International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 9 Issue 7 ǁ 2021 ǁ PP. 28-34

Process Parameters Optimization on CNC Engraving Machine by Using Response Surface Methodology (RSM)

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Abstract
In this report, a comprehensive and in-depth review on optimization of different process parameters were carried out using different optimization tools. Milling machine is superior to other machine as regards accuracy and better surface finish. Every manufacturing industry is trying to achieve the high-quality products in a very short period of time with less input. In engraving machine, there are many process parameters like spindle speed, feed rate, depth of cut, coolant, tool geometry etc. which affected on required quality parameters. So, selections of process parameters are the important for any quality parameters. But, selected process parameters for required quality parameters are not run at optimal condition. So, process parameters are required to be optimizing for required quality parameters. Taguchi methodology is widely used for single optimization. But, sometime multi objective quality parameters are required to be optimized. For multi objective optimization Utility concept, grey relation analysis, PCA etc. are widely used. ANOVA analysis is also used to determine which parameters are the most significant effect on the selected quality parameters.
Keywords *– surface finish, orthogonal array, ANOVA, SN ratio, Optimization of CNC, Principal components analysis, surface roughness, MRR, CNC Engraving, etc.*

Date of Submission: 06-07-2021 Date of acceptance: 19-07-2021

I. INTRODUCTION

CNC engraving is type of milling machine. CNC milling is one of the most commonly used in industry and machine shops today for machining parts to precise sizes and shapes. Among different types of milling processes, end milling is one of the most vital and common metal cutting operations used for machining parts because of its capability to remove materials at faster rate with a reasonably good surface quality. For the milling machine, the different process parameters are Spindle speed, feed rate, depth of cut, coolant, tool geometry etc. The optimization objective may be single or multiple. For single optimization Taguchi, RSM, GA, etc. are used while for multi objective optimization utility concept, grey relation analysis, Principal component analysis, etc. are used. In this research the various surface roughness measurements of the product prepared by CNC end engraving operation are to be studied experimentally and the results will be interpreted analytically.

In a material removal process, mechanical intervention happens over length scales, which extend from atomic dimensions to centimeters. The machine vibration, clearances and tolerances affect the outcome of the process at the largest of length scales (above 10-3 m). The tool form, feed rate, tool radius in case of single point cutting and grit size in multiple point cutting affect the process outcome at the intermediate length scales (10-6 to 10-3 m). The roughness of the tool or details of the grit surfaces influence the final topography of the generated surface at the lowest length scales (10-9 to 10-6 m). It has been shown that surfaces formed by electric discharge machining, milling, cutting or grinding, and worn surfaces have fractal structures, and fractal parameters can reflect the intrinsic properties of surfaces to overcome the disadvantages of conventional roughness parameters.

II. EXPERIMENTAL PROCEDURE:

Surface finish and material removal rate are one of the most important quality characteristics in manufacturing industries which influences the performance of mechanical parts as well as cost. In recent times, modern industries are trying to achieve the high-quality products in a very short period of time with less input. For that purpose, the computer numerically controlled (CNC) machine tools with automated and flexible manufacturing systems have been implemented In actual practice, there are many factors which affect responding parameters, e.g., cutting conditions, tool variables and work piece variables. Cutting conditions include spindle speed, feed rate and depth of cut whereas tool variables include tool material, flute angle, helix angle, rake angle, peripheral 2nd relief angle etc. and work piece variable include material hardness and other mechanical properties. However, it is very difficult to control all the parameters at a time.

- Selection of quality parameters for given machine.
- Selection of Process parameters & their levels.
- Perform the experiments.
- Measure the quality parameters.
- Analysed the data with help of different tools.
- Confirmation runs.
- Implemented the results.

3.1. MACHINE SPECIFICATIONS:

Model	SE 4454-S
T slots	5 Nos, CD (mm)90, Size(mm) 16*9*20
Machining Area(mm)	410*410*150
XYZ Axis Travel (mm)	420*420*200
Distance of Spindle Bottom from table(mm)	240
Accuracy X, Y, Z (mm)	<0.02
Repeatability X, Y, Z (mm)	<0.01
Table Flatness (mm)	<0.03
Gantry Width (mm)	480
Max. Load Weight (kg)	100
Pressure Deformation of Working Table @ 300kg(mm)	<0.02
Spindle Power (KW)	3.6

Spindle Speed (RPM) (Max)	24000
Tool Collets	ISO25/ER25
Max Tool Size (mm)	10
Rapid Rate (m/min)	10
Feed Rate (m/min)	2
Power	5.5 Kw 3 phase 415V
4th Axis	NA
Net Weight	1100 kg
Automatic Tool changer	Optional

3.2.1. WORKPIECE MATERIAL: ALUMINIUM 7075.

3.2.2. TOOLS: **1)** End mill cutter of 5mm of carbide.
2) Ball nose of 2 mm of carbide.

(1)

(2)

3.3 PROCESS PARAMETERS:

INPUT PARAMETERS	OUTPUT PARAMETERS
Spindle speed (RPM)	**Material removal rate (gm/sec)**
Feed rate (mm/ min)	**surface finish (microns)**
Depth of cut (mm)	

III. RESPONSE SURFACE METHODOLOGY:

In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The method was introduced by George E. P. Box and K. B. Wilson in 1951. The main idea of RSM is to us a sequence of designed experiments to obtain an optimal response. Box and Wilson suggest using a second-degree polynomial model to do this. They acknowledge that this model is only an approximation, but they use it because such a model is easy to estimate and apply, even when little is known about the process.

- **First-order model**

A linear function of the factors, the first-order model is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon$$

Where Y = response, X = factors, Bk = regression coefficients, and e= error term with a normal distribution, mean of 0.

- **Second- order model**

If there is curvature in the data, then a polynomial model of higher degree is used. The second-order model is:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon$$

- **Forward selection procedure**

A method for determining which variables to retain in a model. Forward selection adds variables to the model using the same method as the stepwise procedure. Once added, a variable is never removed. The forward selection procedure ends when none of the candidate variables have a p-value smaller than the value specified in Alpha to enter.

- **Backward elimination procedure**

A method for determining which variables to retain in a model. Backward elimination starts with the model that contains all the predictors and then removes variables, one at a time, using the same method as the stepwise procedure. No variable can re-enter the model.

- **Fitted values**

Y-hats or predicted values. The fitted values are point estimates of the mean response for the given values of the factors.

- **Residuals**

Residuals are the difference between the observed values and predicted or fitted values (data minus fits). This is the part of the observation that is not explained by the fitted model.

- **Standardized residuals**

Also called the internally Studentized residual. The residual is scaled by its standard deviation. The standardized residual is helpful in identifying outliers.

- **Deleted (Studentized) residuals**

$$\sqrt{s^2\left[\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum(x_i - \bar{x})^2}\right]}$$

Also called the externally Studentized residuals. Before calculating the deleted residual for the I^{th} observation, Minitab removes the I^{th} observation from the data set. Because model used for the estimates of the I^{th} observation is calculated with this observation deleted from the data set, the I^{th} observation cannot influence these estimates.

- **Standard error of fitted value**

The standard error of the fitted value; also, the estimated standard deviation of the fitted value.

- **Confidence interval**

The range in which the estimated mean response for a given set of predictor values is expected to fall. The interval is defined by lower and upper limits, which Minitab calculates from the confidence level and the standard error of the fits.

- **R2 (R-sq.)**

Coefficient of determination; indicates how much variation in the response is explained by the model. The higher the R2, the better the model fits your data.

- **t-value (T)**

Compare the t-value to the t-distribution to determine if a predictor is significant. The bigger the absolute value of the t-value, the more likely the predictor is significant. The formula is:

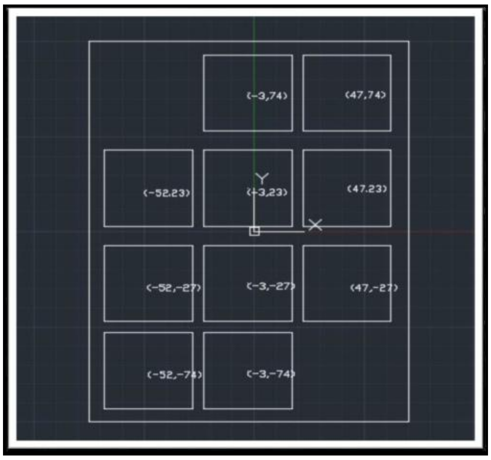
$$\frac{\text{Estimated coefficient}}{\text{Standard error of the coefficient}}$$

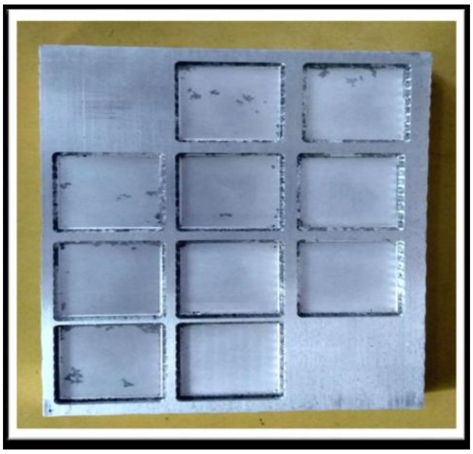
- **p-value (P)**

Used in hypothesis tests to help you decide whether to reject or fail to reject a null hypothesis. The p-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true. A commonly used cut-off value for the p-value is 0.05. For example, if the calculated p-value of a test statistic is less than 0.05, you reject the null hypothesis.

IV. EXPERIMENTATION:

For experimentation on cnc engraving machine, we have made the cad model showing the centre point co-ordinate of each box. The cad model of the plate is as follow -





The design of experiments (DOE, DOX, or experimental design) is the design of any task that aims to describe or explain the variation of information under conditions that are hypothesized to reflect the variation. The term is generally associated with experiments in which the design introduces conditions that directly affect the variation, but may also refer to the design of quasi-experiments, in which natural conditions that influence the variation are selected for observation. Main concerns in experimental design include the establishment of validity, reliability, and replicability.

- **Roughness measurement:**

we have used portable surface tester for the measurement of the surface roughness. We have taken 3 different readings from the same sample and then their average is taken-

Ra = (R1+R2+R3)/ 3

Where, R1- Reading no. 1
R2- reading no. 2
R3- reading no. 3

Std Order	Run Order	Pt Type	Blocks	coded values			actual values			surface roughness (Ra)	MRR (g/min)
				Speed (rpm)	feed rate (mm/min)	depth of cut (mm)	Speed (rpm)	feed rate (mm/min)	depth of cut (min)		
8	1	1	1	1	1	1	12000	800	0.25	0.847	0.547
7	2	1	1	-1	1	1	8000	800	0.25	0.726	0.548
18	3	0	1	0	0	0	10000	600	0.15	1.102	0.337
16	4	0	1	0	0	0	10000	600	0.15	0.880	0.337
11	5	-1	1	0	-1	0	10000	400	0.15	0.853	0.225
2	6	1	1	1	-1	-1	12000	400	0.05	0.592	0.122
13	7	-1	1	0	0	-1	10000	600	0.05	0.915	0.183
15	8	0	1	0	0	0	10000	600	0.15	0.625	0.337
12	9	-1	1	0	1	0	10000	800	0.15	1.315	0.45
6	10	1	1	1	-1	1	12000	400	0.25	1.004	0.274
10	11	-1	1	1	0	0	12000	600	0.15	0.977	0.338
17	12	0	1	0	0	0	10000	600	0.15	1.176	0.333
14	13	-1	1	0	0	1	10000	600	0.25	0.956	0.411
19	14	0	1	0	0	0	10000	600	0.15	0.781	0.337
9	15	-1	1	-1	0	0	8000	600	0.15	0.900	0.338
5	16	1	1	-1	-1	1	8000	400	0.25	0.932	0.274
1	17	1	1	-1	-1	-1	8000	400	0.05	0.875	0.122
3	18	1	1	-1	1	-1	8000	800	0.05	1.165	0.244
4	19	1	1	1	1	-1	10000	800	0.05	1.038	0.245
20	20	0	1	0	0	0	10000	600	0.15	1.119	0.338

The above table shows the doe by using response surface methodology, it is done by using MINITAB software.

V. RESULTS:

5.1 Surface roughness

- **Response Surface Regression: Ra versus speed, feed, doc**

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.073519	0.024506	0.69	0.569
Linear	3	0.073519	0.024506	0.69	0.569
speed	1	0.002357	0.002357	0.07	0.799
feed	1	0.066252	0.066252	1.88	0.190
doc	1	0.001061	0.001061	0.03	0.865
Error	16	0.564751	0.035297		
Lack-of-Fit	11	0.322972	0.029361	0.61	0.772
Pure Error	5	0.241779	0.048356		
Total	19	0.638270			

Table 4. Response surface Regression (Ra)

- **Model Summary**

S	R-sq	R-sq (adj)	R-sq(pred)
0.187875	11.52%	0.00%	0.00%

Table 5. Model summary (Ra)

- **Regression Equation in Uncoded Units**

Ra = 0.790 - 0.000008 speed + 0.000409 feed - 0.104 doc.

5.2 Material Removal Rate

- **Response Surface Regression: MRR versus speed, feed, doc**

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.233343	0.07781	64.47	0
Linear	3	0.233343	0.07781	64.47	0
speed	1	0.000410	0.000410	0.34	0.568
feed	1	0.103642	0.103642	85.91	0
doc	1	0.126505	0.126505	104.86	0
Error	16	0.019303	0.001206		
Lack-of-Fit	11	0.019287	0.001753	565.61	0
Pure Error	5	0.000016	0.00003		
Total	19	0.252646			

Table 6. Response Surface Regression (MRR)

- **Model Summary**

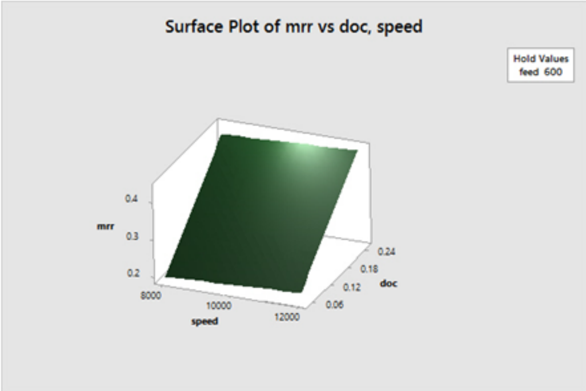
S	R-sq	R-sq(adj)	R-sq(pred)
0.0347335	**92.36%**	**90.93%**	**85%**

Table 7. Model Summary (MRR)

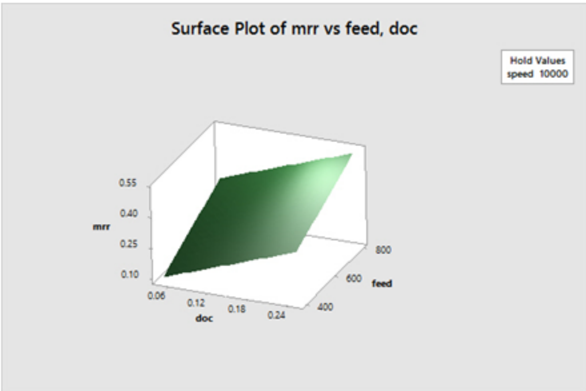
- **Regression Equation in Uncoded Units**

MRR = -0.1937 + 0.000003 speed + 0.000512 feed + 1.131 doc.

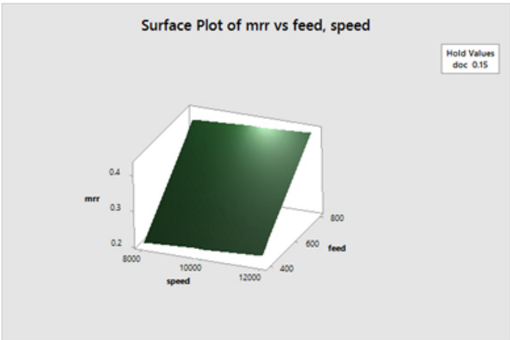
VI. ANALYSIS OF EXPERIMENTATION:



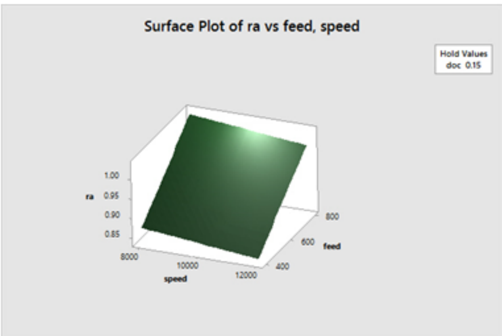
Here the graph of MRR vs speed, doc is obtained from software keeping the feed constant. It shows mrr on x- axis, speed on y- axis and doc on z-axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is speed and doc affect mrr in certain way. Change in mrr with increasing speed are mediocre but as depth of cut increases mrr also escalates. So, doc is more dominating factor for the changes in mrr.



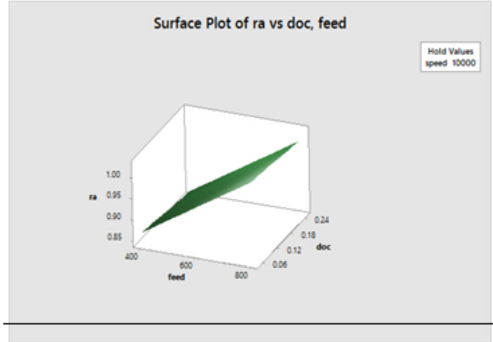
Here the graph of mrr vs feed, doc is obtained from software keeping the feed constant. It shows mrr on x- axis, doc on y- axis and feed on z- axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is speed and doc affect mrr in certain way. Change in mrr with increasing doc and feed are drastic. As feed and doc increases slope of mrr line increases.



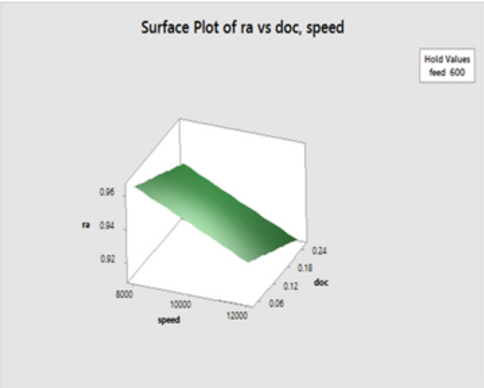
Here the graph of MRR vs speed, feed is obtained from software keeping doc constant. It shows mrr on x- axis, speed on y- axis and feed on z- axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is speed and doc affect mrr in certain way. Change in mrr with increasing speed are mediocre but as the feed increases mrr also escalates. So feed is a more dominating factor for the changes in MRR.



Here the graph of Roughness vs speed, feed is obtained from software keeping doc constant. It shows roughness on x- axis, speed on y- axis and feed on z- axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is speed and doc affect roughness in a certain way. Change in roughness with increasing speed are mediocre but as the feed increases roughness also escalates. So feed is a more dominating factor for the changes in roughness as we are seeking for less surface roughness value.



Here the graph of roughness vs feed, doc is obtained from software keeping the speed constant. It shows roughness on x- axis, doc on z- axis and feed on y- axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is feed and doc affect roughness in certain way. Change in roughness with increasing doc and feed are drastic. As feed and doc increases slope of roughness line increases.



Here the graph of Roughness vs speed, feed is obtained from software keeping feed constant. It shows roughness on x- axis, speed on y- axis and doc on z- axis. Contemplating the graph, one could understand relationship between these factors. Therefore, the conclusion is speed and doc affect roughness in a certain way. Change in roughness with increasing speed and doc are deplorable.

VII. CONCLUSION

- The research has taken spindle speed, feed rate and depth of cut as input parameters. Spindle speed, feed rate and depth of cut are the important parameters while studying the effects of process parameters on the required responding characteristics.
- For any manufacturing industries surface quality is the most important quality parameter. So, we have taken surface roughness as the quality parameter.
- We tried to optimize the quality/performance characteristics according to problem taken. All performance characteristics are equally important according to industries problem.
- RSM combined with ANOVA are good methodologies to analyze the result data. RSM helps to determine optimal solution and ANOVA technique helps to determine which parameters are most significant and their percentage contribution.
- Taguchi methodology widely used for the single optimization.
- From the experiments we have concluded that run order 6 gives best surface finish and run order 2 gives maximum material removal rate.

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