8750) and Predicted R square (0.8476) and the R squared (0.8990), coupled with the fact that they were all close to 1. This is also a good indication that the model terms are significant and that the model equation is fit for predictive purpose.

TABLE VIII. THE ANALYSIS OF VARIANCE (ANOVA) FOR THE DEVELOPED MODEL

Parameter	Value	Remarks
R-Squared	0.8990	Significant
Adjusted R Squared	0.8750	Significant
Predicted R-Squared	0.8476	Significant

The results of the physical experimentations serve as input into the numerical analysis carried out using the RSM. This was used to obtain a predictive model equation (Equation 1) for determining the magnitude of surface roughness as a function of the three cutting parameters employed (feed rate, depth of cut and cutting speed).

$$Surface\ roughness = +0.75 + 0.024A - 0.026B + 0.026C + 0.018AB + 0.036AC + 0.009875BC \quad (1)$$

where: A is the depth of cut (mm), B is the feed rate (mm/rev) and C is the cutting speed (m/min).

Fig. 7 is the normal plot of residual for the model developed for predicting the magnitude of surface roughness. It is an indication of the degree of the normal distribution of the data set [18]. The plot shows the closeness of the data set to the diagonal (average) line which implies that the data set is approximately linear and normally distributed though with an inherent randomness left over within the error portion. However, the variation of data points from the diagonal line is permissible (within the range of ±10%). Figure 8 is the residuals versus the experimental run order plot which helps to know if there is any correlation between the error terms that are near each other in the sequence.

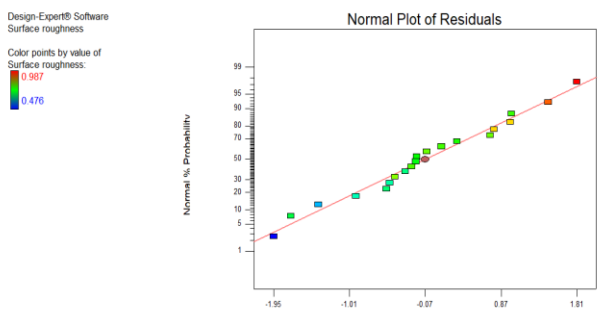

Figure 7. The normal plot of residual for the developed model

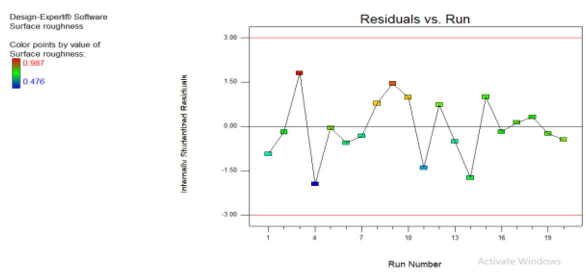

Figure 8. The residuals versus the experimental run order plot

Figs. 9 and 10 show the 2-dimensional and 3-dimensional plots respectively of the cross effect of depth of cut and feed rate on the surface roughness. The plots indicate that the magnitude of the surface roughness decreases with an increase in the values of the feed rate and depth of cut. The feed rate measures of the velocity at which the cutting tool advances against the workpiece while the depth of cut is a measure of the distance that the cutting tool moves into the workpiece for material removal [19]. As the magnitude of the feed rate and depth of cut increases, there may be tendency for strain hardening of the material due to increase in the magnitude of the cutting force. This may promote reduction in the magnitude of the surface roughness. Sivaraman *et al.* [20] had earlier established a direct relationship between an increase in the magnitude of the cutting force as the feed rate and depth of cut increases. Lower depth of cut can trigger friction most especially for hard materials with increase in surface roughness, hence, the surface finish of a material may improve when the depth of cut increases and kept within the optimum range of values.

Machining at lower feed rates stand the risk of abrasive wear depending on the material's homogeneity. Chipping phenomenon can also causing damage to the cutting edge of the tool [21-23].

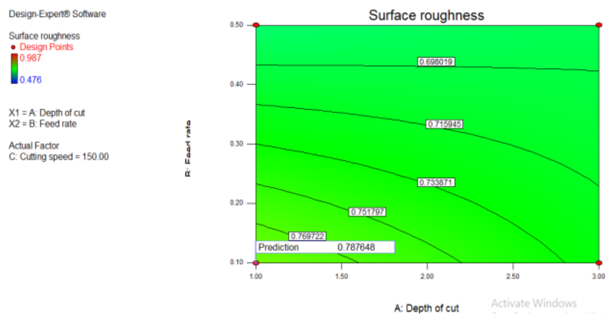

Figure 9. The contour plot of the effect of the depth of cut and feed rate on the surface roughness

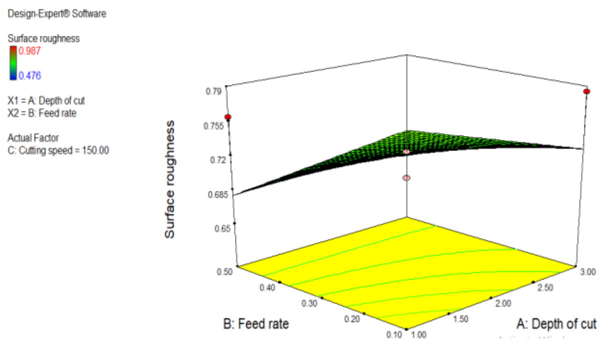

Figure 10. The 3D plot of the effect of the depth of cut and feed rate on the surface roughness

Figs. 11 and 12 show the contour plot and the 3D plot of the effect of the depth of cut and cutting speed on the surface roughness respectively. A direct relationship cannot be established between these two cutting parameters as it affect the magnitude of the surface roughness in this study. This validates the numerical analysis which established that the effect of factors A (depth of cut) and C (cutting speed) is statistically insignificant due to the fact that the "p-value Prob > F" of factor AC was less than 0.050.

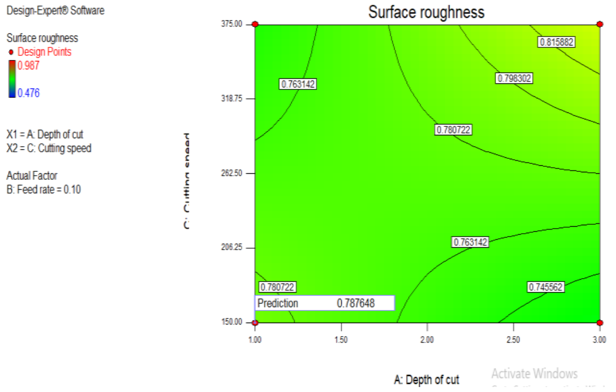

Figure 11. The contour plot of the effect of the depth of cut and cutting speed on the surface roughness

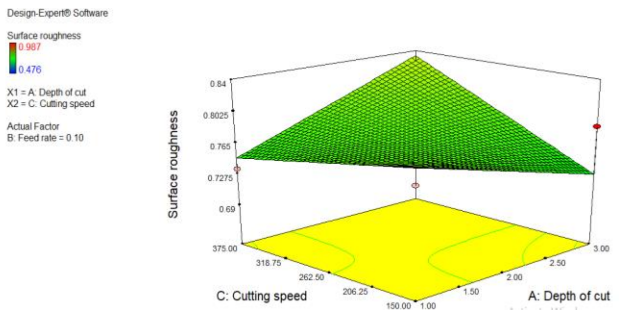

Figure 12. The 3D plot of the effect of the depth of cut and cutting speed on the surface roughness

Figs. 9 and 10 show the 2-dimensional and 3-dimensional plots respectively of the cross effect of depth of cut and feed rate on the surface roughness. The results indicate that the magnitude of the surface roughness decreases when the values of the feed rate and cutting speed increases. This agree significantly with the findings of Ibrahim *et al.* [24] during the end milling operation of mild steel. Cutting speed measures the relative velocity between the workpiece surface and the cutting tool. High cutting speed can promote high temperature at the workpiece-tool interface with increase in the rate of plastic deformation of the material. Under controlled conditions of effective cooling, chips removal and adequate feed rate it can result in strain hardening with resulting decrease in surface roughness values.

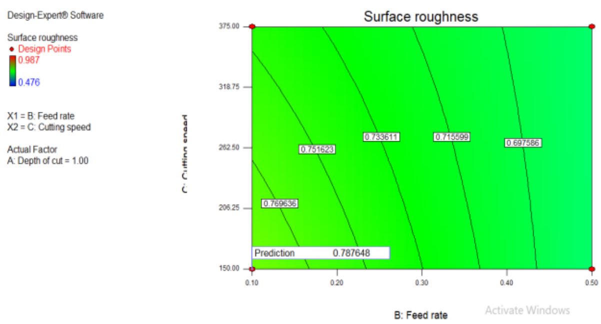

Figure 13. The contour plot of the effect of the feed rate and cutting speed on the surface roughness

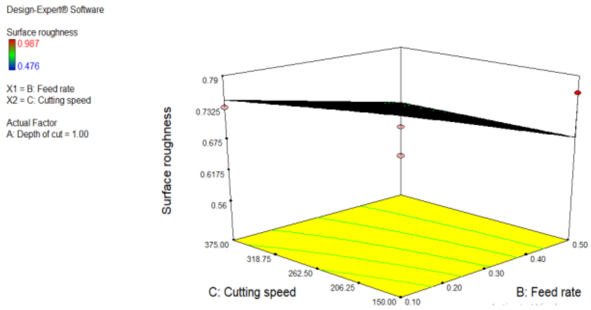

Figure 14. The 3D plot of the effect of the feed rate and cutting speed on the surface roughness

IV. Conclusion

This study employs the Response Surface Methodology (RSM) and physical experimentations for establishing the feasible range of cutting parameters during the pocket milling operation of AISI D3 alloy steel. The feasible process parameter which produced the least surface roughness ($0.476\,\mu m$) include: feed rate (0.30 mm/rev), depth of cut (2.00 mm), and cutting speed (175 m/min).

A predictive model equation for determining the magnitude of surface roughness as a function of the three cutting parameters employed (feed rate, depth of cut and cutting speed) was obtained and statistically validated to be significant. This was evident in the closeness of the outputs of the predictive model when compared to the results of surface roughness obtained via the physical experiments. Furthermore, the results obtained indicate that the magnitude of the surface roughness decreases with an increase in the values of the feed rate and depth of cut. A direct relationship cannot be established between the depth of cut and cutting speed as it affect the magnitude of the surface roughness in this study. The results also indicate that the magnitude of the surface roughness decreases when the values of the feed rate and cutting speed increases.. The findings of this study may assist machinist in achieving good surface quality during the milling operation of AISI D3 alloy steel. The pocket milling operation was carried out under the conventional cooling condition, thus, future works can investigate the optimisation of the identified cutting parameters under other cooling condition such as the cryogenic condition.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The conceptualization, experimentation, results analysis, writing-original draft, visualization, data curation, format analysis and editing were the collective work of all the authors.

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