Cutting time based performance investigation of C & L shaped Die (D3) steel workpiece using CNC vertical milling machine

[1] Manjeet Manjeet Singh Sindal,
M.Tech Scholar, Department of Mechanical Engineering, SS College of Engineering, Udaipur, India,

[2] Dheeraj Soni,
Assistant professor Department of Mechanical Engineering SS College of Engineering, Udaipur, India

ABSTRACT

High precision machining is possible in the present era because of computer numeric controlled (CNC) machining processes like CNC turning, CNC milling, CNC drilling and many more. In today's competitive market, all industrialists are tending towards upgraded technologies. CNC is stepping ahead for keeping pace in this competitive era. Mass production with customer's satisfaction has become a need of today's customized market which is also the ultimate goal of 'Make In India' initiative as started by Govt. of India in the past few years.

In the present research study, CNC milling machining was adopted to optimize the selective process parameters for machining of high strength Die steel (D3) workpiece. In the present study, three process parameters were selected, i.e. feed, spindle speed and depth of cut followed by response parameter i.e. Cutting Time (CT). Three levels of each cutting parameter were chosen. Design of experiment (DOE) was applied to find the minimum tests for this research study resulting in nine experimental runs as per L9 orthogonal array (OA). Furthermore, Signal to noise (S/N) ratio analysis, analysis of variance (ANOVA), Contour & Interaction plots analysis etc. are used to analyze the results of experimentation. Regression Modeling is also used in the present research to predict the linear regression equation for the response parameter. An optimal solution is generated for a single and Multi response variable both. This study will be beneficial for researchers and industrialists working in this field.

Keyword: - *CNC, ANOVA, S/N Ratio, Multi-Objective Optimization, Orthogonal Array (OA)*

1. INTRODUCTION

CNC Milling Machine, a Computer armed with software that converts the computer programmed code or set of instructions into the movement of the tool according to the workpiece requirements. It grants the machine to work with a high degree of accuracy. A CNC milling machine uses a rotating cutting tool known as "Milling Cutter". It is held in the Spindle and rotates with it. The Size of the milling cutters depends upon the machining operation. CNC Milling machine can cut in various angles and also move along in different directions.[1]

Taguchi has formulated a new approach to the design of experiments. This method uses a unique set of arrays called orthogonal array. These standard arrays determine how to perform the minimum number of trials that provide complete information on all factors affecting the performance parameter. The basic of the orthogonal matrix method is to select the level combinations of input design variables for each experiment.[34]

Three process parameters is selected, i.e. feed, spindle speed, and depth of cut for studying effects of these parameters on response Cutting Time (CT). Three levels of each cutting parameter were chosen. Taguchi Method was applied to find the minimum tests. L9 orthogonal array (OA) is selected for performing the experiments. For analysis of experimentation, Signal to noise (S/N) ratio, ANOVA, Contour & Interaction plots were generated using MiniTab 17 Software. Regression Modeling is also used to predict the linear regression equation for Cutting time.

2. EXPERIMENTAL PROCESSES

2.1 CNC MILLING MACHINE

A machine that is used for this study is MAXMILL MATB CNC MILLING machine. This Machine is a product of Batliboi Machine Tools Ltd. It is used for experimentation in the present work on the specimen to obtain required shape. It is a three-axis vertical milling machine. The design of the cut is performed on the test-piece with the help of milling machine. The end mill milling cutter of diameter 5mm is used for the machining operations. The cutting time for each cut is noted with the help of the stopwatch. All the experimentation were conducted at CIPET, Jaipur.

2.2 WORKPIECE MATERIAL

Die Steel (D3) is used as workpiece material. It is a tool steel with high carbon and very high wear resistance. It hardens with a slight change in size. The alloy has a very high compressive strength and is deep-hardened. The machinability index of D3 is approximately 25% of the free machining of 1018 carbon steel. Because of its abrasion resistance, the treatment in the hardened state must be limited to the grinding surface. D3 is used in tool applications that require a high grade of exactitude in hardening, such as extraction dies, forming rollers, metal powder tools and cutting dies[31].The industrial alloy DIE STEEL (D3) having a size of 100 mm × 95 mm × 15 mm was used as the workpiece material for the current experiments.

2.3 DESIGN OF CUT SELECTION

In the present research work, a simple rectangular cut is selected because of easiness and simplicity. The Cut is planned to machining as English alphabets letters “C” and “L” by the milling machine. The Cut starts from the border of the work piece. The tool travel in both cases is the same. The design of cut for the work is shown in fig.1.

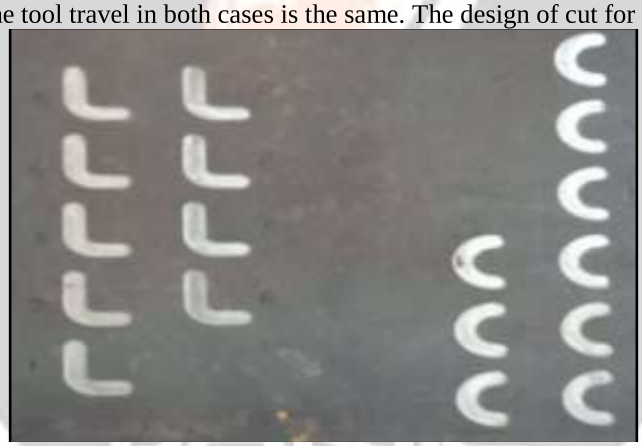

Fig.1. Design of Cut for the Present Work

2.4 FACTORS AND THEIR LEVELS

In research work, Feed (F), Spindle Speed(SS) and Depth of Cut (DOC) is taken as Input Parameters. Each Parameter has three levels. The Factors and their levels are shown in Table-1.

Table-1 Factors and their levels

S. No	Process Parameter	Level 1	Level 2	Level 3
1	Feed (F) (mm/min)	600	800	1000

2	Spindle Speed (SS) (RPM)	3200	3500	3800
3	Depth of Cut (DOC) (mm)	0.065	0.070	0.075

3. EXISTING METHODOLOGY AND DATA COLLECTION

3.1. DESIGN OF EXPERIMENTS

To indicate the relationship between parameters and responses,the design of the experiment is used. In the field of Science and Technology, DOE has a broad application that works on an experimental basis Modeling. By using analysis techniques such as ANOVA and by using regression analysis,a mathematical model is being established. This mathematical model shows the relationship between the input parameters and the output responses.

Taguchi has formulated a new method to design of experiments. This method uses a unique set of arrays called orthogonal array. These standard arrays determine how to perform the minimum number of trials that provide complete information on all factors affecting the performance parameter. The basic of the orthogonal matrix method is to select the level combinations of input design variables for each experiment.

The minimum number of trials required to perform the Taguchi method can be calculated based on the degree of freedom approach. The assumption implies that the individual or main effects of the independent variables are separable to the performance parameter. Under this statement, the impact of each factor can be linear, quadratic, or higher, but the model assumes that there are no cross-product effects between individual factors.[34]

3.2 SIGNAL TO NOISE RATIO

The ideal product responds only to operator signals and is not affected by random noise factors. Therefore, the goal of quality improvement efforts may be to maximize the signal-to-noise ratio (S/N) for each product. The S/N relationships were proposed by Taguchi (1987). The ratio depends on the high-quality characteristics of the product/technique to be optimized. The general S/N ratios generally used are as follows: - Nominal is Best (NB), Lower the Better (LB) and Higher the Better (HB). In the Present Work for the Cutting Time (CT), it is Lower is Better is used. The Formula for the same is : $S/N = -10 \text{ X } \log\{\Sigma(Y^2)/n)\}$

3.3 ORTHOGONAL ARRAY AS PER TAGUCHI METHOD

For the current experiment, L9 Orthogonal array is generated using MiniTab-17 Statistical software. According to L9 OA total 9 tests were performed. The eexperiments were performed as shown in Table -2

Table -2 L9 Orthogaonal Array

Sr. No	**Feed**	**Speed**	**DOC**
1	600	3200	0.065
2	600	3500	0.07
3	600	3800	0.075
4	800	3200	0.07
5	800	3500	0.075
6	800	3800	0.065
7	1000	3200	0.075

8	1000	3500	0.065
9	1000	3800	0.07

3.4 EXPERIMENTAL DATA COLLECTION

Table-3 Experimental Data Collection for Work

Sr. No.	Variable Parameters			Response Parameter (CT) (Sec.)	
	Feed	**Speed**	**DOC**	**For C Cut**	**For L Cut**
1	600	3200	0.065	25.3	26.4
2	600	3500	0.07	25.9	26.1
3	600	3800	0.075	24.8	25.1
4	800	3200	0.07	20.9	22.1
5	800	3500	0.075	21.7	20.8
6	800	3800	0.065	21.4	19.7
7	1000	3200	0.075	17.6	18.6
8	1000	3500	0.065	17.9	18.2
9	1000	3800	0.07	18.3	18.8

4. RESULTS AND DISCUSSION

In the current research, the study of results is strategic in two phases. In the first phase, it is proposed for the results of "C Cut". In these effect to variable parameters on their responses parameters is taken for the study. In the Second Phase, it is strategic for the results of "L Cut". Statistical Software Minitab 17 is used the analysis of the results. Both phases consist of the following results: Signal to Noise Ratio Analysis, Contour Plot Analysis and Interaction Plot Analysis, Linear Regression Modeling and Multi-Objective Optimization.

4.1 RESULT AND DISCUSSION OF CT FOR C CUT

In Table 4, the Signal to Noise ratio is calculated. Signal to Noise Ratio for Cutting time is assumed as " Smaller is better.

Table-4 S/N Ratio for C Cut

S No	Feed	Spindle Speed	DOC	CT	S/N Ratio

1	600	3200	0.065	25.3	-28.0624
2	600	3500	0.07	25.9	-28.266
3	600	3800	0.075	24.8	-27.889
4	800	3200	0.07	20.9	-26.4029
5	800	3500	0.075	21.7	-26.7292
6	800	3800	0.065	21.4	-26.6083
7	1000	3200	0.075	17.6	-24.9103
8	1000	3500	0.065	17.9	-25.0571
9	1000	3800	0.07	18.3	-25.249

Table 5 shows the Rank identification of the effect of the Variable parameters on response parameters. Table 5 gives the rank according to the impact on machining by the factors. According to the table, the First rank is given to the Feed, the Second rank to Spindle Speed and third rank given to the Depth of Cut.

Table-5Rank Identification of C Cut

Level	**Feed**	**Spindle Speed**	**DOC**
1	-28.07	-26.45	-26.57
2	-26.58	-26.68	-26.63
3	-25.07	-26.58	-26.50
Delta	3	0.23	0.13
Rank	1	2	3

The main effect diagrams show how each factor influences the response characteristic. The main effect exists when different levels of a factor change the attributes differently. Fig.2 shows the main effect plot for S/N Ratio versus all input factors. Since it is always required that Cutting time should be shorter, the CT Smaller is the better option selected.

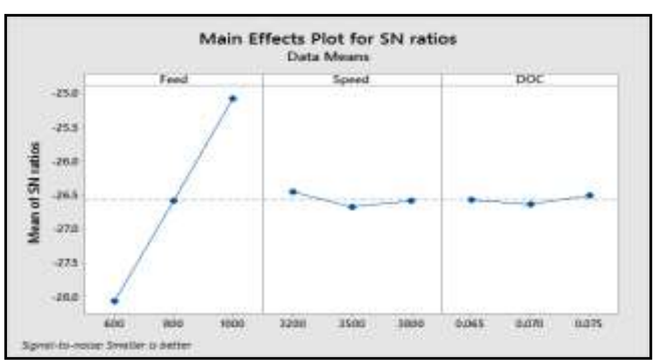

Fig.2 Main Effect plot for C Cut

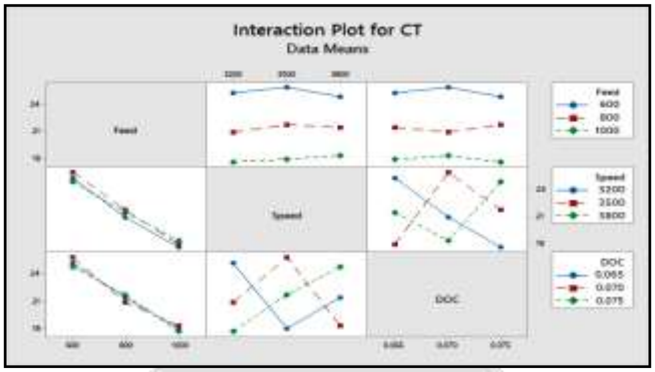

Fig.3 Interaction plot for C Cut

The maximum average value of Signal to Noise ratio is always present the optimal solution, and if we find an optimal solution from figure 2, then the optimal solution is found by using the top level of each factor. The optimal solution for cutting time for C Cut is Feed of 1000 mm/min, Spindle Speed of 3200 RPM and Depth of Cut of 0.075 mm.

Contour plots show the 3D Surface on 2D Plane. It is the graph between the two factors and one response variable as a contour. In the present work, three contour plot is obtained. In which response CT took as a Contour and Pair of two factors taken in account for drawing the contour plots.

In Fig.4, the Contour plot is plotted between the two factors, i.e. feed and spindle speed and response Cutting Time. One Factor Feed is taken on Y-axis and another factor Spindle speed gained on the X-axis. Contour line shows the response. From Fig. 4, it is clear that if the feed is reserved nearby 1000 mm/min and the Spindle speed ranging between the 3200 to 3600 RPM, Cutting time value is minimal. So it is suggested to keep the variable in above limit.

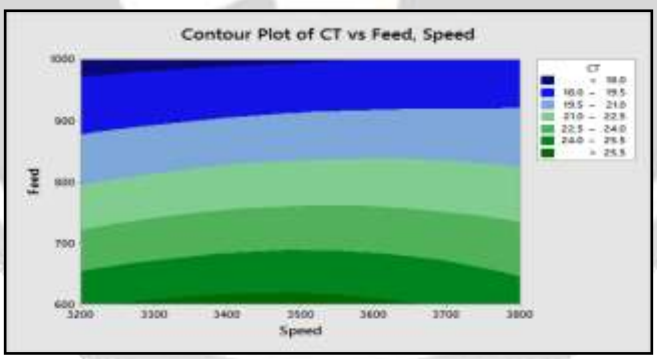

Fig. 4 – Contour plot of CT vs Feed, Speed

Fig. 5 shows a contour plot between the two factors feed and Depth of cut. By this plot, it is observed that if less cutting time is preferred, kept the feed near at 1000 mm/min and depth of cut is taken between 0.0725 to 0.0750 mm.

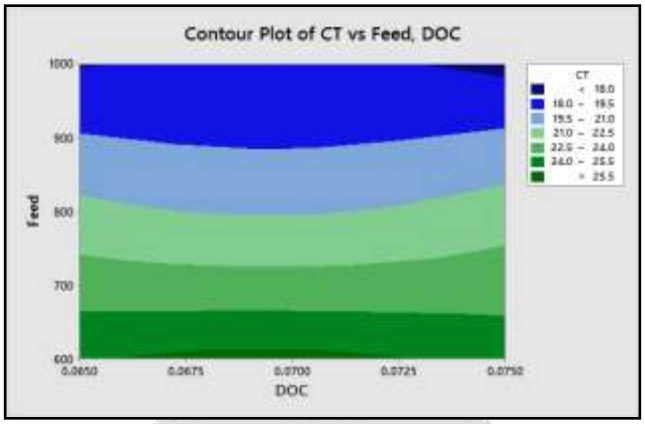

Fig. 5 – Contour plot of CT vs Feed, DOC

Fig. 6 also displays a contour plot between two variable parameters, i.e. Spindle Speed and Depth of Cut. There are two conditions to obtain minimum cutting time. The First condition is to take spindle speed ranges between 3500 to 3600 RPM, and DOC is close to 0.065mm. In the Second Condition the spindle speed kept near 3200 RPM, and DOC close to 0.075mm.

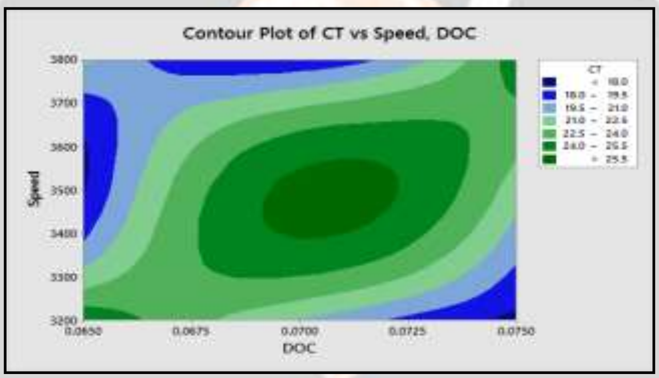

Fig. 6 – Contour plot of CT vs Speed, DOC

The regression modelling generates an equation describing the statistical relationship between one or more variables parameters and the response parameter.

Source	**DF**	**Seq SS**	**Contri bu-tion**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	82.2633	98.52%	82.2633	27.4211	110.87	0
Feed	1	82.14	98.37%	82.14	82.14	332.1	0
Spindle Speed	1	0.0817	0.10%	0.0817	0.0817	0.33	0.59
DOC	1	2	0.05%	0.0417	0.0417	0.17	0.698

Error	5	1.2367	1.48%	1.2367	0.2473		
Total	8	83.5	100.00 %				

Model Summary S	**R-sq**	**R-sq(adj)**	**PRESS**	**R-sq(pred)**
0.497326	98.52%	97.63%	3.75494	95.50%

Table-6 ANOVA Analysis for C Cut

Regression Equation

(CT) = 36.14 - 001850 (F) + 0.000389 (SS) - 16.7 (DOC)

By Using equation, we can predict the values of CT at any range of varying parameters. From Table 6, It is shown that Feed Contains higher F-Value than the other factors. So it is assumed that the Feed has a higher impact on the machining process. So always keep feed in the desired limit so better results can be obtained. The R-Sq Shows the result of 98.52%; it shows the predicted equation gives a better response.

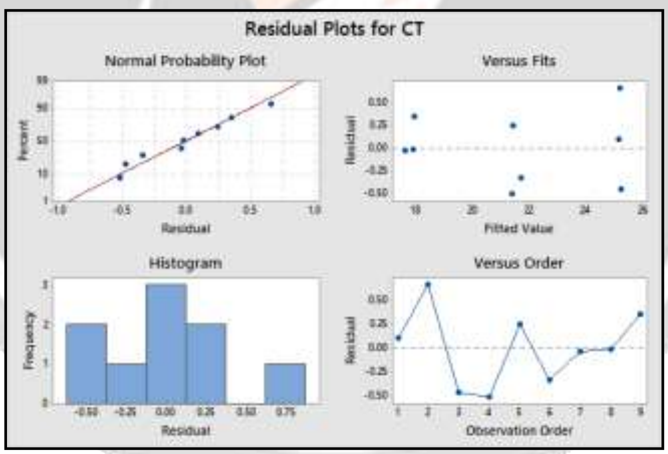

Fig7- Residual Plot for CT of C Cut

The residual plot is a graph used to examine the goodness-of-fit in regression and ANOVA. The residues have a constant variation because they remain arbitrarily distributed around zero in residues versus adjusted values. Since the residues show no clear pattern, there is no error in the time of data collection.

4.2 RESULT AND DISCUSSION OF CT FOR L CUT

The individual S/N Ratio is present in Table 7 for cutting time and rank identification for the cutting time is present in Table 8 for the L Cut.

Table 8 gives the rank identification of the factors. According to the table, the First rank is given to the Feed, Second rank to Spindle Speed and third rank given to the Depth of Cut.

Table-7 S/N Ratio for L Cut

S No	Feed	Speed	DOC	CT	S/N Ratio
1	600	3200	0.065	26.4	-28.4321
2	600	3500	0.07	26.1	-28.3328
3	600	3800	0.075	25.1	-27.9935
4	800	3200	0.07	22.1	-26.8878
5	800	3500	0.075	20.8	-26.3613
6	800	3800	0.065	19.7	-25.8893
7	1000	3200	0.075	18.6	-25.3903
8	1000	3500	0.065	18.2	-25.2014
9	1000	3800	0.07	18.8	-25.4832

Table-8 Rank Identification for L Cut

Level	Feed	Speed	DOC
1	-28.25	-26.90	-26.51
2	-26.37	-26.63	-26.90
3	-25.35	-26.46	-26.58
Delta	2.90	0.45	0.39
Rank	1	2	3

Fig.8 shows the main effect plot for S/N Ratio versus all input factors. Since it is always required that Cutting time should be shorter, the CT Smaller is the better option selected. The Main Effect Plot for S/N Ratio of CT for L Cut. It gives the Optimal Values of each Factor. The higher value of each factor taken for the optimal solution.

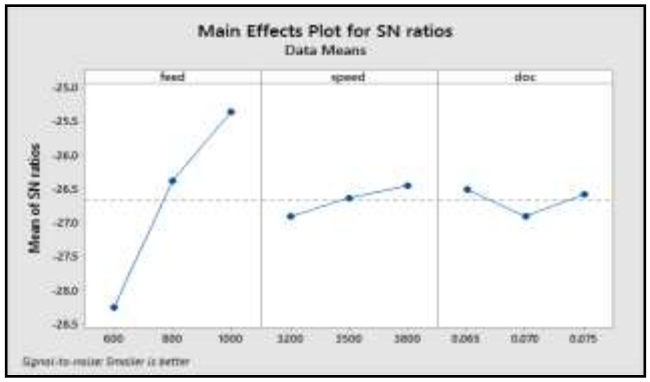

Fig 8- Main Effect plot for L Cut

The maximum average value of Signal to Noise ratio is always present the optimal solution, and if we find an optimal solution from figure 8, then the optimal solution is found by using the top level of each factor The optimal solution for cutting time for C Cut is Feed of 1000 mm/min, Spindle Speed of 3800 RPM and Depth of Cut of 0.675 mm.

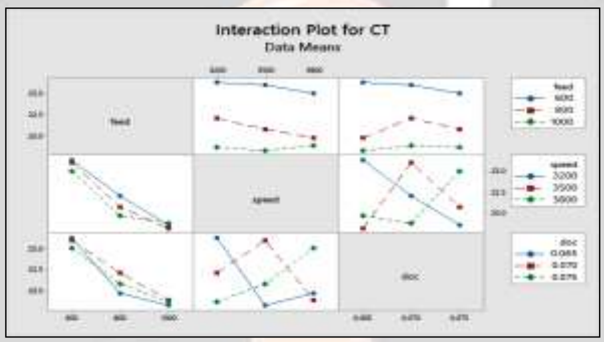

Fig. 9 – Interaction Plot for CT

Fig.10 shows the contour plot between Spindle Speed and Feed. For the minimal Cutting time, as per fig.4.17 Spindle speed is does not affect the response, but have to take a feed of 900 to 1000 mm/min

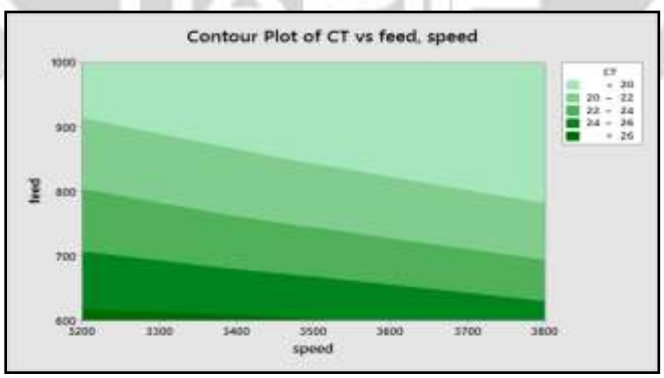

Fig. 10 – Contour plot of CT vs Feed, Speed

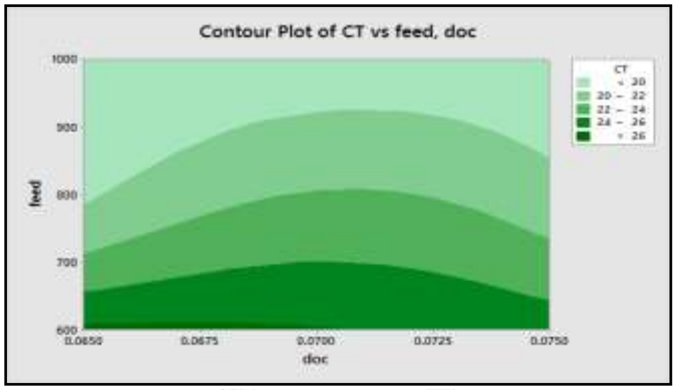

Fig. 11 – Contour plot of CT vs Feed, DOC

Fig.11 shows the plot between the two factors feed and depth of cut. The Contour shows the response. The feed is taken as 900 to 1000 mm/min. And depth of cut does not affect the response. If the feed is lowered than 900 mm/min., feed has kept a minimum for great result.

In Fig 12, a contour plot is plotted between the Spindle speed and DOC. The figure describes that lower cutting time is found by spindle speed as maximum (3500 to 3800 RPM)

and depth of cut taking nearly to the 0.0650. Another condition for the better responses is to keep the DOC almost at 0.0750, and the spindle speed is kept near to the 3300 RPM.

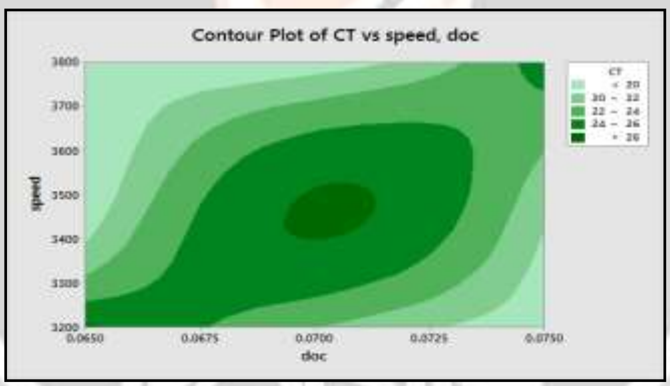

Fig. 11 – Contour plot of CT vs Speed, DOC

Table 9 Shows the ANOVA Table for the L Cut. A regression modeling equation is predicted to find out the value of response at any input parameters.

Table 9 – ANOVA Analysis for L Cut

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	82.715	93.76%	82.715	27.5717	25.03	0.002
feed	1	80.6667	91.44%	80.6667	80.6667	73.24	0

speed	1	2.0417	2.31%	2.0417	2.0417	1.85	0.232
doc	1	0.0067	0.01%	0.0067	0.0067	0.01	0.941
Error	5	5.5072	6.24%	5.5072	1.1014		
Total	8	88.2222	100.00%				

Model Summary S	**R-sq**	**R-sq(adj)**	**PRESS**	**R-sq(pred)**
1.0495	93.76%	90.01%	16.6962	81.07%

Regression Equation -

(CT) = 42.76 - 0.01833(F) - 0.00194(SS) - 6.(DOC)

Using equation, we can predict the values of CT at any range of varying parameters. From Table 9, It is exposed that Feed Contains higher F-Value than the other factors. So it is assumed that the Feed has a higher impact on the machining process. So always keep feed in the desired limit so better results can be obtained. The R-Sq Shows the result of 93.67%. It shows the predicted equation gives a better response.

In the Fig.12, Residual plots of Cutting time for the L Cut is shown. In the Normal Probability plot , the data is normally-distributed near regression line. An approximate nature of the histogram tells that residuals are normally distributed. The residual follows a roughly straight line normal probability plot. A non-linear relationship exists between the residual and the fitted values.

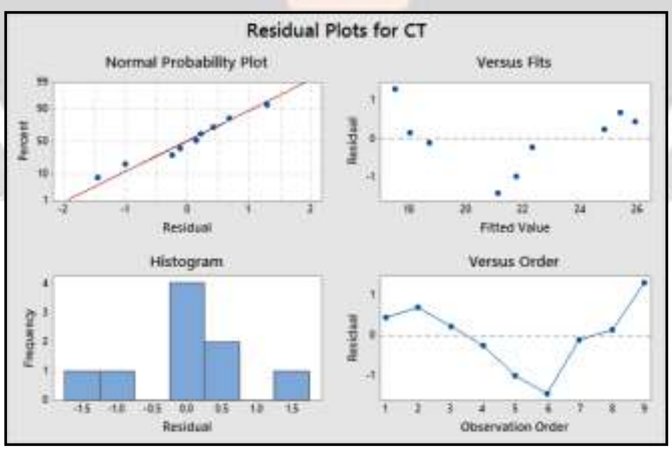

Fig. 12 – Residual Plots for CT

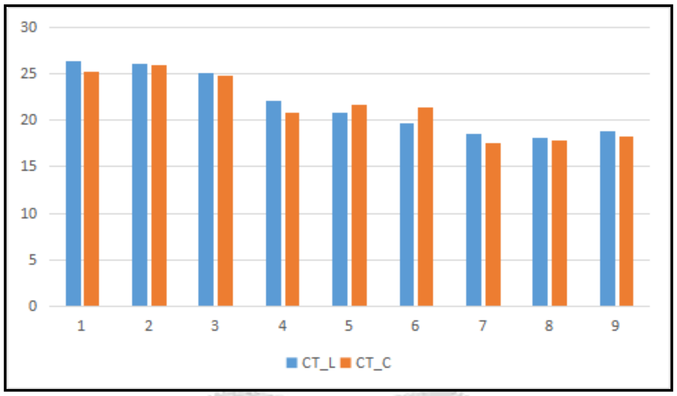

Fig. 13 – Comparison of CT for L & C Cut

Fig 13 Shows the Comparison between L Cut and C Cut for the Cutting Time.

5. CONCLUSION

In this research work, the Performance investigation of C and L shape machining using CNC vertical milling process on Die Steel (D3) Steel workpiece was carried out. The study was based on the effect of the variable parameters on the response parameters. Different conclusion of the work is pinpointed as:

(A) It was found that the most influential factor is Feed that significantly affects the Cutting time, whereas the impact of spindle speed and depth is much slighter for machining the C Cut and L Cut on Die Steel (D3).

(B) Rank identification table shows the rank of the most affecting factor on the response. For the Cutting time (CT), the First rank is given to the Feed (F), the second rank to the spindle speed (SS) and third to the depth of Cut (DOC) for both cuts.

(C) It is concluded from the ANOVA Table that Feed having higher F- Value than the factors for the response cutting time.

(D) The Regression modelling shows that the value of R-Sq. is always greater than 75% for every case. It shows the close level of accuracy.

(E) Linear regression modelling equation was generated for response parameters. The model equation can predict the value of response parameters. For L Cut and C Cut, a total of 2 equations were generated for the CT by which response values can be predicted by entering input varying parameters as per our suitability.

5. REFERENCES

[1] https://www.thomasnet.com/articles/custom-manufacturing fabricating/understanding- cnc-milling/

[2] https://all3dp.com/2/what-is-cnc-milling-simply-explained/

[3] Chang Y-F., Hong R.-C., “ A Practical approach to generating accurate iso-cusped toolpaths for three-axis CNC milling of sculpture surface parts”, *Journal of manufacturing processes*, Vol.8, No.1, pp. 29-38, 2006

[4] Colak O., Kurbanoglu C., Kayacan M.C., “ Milling surface roughness prediction using evolutionary programming methods”, *Materials & Design*, Vol.28, No.2 pp. 657-666, 2007

[5] Salami R., Sadeghi M.H., Motaket B., "Feed rate optimization for 3- axis ball-end milling of sculptured surfaces", *International Journal of Machine tools and Manufacture*, Vol. 47, No. 5, pp. 760-767, 2007

[6] Osornio-Rios R.A., de Jesus Romero-Troncoso R., Heirera-Ruiz G., Castaneda-Miranda R., "The application of reconfigurable logic to high speed CNC milling machines controllers", *Control Engineering Practice*, Vol.16, No. 6, pp. 674-684, 2008

[7] Zaghbani I., Songmene V., "A force-temperature model including a constitutive law for dry high speed milling of aluminium alloys", *Journal of Materials Processing Technology*, Vol. 209, No. 5, pp. 2532-2544, 2009.

[8] Tang W.X., Song Q.H, Yu S.Q., Sun S.S., Li B.B., Du B., Ai X., "Prediction of chatter stability in high-speed finishing and milling considering multi-mode dynamics", *Journal of Materials Processing Technology*, Vol. 209, No. 5, pp. 2585-2591, 2009.

[9] David Edwards, J. and Robert Mee, W. Thesis report on Fractional Box-Behnken Designs, Germany, 2009

[10] Topal E.S. "The role of step-over ratio in prediction of surface roughness in flat-end milling", *International Journal of Mechanical Sciences*, Vol.51, No. 11-12, pp. 782-789, 2009

[11] Arif, Mustafizur Rahman, and Wong Yoke San, "Analytical modeling of ductile-regime machining of tungsten carbide by end milling Muhammad", *International Journal of Advanced Manufacturing Technology*, 2010.

[12] Kious M., Ouahabi A., Boundraa M., Serra R.., Chekname A., "Detection process approach of tool wear in high-speed milling". *Measurement*, Vol. 43, No.10, pp.1439-1446, 2010

[13] Alao, A.R. and Konneh, M. "Application of Taguchi and Box-Behnken designs for surface roughness in precision grinding of silicon", *International Journal of Precision Technology*, Vol. 2, No. 1, pp. 21-38, 2011

[14] Mahdavinejad, R.A. and Saeedy, S "Investigation of the influential parameters of machining of AISI 304 stainless steel", *Sadhana* Vol. 36, Part 6, pp. 963-970, 2011

[15] Kaya B., Oysu C.Ertunc H.M., "Forced-torque based on-line wear estimation system for CNC milling of Inconel 718 using neural networks", *Advances in Engineering Software*, Vol. 42, No.3, pp.76- 84, 2011.

[16] Farouki R.T., Li S., "Optimal Tool orientation control for 5 Axis CNC milling with ball-end cutters", *Computer Aided Geometric Design*, Vol. 30, No.2, pp. 226-239, 2013

[17] Zuperl V., Cus F., Reibenschuh M., "Neural control strategy of constant cutting force system in end-milling", *Robotics and Computer- Integrated Manufacturing*, Vol. 27, No. 3, pp. 485-493, 2011.

[18] Heo E.Y. Kim .D.W., Lee J.Y., Lee C.S., Chen F.F., High-speed pocket milling planning by feature based machining area portioning", *Robotics and Computer-Integrated Manufacturing*, Vol.27, No.4, pp. 706-713, 2011

[19] Shokrani, Dhokia V., Newman S.T., Imani-Asrai R." An initial study of the effect of using liquid nitrogen coolant on the surface roughness of Inconel 718 nicked-based alloy in CNC milling, *Procedia CIRP*, Vol.3, pp.121-125, 2012

[20] Wojciechowski S., Twardowski P., " Tool life and process dynamics in high-speed ball-end milling of hardened steel", *Procedia CIRP*, Vol. 1, pp. 289-294, 2012

[21] Dumitrache A., Borangiu T., "IMSIO- image-based milling tool paths with tool engagement control for complex geometry", *Engineering Applications of Artificial Intelligence*, Vol.25, No.6, pp. 1161-1172, 2012

[22] Imani B.M., Pour M., Ghoddosian A., Fallah M., "Improved dynamic simulation of end-milling process using time series analysis", *Scientia Iranica*, Vol. 19, No.2, pp.294-302, 2012

[23] Kasim M.S., Che-Haron C.H., Ghani J.A., Sulaimon M.A., Yazid M.Z.A., "Wear mechanism and notch wear location prediction model in ball nose and milling of Inconel 718," *Wear in press*, 2013

[24] Kuram, Emel & Ozcelik, Babur. (2013). Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill. *Measurement*. Vol.46. pp.1849–1864, 2013

[25] Armin Afkhamifar, Dario Antonelli, Paolo Chiabert, "Variational Analysis for CNC Milling Process", *Procedia CIRP*, Volume 43, pp.118-123, 2016

[26] Radu Eugen, Breaza Octavian, Bologaa Sever, Gabriel Racz, "Selecting industrial robots for milling applications using AHP", *Procedia Computer Science*, Volume 122, Pages 346-353, 2017

[27] Xian Wu, Liang Li, Ning He, Guolong Zhao, Feng Jiang, Jianyun Shen, "Study on the tool wear and its effect of PCD tool in micro milling of tungsten carbide", *International Journal of Refractory Metals and Hard Materials*, Volume 77, pp.61-67, 2018

[28] Karaguzel, Umut & Uysal, Emre & Budak, Erhan & Bakkal, Mustafa. (2015). Effects of Tool Axis Offset in Turn-Milling Process. *Journal of Materials Processing Technology*. 231. 10.1016/j.jmatprotec.2015.12.020.

[29] Zhang, Ren & Tao, Cheng-An & Chen, Rui & Wu, Lifang & Zou, Xiaoxuan & Wang, Jianfang. (2018). Ultrafast Synthesis of Ni-MOF in One Minute by Ball Milling. *Nanomaterials*. 8. 1067. 10.3390/nano8121067.

[30] Urbikain, Gorka & Olvera Trejo, Daniel & Lacalle, Luis. (2017) "Stability contour maps with barrel cutters considering the tool orientation." *The International Journal of Advanced Manufacturing Technology*. 89. 10.1007/s00170-016-9617-x.

[31] https://www.suppliersonline.com/propertypages/D3.asp

[32] https://www.keyence.com/ss/products/microscope/roughness/line/index.jsp

[33] https://www.salutron.de/en/surface-roughness-tester/tr110/

[34] http://www.ecs.umass.edu/mie/labs/mda/fea/sankar/chap2.html

[35] https://documentation.statsoft.com/sn-ratio.html

[36] https://www.analyticsvidhya.com/blog/2015/08/comprehensive-guide-regression/

[37] https://blog.minitab.com/blog/marilyn-wheatleys-blog/minitab-17-and-minitab-express-a-comparison-of-software-features

[38] Sarikaya, Murat, and Abdulkadir Gullu. "Multi-response optimization of minimum quantity lubrication parameters using Taguchi-based grey relational analysis in turning of difficult-to cut alloy Haynes 25", *Journal of Cleaner Production*, 2015.

[39] Bouacha, Khaider, Mohamed Athmane Yallese, Samir Khamel, and Salim Belhadi. "Analysis and optimization of hard turning operation using cubic boron nitride tool", *International Journal of Refractory Metals and Hard Materials*, 2014.

[40] Ender Hazir, Tuncay Ozcan. "Response Surface Methodology Integrated with Desirability Function and Genetic Algorithm Approach for the Optimization of CNC Machining Parameters", *Arabian Journal for Science and Engineering*, 2018

[41] D. Palanisamy, P. Senthil., "Optimization on Turning Parameters of 15-5PH Stainless Steel Using Taguchi Based Grey Approach and Topsis", *Archive of Mechanical Engineering*,2016

[42] Chakradhar Bandapalli, Bharatkumar Mohanbhai Sutaria, Dhananjay Vishnuprasad Bhatt, Kundan Kumar Singh., "Experimental Investigation and Estimation of Surface Roughness using ANN, GMDH & MRA models in High Speed Micro End Milling of Titanium Alloy (Grade-5)", *Materials Today: Proceedings*,2017

[43] Necati Ucak, Adem cicek., "The effects of cutting conditions on cutting temperature and hole quality in drilling of Inconel 718 using solid carbide drills", *Journal of Manufacturing Processes*, 2018

[44] R. Ramesh., "Automated intelligent manufacturing system for surface finish control in CNC milling using support vector machines", *The International Journal of Advanced Manufacturing Technology*, 2008

[45] C. Bandapalli , K. K. Singh, B. M. Sutaria , D. V. Bhatt., "Experimental investigation of machinability parameters in high-speed micro-end milling of titanium (grade-2)", *The International Journal of Advanced Manufacturing Technology*, 2015

[46] Abhineet Saini, Deepam Goyal, Vanraj, S. S. Dhami, B. S. Pabla., "Prediction of multi response parameters in material removal processes using soft computing — A review", *International Conference on Advances in Computing, Communication, & Automation(ICACCA) (Spring)*, 2016

[47] Bala Murugan Gopalsamy.,"Optimisation of machining parameters for hard machining: grey relational theory approach and ANOVA", *The International Journal of Advanced Manufacturing Technology*, 2009