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Optimization of cutting parameters to improve power consumption and material removal rate in high efficiency milling

This study is an attempt to obtain a suitable combination of the milling parameters to optimize electrical power and material removal rate (MRR) in slot milling of aluminium 6061. Machining parameters of radial depth of cut (RDOC), feedrate (Fr) and axial depth of cut (ADOC) are optimized using high efficiency milling cutting strategy. The results are analyzed through response surface and ANOVA for power and MRR. Response surface optimization shows that the optimized results are RDOC=48.8 mm, Fr=3000 mm/min, ADOC=6mm. The error between the predicted and the confirmation results is 4.3%.

Keywords: Optimization, high efficiency, carbon emission, energy.

1.0 Introduction

Recently, the total worldwide energy demand is increasing per year. The noticeable elevation in demand of new product contribute to the increased carbon emission in the world, accounting for about 33% of primary energy use and 38% of CO_2 emissions globally [1,2]. Therefore, there is a need to review and improve manufacturing process focused on energy efficient machining [3,4]. In manufacturing, CNC milling machine is widely being implemented for the variety of complex operations and consumed large amount of energy. Previous work focused on cutting parameters of radial depth of cut, axial depth of cut and feed rate on energy using conventional cutting strategy [5,6,7] which resulted lower MRR. In this work, high efficiency milling (HEM) strategy will be investigated to reduce the power consumption and improve MRR.

HEM is a milling technique for roughing that utilizes a lower radial depth of cut (RDOC) and a higher axial depth of cut (ADOC) [8]. This evenly distributes wear across the cutting edge, dissipates heat which can sustain less stress, and lowers the risk of tool failure. In modern machine shop online stated that, when compared HEM over conventional machining, the constant chip load cutting method can considerably boost roughing efficiency with tiny stepovers, higher feed rates, and deeper cut depths [9].

To optimize the energy and MRR, RSM method is used as a statistical tool to reduce the cost of expensive optimization process [10]. In addition, ANOVA is tested on the samples data, to evaluate the significant response of each cutting parameters [11].

2.0 Experimental test

Experiments are conducted using DMG Mori DMU 50 machining center. Workpiece sample of aluminium 6061 alloy workpieces were prepared with a dimension of 155 (l) × 140 (w) × 30 (t). YG-1 rough flat end mill was used in this study with following parameters:

- Tool diameter = 12.0 mm
- Material = HSS
- Number of flutes = 4
- Flute length = 26.0 mm
- Overall length = 83.0mm

Experimental set up and tooling are shown in Figs.1 and 2.

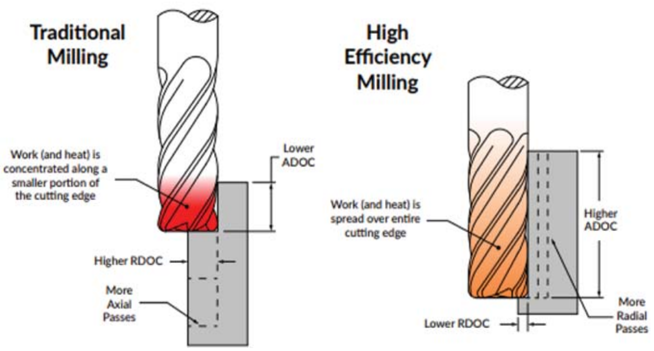

Fig.1: Traditional milling and high efficiency milling [8]

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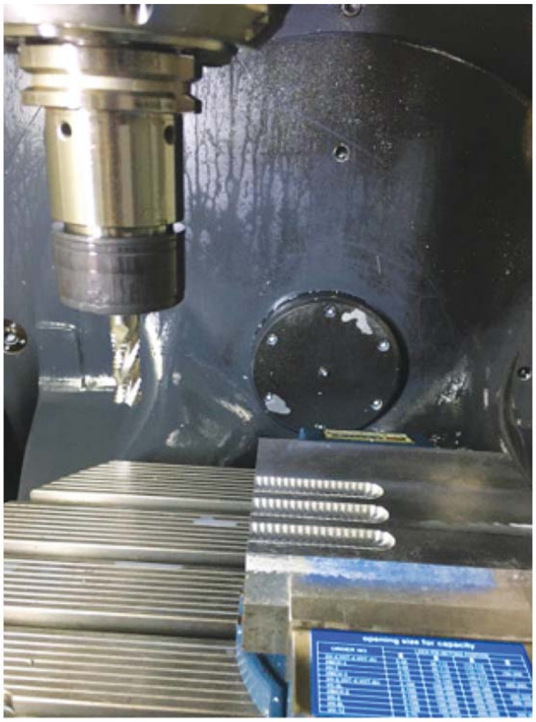
(a)


(b)


Fig.2: (a) Experimental setup, and (b) Rough flat end mill cutter

For each test cut in Table 1, a length of cut is set at L= 57.0 mm (Fig.3a) in Siemens shopmill CAM in open slot programme. Tool wear was measured at the beginning and end of the experiments. Due to small number of samples and less than 2 minutes machining time, wear problem can be neglected. High efficiency milling strategy with trochoidal cutting path (Fig.3b) is used in the experiment by using cutting parameters of feed rate: 1000~3000 mm/min, axial depth of cut (ADOC): 2~6 mm and radial depth of cut (RDOC): 20~ 50% of cutter diameter. Spindle speed is set at 2500 rpm during the testing period.

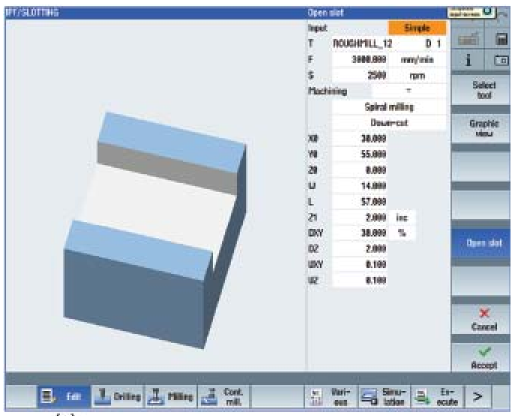
Total 20 numbers of experiments has been finalized according to RSM based on face centered design. Table 2 shows the design layout for experimentation. Power consumption is recorded using Celos energy analyzer and MRR is calculated by using equation (1):

$$MRR = F_r * RDOC * ADOC \quad \text{... (1)}$$

The results of the experimental tests have been evaluated to determine the total power consumption and calculation of material removal rate. From Fig.4 it is seen that power

TABLE 1: DOE OF CUTTING PARAMETERS FOR EXPERIMENTATION

	Feed rate (mm/min)	Radial depth of cut, RDOC (% of D_c)	Axial depth of cut, ADOC (mm)
1	1000	20	2
2	1000	50	6
3	1000	20	6
4	1000	35	4
5	1000	50	2
6	2000	35	4
7	2000	20	4
8	2000	35	4
9	2000	35	2
10	2000	35	4
11	2000	35	4
12	2000	35	4
13	2000	35	6
14	2000	35	4
15	2000	50	4
16	3000	50	6
17	3000	20	6
18	3000	20	2
19	3000	35	4
20	3000	50	2



(a)

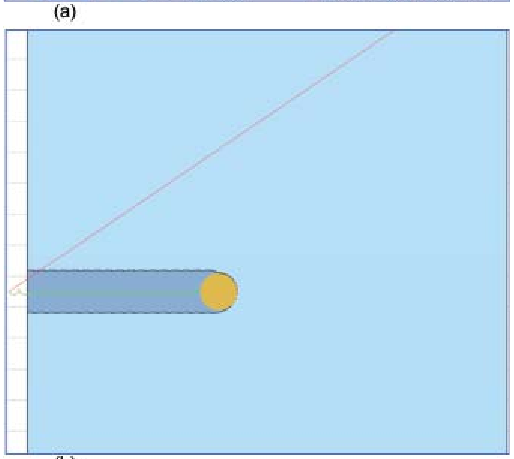

(b)

Fig.3: (a) Shopmill interface for slot process (b) Trochoidal toolpath

Table 2: Result of test

	Feed rate (mm/min)	Radial depth of cut, RDOC (% of D_c)	Axial depth of cut, ADOC (mm)	Power Consumption, kW	Material removal rate (mm^3/s)
1	1000	20	2	3227	80
2	1000	50	6	1888	240
3	1000	20	6	3438	280
4	1000	35	4	1812	200
5	1000	50	2	1852	600
6	2000	35	4	1174	320
7	2000	20	4	2075	280
8	2000	35	4	1180	560
9	2000	35	2	1151	560
10	2000	35	4	1253	560
11	2000	35	4	1152	560
12	2000	35	4	1164	560
13	2000	35	6	1170	560
14	2000	35	4	1334	840
15	2000	50	4	1396	800
16	3000	50	6	998	240
17	3000	20	6	1558	720
18	3000	20	2	1458	840
19	3000	35	4	947	600
20	3000	50	2	881	1800

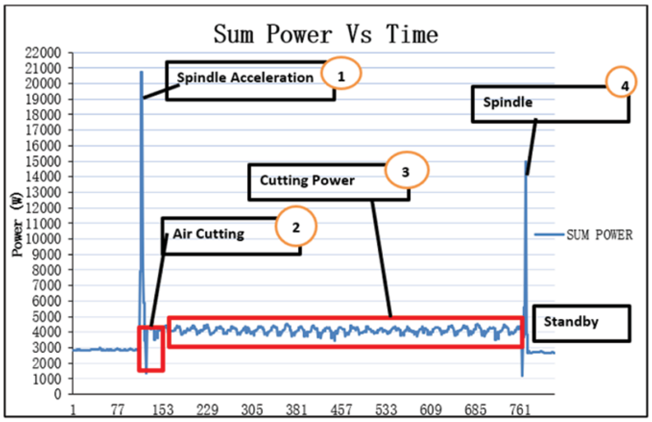


Fig.4: Power profile in slotting

consumption varied during machining process and remained stabilized at stage 3 of cutting power. Power consumption measurement consists of individual axes (X,Y and Z) at stage 3 were considered for data analysis. Sharp power consumption spikes at stages 1 and 4 can be explained by the accelerating and decelerating of the spindle during the cutting.

3. Analysis for power consumption

RSM technique is used to determine the most influencing parameter for power consumption and MRR. Design of the experiments and analysis of experimental results has been done using CCD and face center in Minitab 2019 software. Detailed statistics on power are obtained from the ANOVA summary in Table 3. The p-value for all the parameters are less than 0.05 at 95% confidence interval. The developed mathematical model to predict power consumption is obtained by Equation (2).

Power (kW) = 7150 - 1.918 feed rate (mm/min) - 1677 radial depth of cut (mm) + 53 axial depth of cut (mm) + 0.000208 feed rate (mm/min)* feed rate (mm/min) + 138.3 radial depth of cut (mm)* radial depth of cut (mm) + 5.7 axial depth of cut (mm)* axial depth of cut (mm) + 0.1401 feed rate (mm/min) *radial depth of cut (mm) - 0.0148 feed rate (mm/min) *axial depth of cut (mm) - 10.6 radial depth of cut (mm)*axial depth of cut (mm) (2)

3.1 Main effect plots for power

Fig.5 is generated from Minitab and depicts the effect of each parameter on power. It observed from the graph that as feed rate, radial depth of cut and axial depth of cut increase, power is decreased. Feed rate and radial depth of cut has a predominant role on power.

3.2 Response surface plots and contour plots for power

The response surface methodology (RSM) generated 3D surface plot of power consumption. The 3D surface plot is as shown in Fig.6 This graph contains interaction of the cutting parameters effect on the power. Based on Fig.6, it is observed each of the three cutting parameters give their own impact on the electrical energy. However, the feed rate and radial depth

Table 3: Analysis of variance (ANOVA) of power consumption

Source	DOF	Adj SS	Adj MS	F	P
Model	9	8002785	889198	70.11	0.00000008
Linear	3	5600507	1866836	147.19	0.00000001
Feed Rate	1	3073594	3073594	242.34	0.00000002
Radial depth of cut	1	2503001	2503001	197.35	0.00000007
Axial Depth of Cut	1	23912	23912	1.89	0.19973091
Square	3	1874571	624857	49.27	0.00000269
Feed rate *feed rate	1	119549	119549	9.43	0.01183795
Radial depth of cut *radial depth of cut	1	551936	551936	43.52	0.00006103
Axial depth of cut (mm)*axial depth of cut (mm)	1	1455	1455	0.11	0.74185991
2-Way interaction	3	527707	175902	13.87	0.00067711
Feed rate (RPM)*radial depth of cut (mm)	1	509041	509041	40.14	0.00008512
Feed rate (RPM)*axial depth of cut (mm)	1	6962	6962	0.55	0.47579815
Radial depth of cut (mm)*axial depth of cut (mm)	1	11704	11704	0.92	0.35938290
Error	10	126832	12683		
Lack-of-fit	5	124709	24942	58.75	0.00019337
Pure error	5	2123	425		
Total	19	8129617			
R^2= 98.44%	R^2 (pred)= 87.20%		R^2(adj)=97.04%		

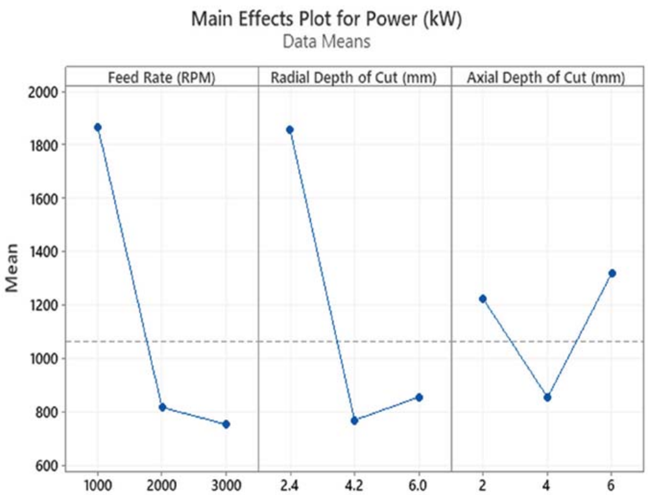


Fig.5: Main effect plots of power

of cut are given out biggest impact on this study.

Fig.7 is the contour plot of power consumption with the variables of axial depth of cut, radial depth of cut and feed rate at a constant spindle speed of 2500 RPM. The plot shows the maximum value of power which is more than 2500 kW. Maximum value of power consumption of 2500 kW at the maximum value of radial depth of cut and feed rate (Fig.3.3a)

4.0 Analysis for MRR

The data in Table 4 shows ANOVA analysis for MRR. The p-value for all the parameters are less than 0.05 at 95% confidence interval. The p-values of square and interaction are more than 0.05 and shows insignificant relation for MRR.

The optimization equation for MRR is formulated using

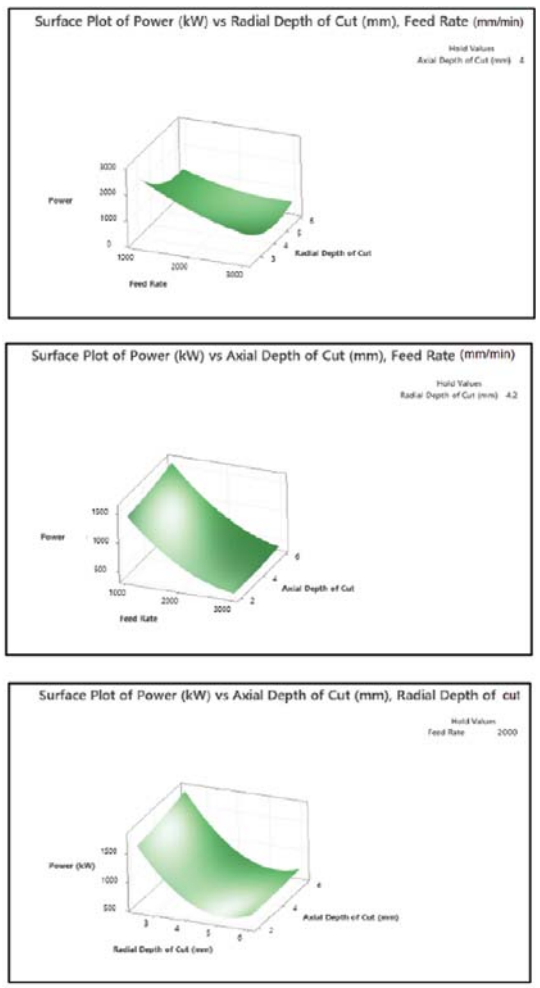


Fig.6: Surface plots on power consumption

TABLE 4: ANALYSIS OF VARIANCE (ANOVA) OF MRR

Source	DOF	Adj SS	Adj MS	F	P
Model	9	17577.8	1953.09	97.65	0.000
Linear	3	14888.9	4962.96	248.15	0.000
Feed rate	1	5444.4	5444.44	272.22	0.000
Radial depth of cut	1	4000.0	4000.00	200.00	0.000
Axial depth of Cut	1	5444.4	5444.44	272.22	0.000
Square	3	0.0	0.00	0.00	1.000
Feed rate *feed rate	1	0.0	0.00	0.00	1.000
Radial depth of cut *radial depth of cut	1	0.0	0.00	0.00	1.000
Axial depth of cut (mm)*axial depth of cut (mm)	1	0.0	0.00	0.00	1.000
2-Way interaction	3	2688.9	896.30	44.81	0.000
Feed rate (RPM)*radial depth of cut (mm)	1	800.0	800.00	40.00	0.000
Feed rate (RPM)*axial depth of cut (mm)	1	1088.9	1088.89	54.44	0.000
Radial depth of cut (mm)*axial depth of cut (mm)	1	800.0	800.00	40.00	0.000
Error	10	200.0	20.00		
Lack-of-fit	5	200.0	40.00	*	*
Pure error	5	0.0	0.00		
Total	19	17777.8			

R^2= 98.88% R^2 (pred)= 73.7% R^2(adj)=97.86%

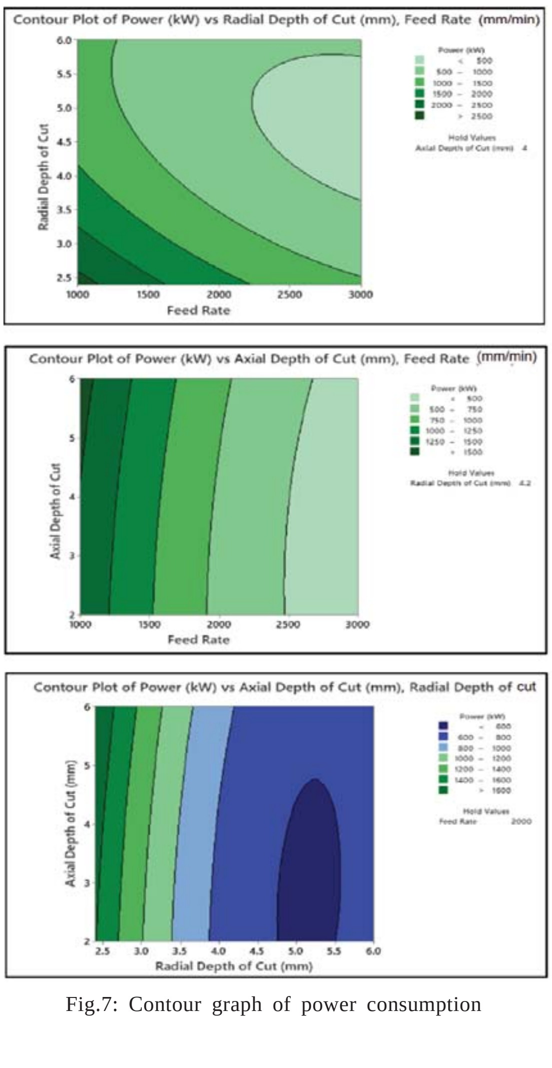


Fig.7: Contour graph of power consumption

RSM as in Equation 3:

Material removal rate = 46.7 - 0.0233 feed rate - 1.333 radial depth of cut- 11.67 axial depth of cut + 0.000000 feed rate *feed rate- 0.0000 radial depth of cut *radial depth of cut+ 0.000 axial depth of cut *axial depth of cut+ 0.000667 feed rate *radial depth of cut + 0.005833 feed rate *axial depth of cut + 0.3333 radial depth of cut *axial depth of cut (3)

4.1 MAIN EFFECT PLOTS FOR MRR

Fig.8 shows factorial plots for Material removal rate. This figure contains three-line graph. For the mean of material removal vs feed rate, radial depth of cut, and axial depth of cut the mean of material removal rate against these parameters increase drastically. But from these parameters we can see that

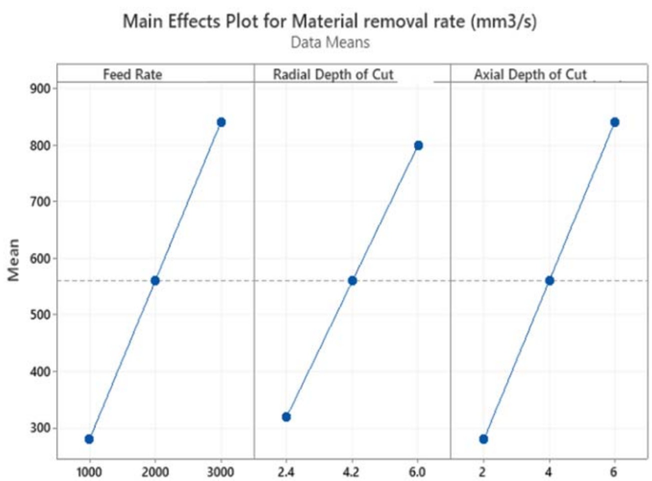


Fig.8: Main effects plot for MRR

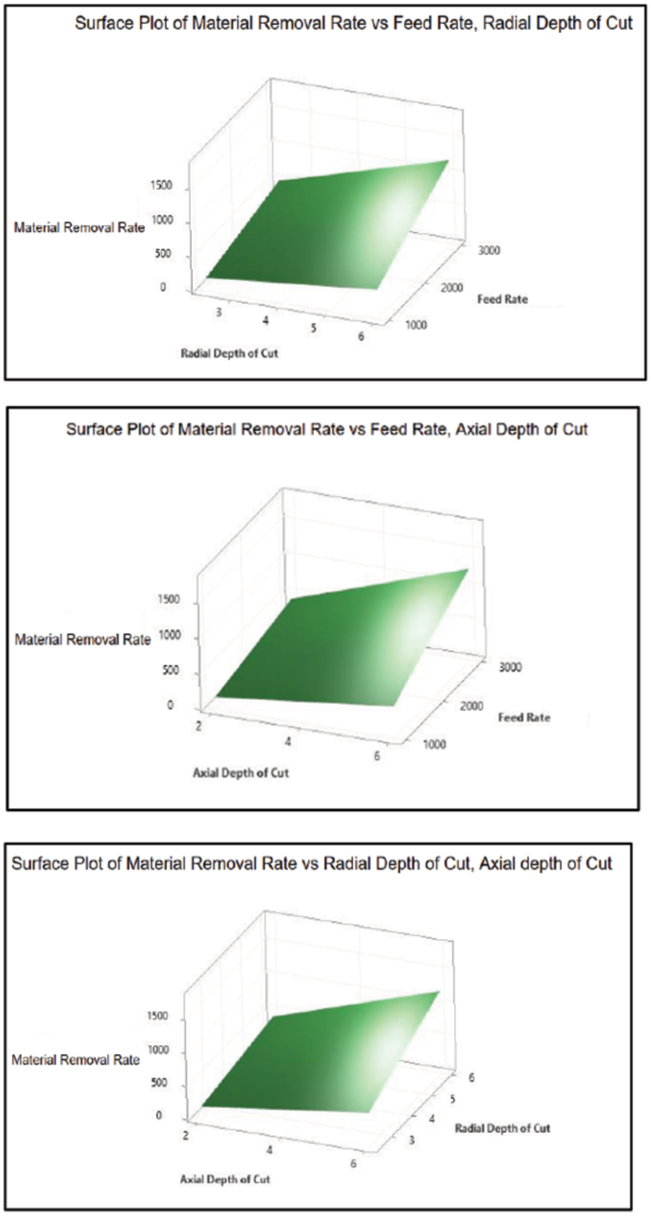


Fig.9: Surface plots of MRR

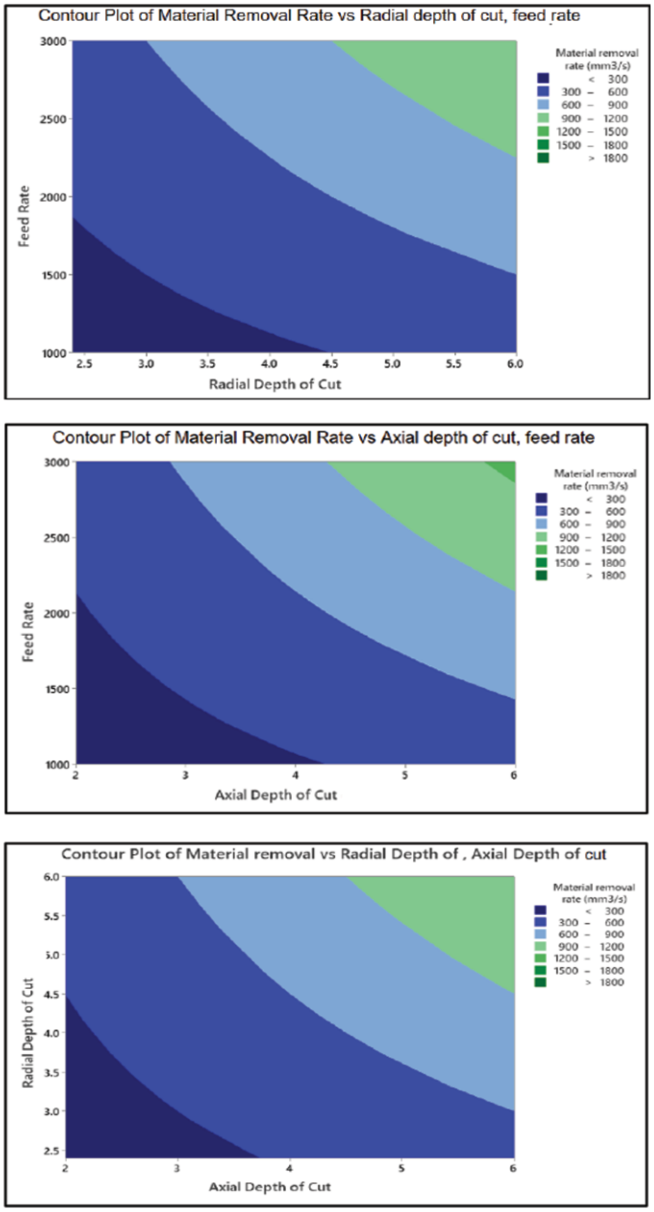


Fig.10: Contour plot for MRR

feed rate and axial depth of cut are giving out the highest mean of material removal rate. This shows the feed rate and axial depth of cut is most influencing parameter in material removal rate.

4.2 Response surface plots and contour plots for power

The three-dimensional figures above shown the relationship of the cutting parameters on the material removal rate. Based on Fig.9, it is observed that MRR increased with the feed rate, axial depth of cut and radial depth of cut. To observe clearly on the impact of the cutting parameters on MRR, contour plot is shown in Fig.10. It shows that the maximum value of MRR > 1800 mm3/s is at Fig.10(b) which are axial depth and feed rate.

5.0 Optimze solution for power consumption and MRR

The parameters are optimized using the Minitab response optimizer. Response optimizer is used to identify the combination of input parameters settings that optimize power consumption. Fig.11 shows that optimal setting for power consumption in rough slotting operation are feed rate at 3000 mm/min, radial depth of cut 5.76mm (48% of D_c) and axial depth of cut 6 mm. The confirmation experiment validates the result and produce an error of 4.3%. The maximum value of MRR is 141.7 mm^3/s and minimum value of power is 983.3 kW at optimal cutting parameters.

The confirmation experiments were performed to facilitate the verification of the obtained optimal slotting parameters of

TABLE 5: CONFIRMATION TEST FOR MINIMUM POWER CONSUMPTION AND MAXIMUM MRR

Optimal cutting parameter			Power Consumption, kW				
Fr, mm/min	RDOC, mm	ADOC, mm	Sample# 1	Sample# 2	Sample#3	Average	Error
3000	5.76	6	940.3	945.7	942.8	942.9	4.3 %

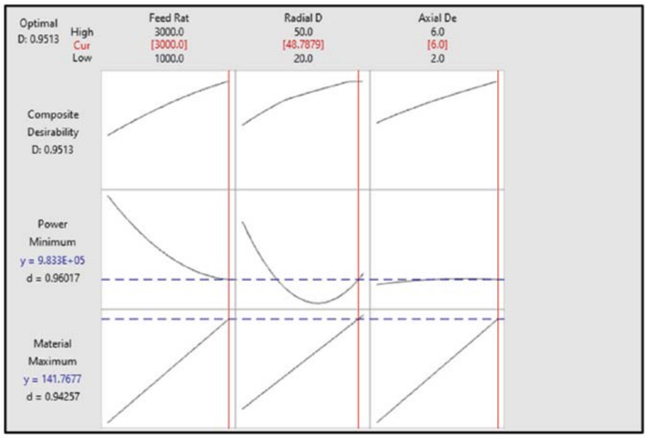


Fig.11: Response optimization plot

Fr= 3000 m/min, RDOC=5.76 mm and ADOC = 6mm for minimum energy consumption and maximum MRR. The result of the confirmation runs for the power consumption in kW are listed in Table 5. The error between the predicted and the confirmation results is 4.3%.

6.0 Conclusions

This study presented RSM method to determine optimal values of machining parameters leading to minimum power consumption and maximum MRR. Further the confirmation experiments are carried out to validate that the developed predictive and optimization models match with the experimental results for slotting operation. The following conclusions are drawn from the study:

- ANOVA reveal that the developed mathematical model using RSM allows prediction of power consumption within 4.2% error.
- All parameters contribute to power consumption and MRR, but feed rate shows more significant impact on the output.
- The optimal machining parameters for minimum power consumption and maximum MRR are feed rate at 3000 mm/min, radial depth of cut 5.76mm (48% of D_c) and axial depth of cut 6 mm.

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