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INVESTIGATION ON THE EFFECT OF PROCESS PARAMETERS ON HIGH-SPEED CNC MILLING OF CAST IRON BILLETS USING BOX–BEHNKEN RSM

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ABSTRACT

This investigative research paper presents simultaneous optimization of input process parameters of high speed CNC milling process for grey cast iron billets using Box-Behnken's response surface methodology. Considerably better material removal rate (MRR) was also achieved while maintaining the surface roughness requirements in job order type precision components manufacturing SMEs. The experiments designed and carried out on cast iron billet, one of the important high hardness materials chosen for analysis due to high strength, hardness, porous nature of material. This study aims at minimization of average surface roughness (R_a) and maximization of material removal rate (MRR) which is vital but contradicting characteristics of any machining process, also for control of parameters and prediction response requirements of high-speed CNC milling process. This research explains the effect of input parameters of high- speed CNC milling process using L27 orthogonal array of design of experiments method covering all possible cases of cutting tool using full coolant open condition. The effect of cutting parameters on R_a was evaluated and optimum cutting conditions for maximizing the MRR were determined and presented. The results show that MRR could be maximized by optimum input parameters while keeping R_a less than 0.25 Microns.

Key Words: High Speed Milling, RSM, Surface Roughness, Material Removal Rate, Parameter Optimization.

I INTRODUCTION

High speed milling of cast iron is studied in this research paper that offers few challenges which needs to be addressed by the academia and industry to enhance the optimality of the process. The cast irons generally made for specific structural requirements. While machining it offers greater resistance due to high hardness value and better machinability due to porous nature of microstructure. The hardness is a key property in any form of cast iron also it is vital when machining, since the force acting on the job during cutting, vibration induced are now a days better controlled by CNC machines using shock controllers. The effects of tool wear rate have been major area of research by the academia on material removal rate and surface roughness requirements. The intention behind the study is to find a suitable set of parameters to perform end milling to minimize the surface roughness and to increase the material removal rate, which would be the requirement of SME's. Hence the input process parameters spindle speed, feed rate, depth of cut and type of tool tip were considered with three levels of variations in DOE operators.

II LITERATURE REVIEW

High speed machining has come to the fore in last decade and production houses have started to re-establish the machining into either a horizontal or a vertical machining center in last few years, which in turn promoted research and development activities. The recent research in this area by Arif et al (2010), developed mechanistic model similar to dynamic model by Ramón Quiza Sardinas et al (2006), and a statistical artificial intelligence models and also two phased optimization method by Yih-Fong and Fu Chen Chen (2005) are some examples of cutting force modeling and optimization approach using parameter design. Zolfaghariy and Liang (2002) addressed dynamic analysis of chip formation, cutting temperatures, tool stresses, and cutting forces. Many researches inferred that the effect of cutting forces developed in milling process can be directly used to estimate process performances of tool wear, cutting time, surface finish, etc. Studies conducted by Kadirgama.et.al (2008) showed peak cutting force component in the feed direction is more sensitive to the tool wear indicator of the flank wear. The importance of tool wear monitoring and optimization brought out by Mike et al 1999, Ning Fang et al (2007). Arif et al (2010) is cutting force measurement is one of the most common method for online tool wear monitoring. The recent research by John Kechagias et al (2011) investigated tool wear in high-speed machining process with new and worn-out milling cutters. The cutting force by the tool is directly affecting the tool life but the case study conducted by us in SMEs of CNC class were able to *survive to the* expectations of surface roughness. The material removal rate is another criterion which summerises the productivity of the process. The CVD coated end milling inserts are not affecting the surface finish levels up to 90 minutes of operation. Hence it is to be noted that during this period surface roughness is directly influenced only by cutting parameters. Proper selection of cutting parameters would result in high quality parts and greater savings in production time and production cost within first 90 minutes of operation.

III EXPERIMENTAL STUDY

The responses surface roughness (R_a) and material removal rate (MRR) in end- milling of cast iron with different end-milling cutters analyzed based on input parameters. The experiments were conducted based on the Box-Behnken response surface methodology (RSM) for four-factor (Spindle speed, feed rate, depth of cut, and type of cutting tool) three level orthogonal experiments. An orthogonal array of L27 used to obtain the objective function for optimization of initial basic feasible results with an analysis of variance (ANOVA). The optimal cutting parameters for minimal surface roughness and maximum possible Material removal rate as per the specifications of the machine. The parameter selection is based on case study at small and medium type enterprises around

Coimbatore for high-Speed machining job order type production houses for precision parts. Requisite quadratic equations for surface roughness and Material removal rate were established using ANOVA and statistical correlation analysis by design expert software gives a non- linear model best fits to the variation of cutting parameters and the quadratic model best describes the variation of surface roughness and Material removal rate. A response surface is developed to predict material removal rate (volume/sec) and set of cutting parameters for the optimum roughness is selected for a given range of material removal rate until the tool wear reaches 0.6µm, by which the surface roughness is not affected.

Table 1. Parameters and their Range

Factor	Spindle speed(A) rpm	Feed rate (B) mm/s/teeth	Depth of cut (C)mm	Insert type (D)
Range	3000 - 12000 rpm	600 – 1800 mm/s	0.3- 0.9mm	Bull, Flat and Ball of 12mm diameter

The average surface roughness (R_a) measured after machining, in feed direction using Mitutoyo roughness measuring instrument (SJ-210 Series). The measured values and parameters are as listed and studied include the average (R_a) and the material removal rate.

The Experiments based on designed L27 array were conducted on a standardized vertical machining center (DECKEL MAHO 64V Linear, 4 axis milling center) with predefined parameter ranges. The tool used in these experiments is CVD coated tungsten carbide end milling cutters with 27 different combinations of input parameters under full coolant supply at 3.5 bar with a flow rate of 120lpm. The effects of the other process parameters on the surface roughness like tool wear rate, built up edge size, chip curl radius and chip thickness are also accounted in determining the Surface roughness but observed that cutting tool wear not affecting responses up to 90 minutes of cutter operation. The requisite response values were also measured, R_a is measured with a Mitutoyo-J210 surface gauge and the stop watch study is done for computing Material removal rate.

Table 2. L27 Orthogonal array - Cast Iron

Speed (rpm)	Feed Rate (mm/s)	Depth of cut (mm)	Insert type	Ra ($mmx10^{-3}$)		MRR (mm^3/Sec)	
				Predicted	Measured	Predicted	Measured
3000	1800	0.6	0	2.83	3.42	109.29	538.92
3000	1200	0.9	1	2.67	3.35	239.52	812.03
3000	1200	0.3	0	2.63	2.61	245.399	243.57
3000	600	0.6	1	2.13	2.87	353.982	497.92
7500	1800	0.9	0	3.42	3.07	247.934	779.22
7500	1800	0.3	-1	2.32	2.58	151.515	242.58
7500	1200	0.6	1	3.31	3.12	666.667	523.25
7500	600	0.9	-1	4.36	6.43	294.118	915.25
7500	600	0.3	0	1.18	1.29	110.497	206.89
12000	1800	0.6	0	0.28	0.5	175.439	679.24
12000	1200	0.9	-1	0.77	0.6	779.221	1285.71
12000	1200	0.3	1	1.31	1.81	1935.48	219.78
12000	600	0.6	0	0.84	0.93	1764.71	371.13
3000	1200	0.6	1	2.53	3.03	754.717	516.49
7500	1800	0.6	0	0.63	0.59	245.399	382.57
7500	1200	0.9	-1	0.24	0.66	123.457	572.03
7500	1200	0.3	0	0.31	0.42	86.5801	187.89
7500	600	0.6	-1	0.14	0.38	1857.14	374.22
12000	1200	0.6	0	0.38	0.78	1052.63	390.45
3000	1200	0.6	0	0.95	1.74	421.053	435.83
7500	1800	0.6	0	0.63	1.01	245.399	400.45
7500	1200	0.9	0	1.03	1.14	245.399	609.48
7500	1200	0.3	0	1.63	1.65	245.399	215.57
7500	600	0.6	-1	0.66	0.95	606.061	397.79
12000	1200	0.6	1	0.98	1.35	1052.63	416.18
12000	1200	0.9	0	0.62	0.72	322.581	583.15
7500	1800	0.6	0	0.87	1.08	209.059	378.15

ANOVA FOR INPUT PARAMETERS ON RESPONSES

The Model F-value of 17.27 implies the model is significant. There is only a 0.01% chance that Model F-Value is large could occur due to noise. Values of “Prob > F” less than 0.0500 indicates model terms are significant. In this case A, B, D, AD, BC, BD, D^2 are significant model terms. It has been pointed out that an increase in tool life would lead to reduction in production cost, whereas increase in productivity would lead to reduction in production cost.

ANOVA for Surface Roughness (R_a) and MRR

By natural understanding of the process it is to be noted that gain in productivity is possible by increasing metal removal but contradicts the surface roughness. Hence it is to develop adequate models for end-milling process to achieve the benefits of productivity and quality simultaneously. Though the objectives for roughing and finish machining are different but volume of material to be removed is still remains one of the output targets in rough and finish end-milling. A good surface finish and dimensional accuracy are the vital factors in finish end-milling.

Prediction equation for R_a

Minimize Ra = -3.76954+3.01173E-004 A+5.89028E-003B+9.08611C-1.86000D-9.07407E-008AB-3.61111E-004 BC +1.03333E-004AD+1.58333E-003BC +4.12500E-004BD+0.62500CD-1.20165E-008A^2 -2.32870E-006B^2-7.10648C^2 -1.40458D^2 ..(1)

Prediction equation of MRR

Maximize MRR = +1132.01925-0.10631A-1.14282B-774.74782C+654.57553D +3.63382E-005AB+0.14576A C -0.017465AD-0.92297BC-0.38063BD+23.15794CD +1.15975E-006A^2+5.42920E -004B^2+1289.64738C^2+239.42229D^2 ....(2)

III DISCUSSION ON THE RESPONSES

The range of inputs and the responses were analyzed using the graphs in (figures1, 2, & 3) which shows the values of R_a varies geometrically with respect to change in input parameters but it is very much complex to suggest that a particular factor is more dominant than other. But has a definite relationship as expressed by the eqn (2) above. Thus it is to be noted that a feasible solution is wide ranged inside the confirmed domain surrounded by the parameter range space. Now a machinist has to decide based on the graphs or standerdised optimum charts for a required level of (R_a) (say 0.20-0.40 micron) finish. Generally by considering the graph it is recommended to choose higher depth of cut (D_c) say 0.8 -0.85 of Max value of the parameter range instead of choosing mid value recommended by manufacturer to get the better values of MRR. When the speed of the spindle and feed rate may also be taken above the mid value to get the desired levels of R_a and MRR.

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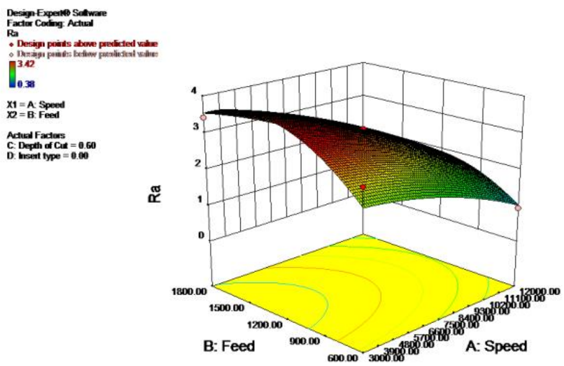


Fig.1 R_a Vs Speed and feed rate

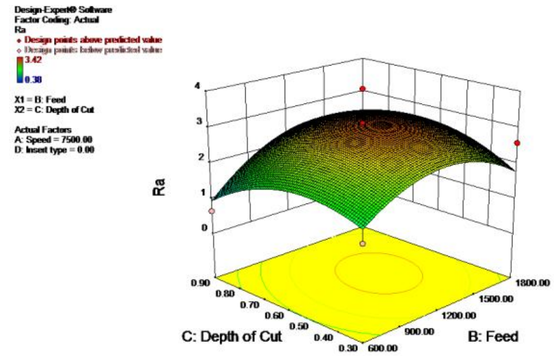


Fig.2. R_a Vs Feed and Depth of cut

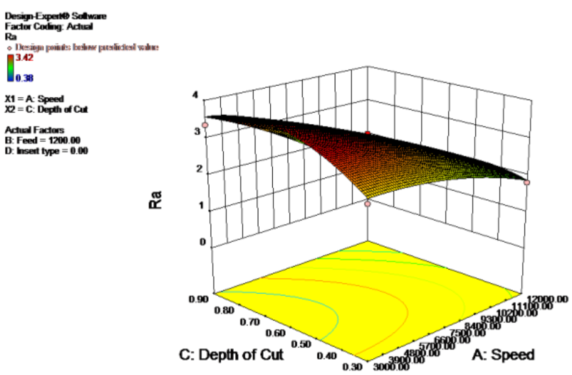


Fig.3. R_a Vs Depth of cut and Speed

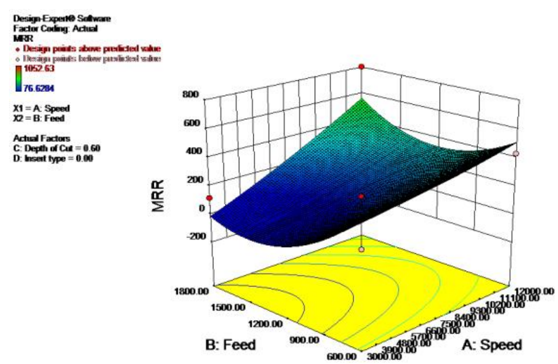


Fig.4. MRR Vs Speed and Depth of cut

The graphs 4 to 6 indicates the variation of MRR with respect to the input parameters in the 3 dimentinal mode to accommodate comparision of more than one factor at a time and draws a conclusive non mid point optimum for the different input parameter. Thus it could be infered such that the mid point strategy of these SME's can be replaced with our methods of deciding the optimum parameter values to improve their performance without affecting the quality ie. surface roughness requirements. Similarly from the graphical illustrations the the broadly used mid point selection of the input parameters were proved non optimum but generally serves the purpose by increased spending of time and effort.

Thus the mid point strategy of choosing the input parameters and thump rule based selection procedure can be restructed with scientificaly proved and easy method provided by this study. The detailed analysis reported using the graphs drawn shows that the variation of the surface roughness (Ra) and MRR is more of a linear in nature those graphs are not presented.

The surface roughness values against each of the parameter set is plotted for the spindle speed (A) and feed rate (B), the high and low values are occuring on all three levels of the parameter but independant and have cumulative effect in nature. The graphs drawn out of the results are showing the occurrences of the nonlinear values of highs and lows of the material removal rate for the given input values. The analysis shows the values of R_a and MRR that are dependent of the input parameters and relatively complex in suggesting a particular factor is more dominating. The general idea that can be derived is that the input parameters are equally vital and has a cumulative effect on the responses. Thus the mid point strategy of these SMEs can be replaced with our method by adopting the optimum parameter values to improve their performance without affecting the quality ie. surface roughness requirements. Similarly from graphical illustrations the broadly used mid point selection of the input parameters were proved non optimum but generally serves the purpose resulting in increased time of operation and effort. Thus the mid point strategy of choosing the input parameters and thumb rule based selection procedure can be restructured with scientifically proved and easy method of this study.

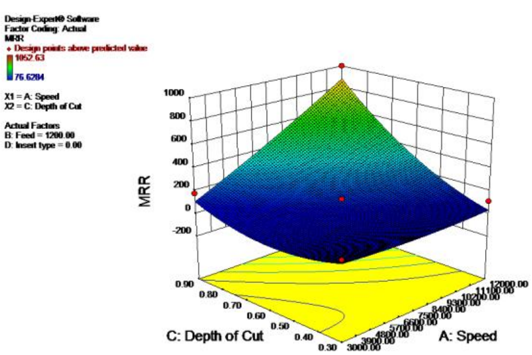


Fig.5. MRR Vs Feed rate and Depth of cut

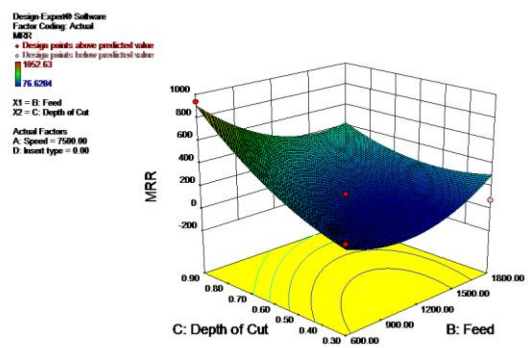


Fig.6. MRR Vs Speed and Feed rate

The higher depth of cut (0.87mm) and feed rate (624mm/s) would yield better material removal rate with relatively good surface roughness values using a spindle speed (11998 rpm) more than the mid value, which improves productivity. The results shows there is more concentration around the (12 out of 27 iterative values) band of 0.20 – 0.40 microns finish in all the levels of speed. Hence it is to be noted that the mid point values may yield good results but not the optimum results. By adopting this technique the SME's are assured of the optimum performance in the utilisation of the resources for production thereby improving the productivity of the firm.

IV OPTIMIZATION USING RESPONSE SURFACE METHOD

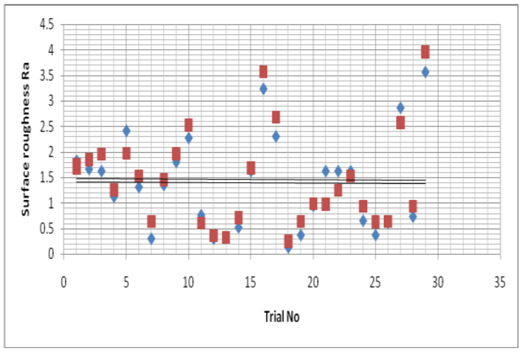
The above analysis shows the input factors are equally vital and needs to be given equal importance as this work is a 4 factor three level factorial technique was employed for the development of design matrix to conduct the required experiments. Surface quality of machined part is the value of surface roughness or the waviness, it is clear that these factors of cutting speed, feed, and depth of cut and type of milling cutter influences the responses in line to the equations (1) and (2) as suggested by the response surface methodology. The criterion for optimization the R_a has to be minimized and MRR is to be maximized but are contradictory in nature, while getting a trade off function between these two responses the priority is fixed as that R_a minimization is given first priority. Since the study mainly focuses on the precision component manufacturing to reduce value of R_a and enhance MRR. Table 5 gives the optimization run by the statistical correlation tool based on Design Expert version 6.3, the typical values of the R_a and MRR by response surface method prediction.

Table.3 Optimization Table for Box-Behnken RSM

Sl no	Speed	Feed rate	Depth of cut	Insert type	Ra	MRR
1.	6688	604	0.71	1	0.27	1092.17
2.	11417	646	0.90	-1	0.91	1100.69
3.	11804	896	0.89	-1	0.92	1076.51
4.	11814	841	0.89	-1	0.97	1066.58
5.	11545	644	0.89	-1	0.12	1077.61
6.	11996	1728	0.90	-1	0.14	1054.06
7.	10940	613	0.89	0	0.08	1066.32
8.	10641	992	0.88	1	0.04	1125.75
9.	7965	609	0.86	1	0.08	1324.55
10.	11344	947	0.90	1	0.25	1244.29
11.	6984	624	0.76	1	0.34	1103.99
12.	11458	1767	0.89	-1	0.04	1069.13
13.	5429	606	0.89	1	0.17	1317.41
14.	11402	1793	0.75	-1	0.17	1098.78
15.	11755	618	0.88	-1	0.68	1071.73
16.	11948	847	0.90	1	0.01	1223.07
17.	11962	890	0.87	1	0.36	1278.85
18.	6856	627	0.72	1	0.36	1062.7
19.	11399	663	0.88	-1	1.13	1072.53
20.	11072	619	0.88	-1	1.05	1055.82
21.	7107	636	0.78	1	0.24	1148.6
22.	11534	715	0.90	-1	0.97	1087.05
23.	11781	107	0.90	1	0.34	1056.38
24.	11569	768	0.89	0	0.36	1094.4
25.	11788	1694	0.76	-1	0.12	1058.13
26.	6563	601	0.69	1	0.33	1052.75

27.	11998	771	0.87	-1	1.09	1052.86
28.	11340	1743	0.81	-1	0.22	1108.78
29.	11673	655	0.85	0	0.26	1084.9
30.	11706	623	0.81	0	0.27	1066.16
31.	11634	787	0.90	-1	1.05	1090.94
32.	11989	909	0.90	-1	0.58	1057.1
33.	11614	646	0.88	0	0.14	1122.97
34.	7468	630	0.73	1	0.31	1076.89
35.	9642	610	0.79	1	0.15	1155.74
36.	11860	1800	0.61	-1	0.01	1026.42
37.	12000	1767	0.90	1	0.60	955.637
38.	11999	1799	0.49	-1	0.12	951.048
39.	11999	1774	0.90	1	0.54	948.301
40.	11999	1643	0.90	1	0.25	945.514
41.	11999	1800	0.47	-1	0.11	941.756
42.	11967	1800	0.38	-1	0.08	903.686
43.	11999	1800	0.34	-1	0.02	897.59
44.	11998	1796	0.30	-1	0.03	886.96
45.	3000	600	0.44	1	0.30	878.422
46.	3781	600	0.47	1	0.38	869.135
47.	3000	631	0.43	1	0.37	840.96
48.	3565	600	0.31	1	0.26	838.911
49.	11999	1800	0.30	-1	0.17	838.852
50.	11999	1797	0.30	-1	0.45	771.503
51.	8440	1800	0.30	-1	0.66	736.149
52.	3000	978	0.30	1	0.60	551.489
53.	11999	1800	0.50	1	0.59	508.514
54.	5259	1800	0.30	-1	1.29	621.064
55.	9822	1799	0.30	1	0.43	403.164

This is an attempt to avoid the human intervention in optimization problem and decision making process of high speed milling process parameter selection. This study assumes equal priority weightage to both the responses unlike other related research papers (Kadirgama et al 2008). The studies reported in literature mostly concentrate on thecentre line average roughness R_a value for surface quality.



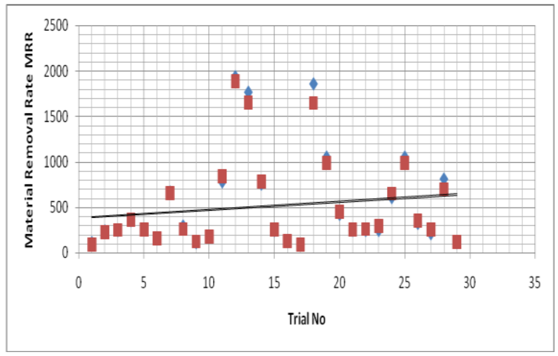


Fig.7 Comparison of Results (Ra) **Fig.8. Comparison of Results (MRR)**

This research paper tried to give the user with an advantage to choose the appropriate requirement either R_a or MRR for a particular operation. Based on case study and tabulated results on quality (R_a) and productivity (MRR) shows the values of MRR is fluctuating between the 2200 mm^3 to 2400 mm^3 even without disturbing prime objective to get the lower R_a.

Predicted values of Box-Behnken method is compared with the actual values of surface roughness and material removal rate during confirmation trials. With reference to the graphs (fig 7,8) shows the prediction is closer to measured values of the responses to variations of input process parameters. The blue diamond shapes (measured) and the maroon squares (predicted) of the following figures, confirms the tests planned and the prediction method followed are found matching to the requirements of the SMEs for prediction and optimization of the surface roughness parameters and material removal rate optimization. Based on trial runs conducted on the same machine, productivity of the process is also improved to an extent of 8.35% during the high precision component machining of high speed CNC machines.

V CONCLUSION

The high speed CNC machining is a vital and costly maching process and a higher depth of cut (0.87.mm) and feed rate (624mm/s) would yield better material removal rate with good surface roughness values using a spindle speed (11998 rpm) more than the mid value, which improves productivity. The results shows there is more concentration around the band of 0.26 – 0.25 microns finish in the levels of Spindle speed as 11998rpm at the Feed rate of 624mm/min and between 0.66mm to 0.87mm of Depth of cut . Hence it is to be noted that the mid point values may yield good results but not the optimum results. By adopting this technique the SME's are assured of the optimum performance in the utilisation of the resources for production thereby improving the productivity of the firm. Efforts are being made to simulate and verify the same with very high speed CNC machining and also to incorporate more materials, there by enable the SMEs better tool for machining optimization solutions.

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