DEVELOPMENT OF SURFACE ROUGHNESS PREDICTION MODEL USING RESPONSE SURFACE METHODOLOGY FOR END MILLING OF HTCS-150

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ABSTRACT: In the present study, a regression mathematical model has been developed to predict the surface roughness in end milling of High Thermal Conductivity Steel 150 (HTCS-150). A number of milling experiments were conducted using the Response Surface Methodology (RSM) approach using CNC variaxis machining centre. The cutting speeds (484-553 m/min), feed rates (0.31-0.36 mm/tooth) and depth of cut (0.1-0.5 mm) were selected as the control factors. Analysis of variance (ANOVA) was used to analyze the most significant control factors affecting the surface roughness. Box-behnken experimental design was employed to create a mathematical model. The results show that the mathematical modeling developed in this study able to predict the output values of the surface roughness for milling HTCS-150. Cutting speed appeared to be the most influencing parameter for fine surface roughness, followed by depth of cut and feed rate. The differences between measured and calculated values stated about 4 % error.

KEYWORDS: *Response Surface Methodology; Box-Behnken; HTCS-150; Surface Roughness; Ball End-Mill Cutting Tool*

1.0 INTRODUCTION

High Thermal Conductivity Steel-150 (HTCS-150) is a new developed engineering material with extremely high thermal conductivity properties up to 66 W/mK. The combination of high impact strength and high wear resistance make this material capable to perform as a die, especially for the application that required high thermal cooling and heating. HTCS-150 mostly applied in hot stamping process where the dies can be used to press, heat and quench the components for complete microstructure transformations from austenite to martensite [1-2]. The process widely used to produce safety components in the car such as chassis, fenders and bumpers [3].

In the hot stamping process, one of the important criteria to control the efficiency of cooling and heating inside die enclosure is surface roughness [4]. Fine surface roughness being important requirement not only to control the precision of the stamped component but also to transfer the heat without disruption of gap between the dies and stamped component. In addition, fine surface roughness significantly improves fatigue strength, corrosion resistance and creep life of the die [5].

In understanding the effect of cutting parameters, various researches [6-10] utilized Response Surface Methodology (RSM) to develop mathematical models that capable to correlate dominant effect that controls the surface roughness. Depended on the type of cutting tools and workpiece materials, some of them reported that the surface roughness mostly affected by cutting speeds [7-8]. Whereas some other researches proposed that the feed rate appeared to be dominant factor affecting surface roughness [9-10]. In addition, the surface roughness also affected by another uncontrolled variable such as material, mechanical properties, type of cutter and vibration during machining process [11-12].

Since the usage of HTCS-150 mostly applied in hot stamping industry, which considered new in Malaysia, the assessment of machining parameters on its surface roughness is still limited. Therefore, this paper presenting the development of surface roughness prediction model based on machining parameters (cutting speed, feed rate, depth of cut) in end-milling of HTCS-150. A number of experiments were conducted using the RSM approach on a CNC variaxis machining centre. Analysis of variance (ANOVA) and Box-behnken experimental design were used to develop regression model that can represent the effect of cutting parameters on the surface roughness.

2.0 EXPERIMENTAL

The HTCS 150 milling processes were carried out in dry condition using a MAZAK Variaxis 5-axis CNC milling machine as shown in Figure 1. The cutting tool used in this study was PVD coated carbide ball end mill coded as SRFT20-VP15TF. Figure 2 shows the cutting tool used in this study. The workpiece material used in this study was High Thermal Conductivity Steel 150 (HTCS-150). The mechanical and thermal properties of the workpiece material is shown in Table 1 and Table 2 respectively. The specimen size for this experiment was standardized in a block form of 60 mm x 60 mm x 10 mm (width x length x height). The experiments were an extension of previous findings [13].

Figure 1: MAZAK variaxis 5-axis CNC milling machine

Figure 2: SRFT20-VP15TF Ball end mill insert

Table 1: Physical and Mechanical properties of HTCS-150 tool steel under 300K test temperature [1]

Mechanical Properties		Unit
Density	7.97×10^3	Kg/m^3
Mechanical Resistance	1305	MPa
Yield Strength 0.2%	1233	MPa
Abrasive Wear resistance	350	Rovalma-coeficient 2
Hardness Strength	56	HRC

Table 2: Thermal properties of HTCS-150 tool steel under 300K test temperature [1]

Thermal Properties		Unit
Thermal diffusivity	12.5	mm^2/s
Thermal conductivity	55	W/mK
Specific heat capacity	496	J/kgK

The control parameters were spindle speed (V_f), feed rate (F_z) and depth of cut (a_p), while the width of cut was kept constant at 0.01 mm. The details of cutting parameters is shown Table 3. Response Surface Methodology (RSM) with Box- Behnken based experimental design was employed where 17 experimental run were carried out to develop prediction model based on surface roughness value. Five (5) of seventeen (17) runs were evaluated with the same parameters, so it can avoid bias during the experimental analysis. Table 4 shows the full test matrix of RSM design. Surface roughness were measured using the Mitutoyo Portable surface roughness where all measurements were performed after completing 1000 passes for each running, which is equal to 20 minutes of machining time. The measurements were made along the feed direction where the stylus traversing length was 8 mm along the center line of sampling.

Table 3: Machining process experiment parameters range

Process Parameter		Unit
Cutting Speed (V_c)	484-553	m/min
Feed Rate (F_z)	0.31-0.36	mm/tooth
Depth of Cut (a_p)	0.1-0.5	mm

3.0 RESULT AND DISCUSSION

Table 4 shows the results of surface roughness based on the experimental design. The results suggest that use of high cutting speed, low feed rate and low depth of cut lead to better surface finish, consistent with the finding from [14]. For instance, the lowest surface roughness value of 0.110 μm can be obtained when the cutting speed was set at a high level of 530.32 m/min, feed rate was set at lowest level of 0.31 mm/tooth and depth of cut was set at minimum depth of 0.1mm. Surface roughness is directly influenced by the tool nose radius. During tool-material engagements, the shearing action from the cutting tool creates peak and valley according to the size of tool nose radius. Low depth of cut generally produces a fine surface finishing due to smaller crescent shape formed between peak and valley profile [14]. High repetition interaction between high cutting speed and low feed rate could generate fast sliding contact and cutting path overlap along the machined surface, thus contributes to fine material removal at the upper layer of the machined surface.

Table 4: Experiment run condition and surface roughness result

Std Run	V_c (m/min)	F_z (mm/ tooth)	a_p (mm)	Surface Roughness, Ra (μm)
Run 1	484.00	0.31	0.30	0.253
Run 2	553.00	0.31	0.30	0.182
Run 3	484.00	0.36	0.30	0.251
Run 4	553.00	0.36	0.30	0.200
Run 5	484.00	0.33	0.10	0.275
Run 6	553.00	0.33	0.10	0.170
Run 7	484.00	0.33	0.50	0.261
Run 8	553.00	0.33	0.50	0.236
Run 9	518.50	0.31	0.10	0.110
Run 10	518.50	0.36	0.10	0.122
Run 11	518.50	0.31	0.50	0.163
Run 12	518.50	0.36	0.50	0.185
Run 13	518.50	0.33	0.30	0.145
Run 14	518.50	0.33	0.30	0.133
Run 15	518.50	0.33	0.30	0.147
Run 16	518.50	0.33	0.30	0.132
Run 17	518.50	0.33	0.30	0.139

Table 5 shows the ANOVA analysis based on the surface roughness recorded. Results from Table 5 show that the F-Value for this study is 47.82 with 0.01% chance of noise occured. It should be noted that the value of Prob>F is less than 0.05, which indicates that the model is significant. Considering the threshold value of "Prob >F" are greater than 0.100, it can be observed that the significant factors are A,C, A2, C2 and AC for the quadratic model development. The regression model from Table 5 can be yielded as

$$\begin{aligned} Ra = {} & 7.2584E-0.005(Vc^2)-6.56(fz^2)+0.24750(ap^2)+5.73710E-0.003(Vc)(fz) \\ & +2.89855E-0.003(Vc)(ap)+0.50(fz)(ap)-0.079(Vc)+1.48940(fz) \\ & -1.71390(ap)\ +20.80671 \end{aligned} \tag{1}$$

where, cutting speed, V_c in m/min, feed rate, f_z in mm/tooth, depth of cut, a_p in mm and surface roughness, Ra in µm. According to the regression model as well as reference from Table 5, the cutting speed appeared to be more influential on surface roughness followed by the depth of cut and feed rate. On the other hand, the interaction effect between cutting speed and feed rate, feed rate and depth of cut are less significant.

Table 5: ANOVA table for response surface model for surface roughness analysis

Source	**Sum of Squre**	**DF**	**Mean Square**	**F-Value**	**Prob>F**
Model	0.046	9	5.091 x 10^{-003}	47.82	<0.0001
A: Cutting Speed (V$_c$)	7.938x10^{-003}	1	7.938x10^{-003}	74.56	<0.0001
B: Feed Rate (F$_z$)	3.125x10^{-004}	1	3.125x 10^{-004}	2.94	0.1304
C :Depth of Cut (a$_p$)	3.528x10^{-003}	1	3.528x10^{-003}	33.14	0.0007
A^2	0.031	1	0.031	295.21	<0.0001
B^2	7.078x10^{-005}	1	7.078x10^{-005}	0.66	0.4417
C^2	4.127x10^{-004}	1	4.127x10^{-004}	3.88	0.0897
AB	1.000x10^{-004}	1	1.000x10^{-004}	0.94	0.3648
AC	1.600x10^{-003}	1	1.600x10^{-003}	15.03	0.0061
BC	2.500x10^{-005}	1	2.500x10^{-005}	0.23	0.6428
Residual	7.453x10^{-004}	7	1.065x10^{-004}		
Lack of Fit	5.605x10^{-004}	3	1.868x10^{-004}	4.04	0.1053
Pure Error	1.848x10^{-004}	4	4.620x10^{-005}		
Cor Total	0.047	16			
R-Squared	0.9840				
Adj R-Squared	0.9634				
Adeq Precison	18.670				

Figure 3 shows the comparison result between the experimental and calculated value of surface roughness. The comparison between predicted value and experimental value demonstrated average errors around 4%. Such error considered still acceptable as general error for the uncertainty prediction in the model development should be below 10% [14]. This indicates the model was moderately fit within the predetermined parameter range.

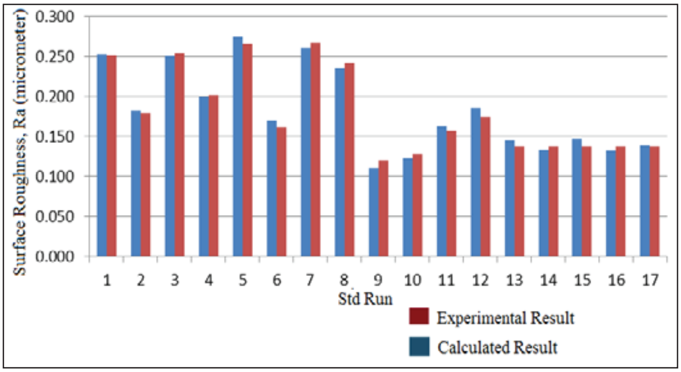

Figure 3: The result comparison between the experimental and calculated model value of surface roughness.

4.0 CONCLUSION

In this study, the prediction model when milling HTCS 150 was developed by RSM and Box-behnken experimental designs. 17 machining trials were conducted with three different variable parameters in dry cutting condition. The minimum surface roughness of 0.110 μm was achieved when the cutting speed, feed rate and depth of cut were set at 530.32 m/min, 0.31 mm/tooth and 0.1mm respectively. Analysis from ANOVA and Box-behnken experimental design demonstrated the development of prediction model which represented the correlation between cutting parameters (cutting speed, depth of cut and feed rate) and surface roughness. The dominant factors influence the surface roughness appeared to be cutting speed, followed by the depth of cut and feed rate. The percentage errors between predicted and experimental values recorded around 4%. This indicates that the development of prediction model in this study is feasible to predict the surface roughness value for end milling of HTCS-150.

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