Optimization of Tool Path and Process Parameters in Slot Milling using Grey Relational Analysis

Parth Harbola

Product Design Engineer, CEAT Tyres Limited, Gujarat, India

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Abstract - End milling is an operation which employs an end mill cutter for face milling, edge milling and slot milling. It is a very widely used machining operation that is extensively used in shipyard, automotive & aerospace industries. Different types of tool paths can be used during the end milling of the AISI D3 material. Each toolpath has its own effects on the performance characteristics of slot milling. Some toolpaths may provide better surface roughness while other toolpaths may provide lower cutting force. The manufacturer wants to produce the machining components with better surface finish. At the same time the manufacturer wants lower cutting force and less amount of energy to be spent while machining the components. Hence, it is important to determine the best toolpath and cutting conditions which will provide lower surface roughness of them machined component, lower cutting force on the tool and less amount of energy spent for the machining. This research result would identify the best toolpath and optimum cutting parameter which will provide better surface finish as well as low cutting force and specific cutting energy.

Key Words: AISI, End Milling, Cutting Force, Toolpath, Surface Finish

1. INTRODUCTION

There has been an increasing demand for high quality machined components that would be highly beneficial to manufacturing industries as it would help the manufacturing engineer and mechanist to select best machining parameters and toolpath strategies. The Different types of tool paths can be used during the end milling of the AISI D3 material. Each toolpath has its own effects on the performance characteristics of slot milling. Cevdet Gologlu et.al [1] investigated the effects of cutter path strategies on the surface roughness of DIN 1.2738 mould steel during pocket milling operations based on Taguchi method. P.E Romero et.al [2] studied the influence of toolpath strategy and pocket geometry on surface roughness, cutting force and machining time. Some toolpaths may provide better surface roughness while other toolpaths may provide lower cutting force. The manufacturer wants to produce the machining components with better surface finish and at the same time want to reduce cutting force and amount of energy to be spent while machining the components. Hence, it is important to determine the best toolpath and cutting conditions which will provide lower surface roughness of the machined component, lower cutting force on the tool and less amount of energy spent for the machining.

The experimental runs were generated using L9 Taguchi orthogonal array. The input parameters selected are Tool path, Cutting speed and feed rate. Depth of cut remains constant during the experiment. Jayakrishnan et.al [3] Taguchi-Grey relational analysis was utilized to optimize the multi response end milling characteristics during the end milling of Aluminum alloy. B. Rajeswari et.al [4] used response surface methodology to generate the design of experiment and then utilized the grey relational analysis to find the optimum machining characteristics. Mastercam X6 software was used to generate the NC codes for the experimental runs required for the machining of the components. Using the NC codes obtained from Mastercam software the experiments were performed in the 3-axis vertical milling machine. The performance characteristics of the machined components were measured. The optimization of the parameters was done using Grey relational analysis. The optimum cutting conditions were obtained from the result which was compared with the initial cutting parameters to verify whether the performance characteristics of the machined components were improved or not.

Thus, the result of this research will help the manufacturer to select the best toolpath strategy and cutting conditions which will help him to manufacture high quality components and simultaneously reducing the cost of production.

1.1 Research Objective

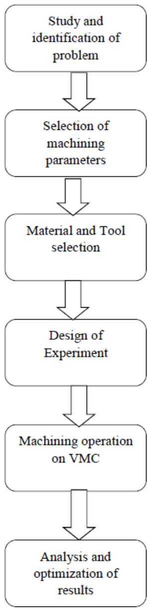
Objective of this research are:

1. To study the influence of tool path (Raster, Trochoidal and Hybrid) with respect to output quality characteristics

2. To analysis the significance of process parameters (speed, feed rate) along with toolpath with respect to output quality characteristics.

3. To optimize the process parameters by utilizing Grey Relational Analysis.

1.2 Research Methodology



2. Experimental Planning

Material used: AISI D3 STEEL

AISI stands for American Iron and Steel Institute. D3 steel has a high percentage of chromium and carbon in its composition which helps the material to provide dimensional stability, wear resistance and resistance to deformation under compressive forces. Composition of AISI D3 material can be clearly seen in Fig.1

Carbide tool materials (Fig.2) was used as cutting tool material which includes carbides of silicon, titanium, tungsten as well as other compounds of a metal. Carbide tools are used in machining various grades of steel materials. The milling experiments are to be conducted on the VMC machine, hence cutting inserts are preferred. The insert to be used for milling operation is R390-11 T3 08 M-PM 1030

(SANDVIK) with a tool nose radius of 0.8 mm and coated with TiAl(N) by physical vapor deposition.

Name of the Element	Percentage by mass (%)
Carbon(C)	2.1
Silicon (Si)	0.3
Chromium (Cr)	11.5
Manganese (Mn)	0.4
Nickel (Ni)	0.31
Vanadium (V)	0.25
Iron (Fe)	Balance

Fig.1 – Composition of AISI D3 Material

Fig.2 – PVD Coated Carbide Material

2.1. Cutting Parameters

Selection of input parameters depends on the work piece and the cutting tool. In this research, four input parameters are used: -

1. Toolpath

2. Cutting Speed (m/min)

3. Feed Rate(mm/tooth)

Cutting depth is the constant parameter while Cutting Speed, Feed rate and toolpath are the controllable cutting parameters to be used in the experiments. The controllable parameters are set into three levels as per the literature survey. As per the specifications of the work piece and cutting tool, the cutting speed has a range from 40 m/min to 80 m/min, the feed rate has a range from 0.05mm/min to 0.15mm/min and toolpaths used are Raster, Trochoidal and Hybrid. Table 3.2 shows the input parameters. Tool path-Trochoidal, DOC-1mm

S. No	Parameters	Level 1	Level 2	Level 3
1	Toolpath	Raster	Trochoidal	Hybrid
2	Cutting Speed (m/min)	40	60	80
3	Feed Path (mm/tooth)	0.05	0.1	0.15

Table -2.1: Process Parameters and their levels

2.2. Design of Experiments

To optimize these parameters and levels, Taguchi L9 orthogonal array is used. Based on this tabulation, experiments are going to be performed. Table 2.2 shows the design of experiments which were generated using Taguchi L9 array for 3 parameters and 3 level design

Ex. No	Toolpath	Cutting Speed (m/min)	Feed Rate (mm/tooth)
1	Raster	40	0.05
2	Raster	60	0.1
3	Raster	80	0.15
4	Trochoidal	40	0.1
5	Trochoidal	60	0.15
6	Trochoidal	80	0.05
7	Hybrid	40	0.15
8	Hybrid	60	0.05
9	Hybrid	80	0.1

Table -2.2: Design of Experiments

2.3. Machining and Experiment

Initially, the 3D simulation of the work piece is done by using MASTERCAM X-6 software. The NC codes are generated with help of this software. Trochoidal tool path strategy

is used. The NC codes which were obtained from the software are uploaded on CNC 828D Siemens VMC Machine. Then the experiments are conducted on the machine (Fig.3).

Fig.3 – Experimental Setup

Specifications of the VMC:

1. Machine Name - 3 Axis VMC
2. Make - BFW
3. Model - Gaurav-BMV 35 T12
4. CNC Controller - Siemens-Sinumerik 828D basic
5. Spindle speed maximum - 8000 RPM

Mastercam X6 software is used to conduct the simulation and NC code were generated.

The figure 4 shows the sample simulation model.

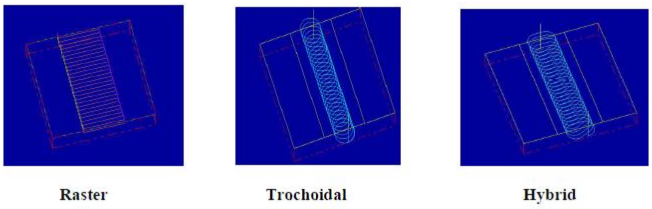


Fig.4 – Toolpath Simulation

To avoid rusting on the machine surface oil is applied on the workpiece after completion of all experiments. Figure 5 shows the machined workpieces. The first workpiece shows the Hybrid toolpath used in 9th experiment. The second workpiece shows the Trochoidal toolpath from the 4th experiment. The third workpiece shows the Raster/One-way toolpath from the 1st experiments. The experiments were performed on both the sides of the AISI D3 material to reduce amount of material used and cost.

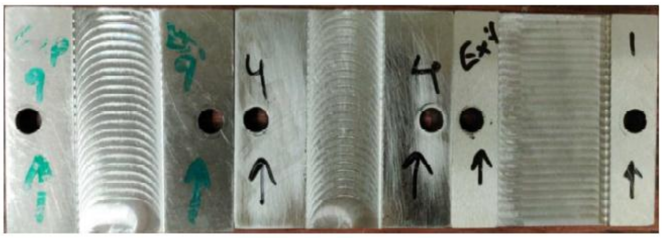


Fig.5 – Machined Workpieces

3. Output Parameters Measurement

3.1. Surface Roughness Measurement

The Surface roughness must be monitored carefully to ensure the product quality. Figure 6 shows Surf com 1400 G, ACCRETECH used for measuring the surface roughness of the machined work piece. It consists of a stylus which moves over the surface to be analyzed. The stylus setup is interfaced with a computer which gives the value of the surface roughness.

Fig.6 – Surface Roughness Tester Setup

3.2. Cutting Force Measurement

Cutting force is measured with the help of KISTLER multi-component dynamometer.

The dynamometer and the acquired results are shown figure.7

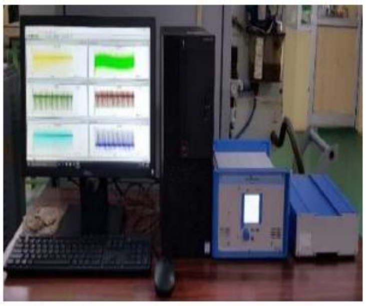


Fig.7 – Dynoware setup

Where Fx, Fy, Fz denote tangential, radial, and axial cutting forces (N) which are obtained from the Dyno ware setup. The cutting forces obtained for raster toolpath (3rd experiment) were shown in fig 8

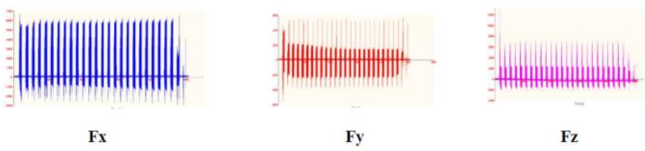


Fig.8 – Cutting Force for Raster Toolpath (Expt. 3)

The cutting forces obtained for trochoidal toolpath were shown in fig.9

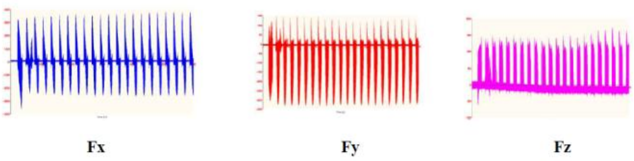


Fig.9 – Cutting Force for Trochoidal Toolpath (Expt. 6)

The cutting forces obtained for hybrid toolpath were shown in fig.10

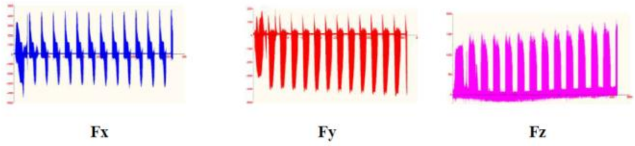


Fig.10 – Cutting Force for Hybrid Toolpath (Expt. 8)

The cutting forces obtained from all the experiments were tabulated in table 3.1

Exp. No	Fx (N)	Fy(N)	Fz(N)	F(N)
1	423	125	216.7	491.4396
2	520	420.8	177	691.9549
3	635.7	563	233.8	880.7644
4	592	228.3	235	676.6165
5	629	273.1	324.1	758.4625
6	361	143.4	148.9	415.9997
7	781.9	264	250	862.3013
8	453.2	191.7	156.3	516.303
9	634	231.7	238	715.7408

Table -3.1: Cutting Forces

The resultant cutting force is obtained from the following formulae.

$F= \sqrt{Fx^2+ Fy^2+ Fz^2}$

Fx = Cutting force in tangential direction

Fy= cutting force in radial direction

Fz= cutting force in axial direction

F= Resultant cutting force

3.3 Cutting Force Measurement

To remove a unit volume of the machined component the amount of energy exerted by the cutting tool is known as Specific Cutting energy.

$$Es = \frac{Fc}{Fz \times ap}$$

Where Es= Specific cutting energy (J/mm3)

Fc= Resultant Cutting force (N)

Fz= Feed rate (mm/tooth)

ap= cutting depth in axial direction (mm)

Now all the output parameters are tabulated as shown in table 3.2

Exp. No	F(N)	Surface Roughness (µm)	Specific Cutting Energy Es (J/mm3)
1	491.4396	0.8791	9.2637
2	691.9549	0.9693	4.3534
3	880.7644	0.4838	2.7671
4	676.6165	1.28	6.3772
5	758.4625	1.0636	3.1781
6	415.9997	0.7444	3.9208
7	862.3013	0.9622	5.4185
8	516.303	0.3399	6.4903
9	715.7408	1.0021	3.3723

Table -3.2: Output Parameters

4. Results and Discussion

4.1 Grey Relational Analysis

The objectives chosen were minimizing the surface roughness, cutting force and specific cutting energy. This analysis is used to determine the optimum set of process parameters for the given set of experiments. Grey relational analysis consists of 3 steps namely:

1. Normalize the obtained output parameters from 0 to 1.

2. Calculate grey relation coefficient for normalized output parameters.

3. Calculate grey relation grade by taking arithmetic mean of the GRCs for each output response in a single experiment.

4. The GRGs are then ranked in descending order and the experiment with the highest value of GRG is the optimum experiment

4.2 Calculation of S/N Ratio

The signal to noise ratio (S/N ratio), where the desirable output is represented by signal and undesirable variation is represented by noise, is used to evaluate the quality characteristics of a control variable. The S/N ratio can be evaluated using two cases, ''Smaller the better'' & ''Larger the better''. As surface roughness, Cutting Force and Specific Cutting energy must be minimized, this study utilizes only the smaller the better case.

The smaller the better S/N ratio equation is given by:

$$\text{S/N ratio} = -10\log\left(\frac{1}{n}\sum y^2\right)$$

The larger the better S/N ratio equation is given by:

$$\text{S/N ratio} = -10\log\left(\frac{1}{n}\sum \frac{1}{y^2}\right)$$

The S/N ratios were calculated for each output characteristic and were tabulated in table 4.1

Exp. No	Surface Roughness (Ra)	Cutting Force (Fc)	Specific Cutting Energy (Es)
1	1.1192	-53.8294	-19.3357
2	0.2708	-56.8100	-12.7766
3	6.3067	-58.8972	-8.8405
4	-2.1442	-56.6069	-16.0925
5	-0.5356	-57.5987	-10.0435
6	2.5639	-52.3819	-11.8676
7	0.3347	-58.7138	-14.6776
8	9.3730	-54.2581	-16.2453
9	0.0182	-57.0935	-10.5586

Table -4.1: S/N Ratios

4.3 Normalization of Output Parameters

As per required procedure normalization is to be done for the output parameters. For calculating normalized values, the following equations are used.

$$X_i^*(k) = \frac{\max(X_i^0(k)) - X_i^0(k)}{\max(X_i^0(k)) - \min(X_i^0(k))}$$

Since all the output parameters comes under the category of 'Smaller the better' , we have used above-mentioned equation where ,

Where $X_i^0(k)$ is the actual sequence

$X_i^*(k)$ is the sequence after data pre-processing

$\max\left(X_i^0(k)\right)$ is the greatest/maximum value of $X_i^0(k)$

$\min\left(X_i^0(k)\right)$ is the least/minimum value of $X_i^0(k)$

4.4 Grey Relational Co-efficient & Grade

The GRC can be calculated as:

$$\xi(k) = \frac{\Delta min + \xi \Delta max}{\Delta 0_i(k) + \xi \Delta max}$$

The weightage for roughness is taken as 0.4 and for cutting force and specific cutting energy is taken as 0.3 respectively.

Whereas Grey relation grade is calculated by taking arithmetic mean of the GRCs for each output response in a single experiment. The GRG is defined as

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k \ \xi_i(k)$$

From the table 4.2, it was observed that the 6th experiment was ranked 1 by Grey relational analysis and hence the optimum parameters are obtained as Cutting Speed 80m/min, Feed rate 0.05mm/tooth and trochoidal toolpath.

The average grey relational grade is calculated. Table 4.3 shows the average relation grade.

Exp. No	Grey relational Co-efficient			Grey Relational Grade (GRG)	Rank
	Surface Roughness (Ra)	Cutting Force (Fc)	Specific Cutting Energy (Es)		
1	0.3582	0.5745	0.2308	0.387837	6
2	0.3360	0.3062	0.4444	0.362231	7
3	0.6004	0.2308	1.0000	0.610389	2
4	0.2857	0.3163	0.3027	0.301581	9
5	0.3174	0.2726	0.7236	0.437829	4
6	0.4035	1.0000	0.5098	0.637801	1
7	0.3376	0.2359	0.3504	0.307965	8
8	1.0000	0.5102	0.2983	0.602858	3
9	0.3291	0.2932	0.6470	0.423092	5

Table -4.2: GRC, GRG & Rank

Input Parameters	Average Grey Relational Grade			Max-Min
	Level 1	Level 2	Level 3	
Toolpath	0.4534	0.4590	0.4446	0.0056
Cutting Speed (m/min)	0.3324	0.4676	0.5570	0.2246
Feed Rate (mm/min)	0.5428	0.3623	0.4521	0.1805

Table -4.3: Average Grey Relational Grade

The average grey relational grade is calculated and from the table 4.3, we could say that the most influential factor among the three parameters is spindle speed. So, the ideal surface finish is obtained by maximizing the spindle speed as much as possible. On the other hand, toolpath is the least influencing parameters because the difference between the maximum and minimum average grey relational analysis is minimum for the toolpath.

4.5 Confirmation Test

The optimum parameters which were obtained from Grey Relational Analysis were used to carry out the confirmation test. The experiment was performed by taking cutting speed as 80m/min, feed rate as 0.05mm/min and trochoidal toolpath. The comparison between the optimum parameters and the initial parameters were shown in table 4.4

Response	Optimum Parameters
Surface Roughness (µm)	0.7214
Cutting Force (N)	415.9098
Specific Cutting Energy (J/mm3)	3.9176
Grey Relational Grade	0.701227

5. Conclusion

Taguchi based GRA was utilized to optimize the process parameters in end milling operation of AISI D3 steel.

1 From the investigation the optimum process parameters were obtained as.

a) Cutting Speed 80 m/min,

b) Feed rate 0.05mm/tooth

c) trochoidal toolpath.

2 The average GRA grade was calculated for each parameter, and it was found that the cutting speed was the most influential parameter followed by feed rate and toolpath.

3 Trochoidal toolpath was found to be ideal toolpath because the engaging time of the tool is less when compared to Raster and Hybrid. Raster and Hybrid tool path contains linear motion which increases the engaging time of the tool.

4 With the obtained optimum parameters, the confirmation test was carried out. The difference in Grey Relational Grade between the experiment performed with optimum parameters and the values are found to be surface roughness 0.7214 µm, cutting force

415.9098 N, specific cutting energy 3.9176 J/mm3, Grey relational grade 0.701227.

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