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Multi-Objective Optimization of Cutting Parameters and Toolpaths in Pocket Milling Considering Energy Savings and Machining Costs

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Abstract. Productivity gains and minimum environmental impacts is the new challenge faced by enterprises, industries, and researchers. Mechanical machining is one of the widely used techniques in manufacturing. So, it's important to accurately and effectively estimate and optimize the overall ecological and economic footprint. Since, cutting energy and machining cost is proportional to machining time, production-costs minimization could be achieved by embracing machining time reduction strategies. These may include the use of more efficient toolpath strategies that reduces machining time, therefore, ecological and economic costs. In the literature, many studies have focused on minimizing cost and environmental impact by examining the entire machining process, while the environmental/economic flow of toolpaths is relatively unexplored. The implementation and selection of a cutting path strategy with appropriate cutting parameters has a significant impact on machining costs. The purpose of this paper is to examine the impact of toolpath strategies in pocket machining. The cutting parameters considered are cutting speed, feed, depth of cut and feed. The aim will be addressed by means of using Taguchi parameter design. This could further raise the integrity of sustainable machining strategies in an earlier step of machining processes.

Keywords. Cutting parameters, toolpaths, cost, energy consumption, optimization, pocket.

1. Introduction

With increasing regulations and mandates in the field of sustainability, the need for high-quality products with minimal environmental impact forces manufacturing to consider not only economic benefits, but also environmental footprints. One of the basic cutting processes is pocket milling. Studying toolpath strategies is necessary to achieve the high quality of the desired cavity. The most commonly used toolpath strategies in pocketing are contour, zigzag, zigzag, and spiral, which can be generated using computer-aided manufacturing (CAM) software. Proper toolpath selection can significantly save machining time, tool life and improve part quality, i.e. machining costs and productivity [1,2]. Toh performed an analytical analysis of the toolpath strategy to evaluate and determine the optimal cutting angle orientation on the plane [1]. Monreal and Rodriguez studied the influence of toolpath strategy and high feed rates on cycle time [2]. Abdali et al. have investigated the influence of different path strategies of the tool on surface roughness, material removal rate and cutting time in face milling [3]. Researchers have worked on the improvement of the performances of milling operations from cutting forces, tool wear and tool life point of view. Therefore, response surface methodology, gray relation analysis and Taguchi methodologies were adopted in order to realize a multi-objective optimization [4,5].

From the previous studies, it is noticeable that the optimization of toolpath strategies is a critical parameter in the improvement of machining processes quality. But the ecological and the economic flows are not taken into consideration in most of these studies. The objective of this paper is to improve the sustainability performance in pocket milling of manufactured parts to meet the industrial and the environmental requirement. Cutting energy, machining cost and material removal rate are considered as key responses, whereas, cutting speed, feed rate, depth of cut and stepover were considered as quantitative inputs and the toolpath strategies as qualitative input. The multi-objective optimization process is performed based on a combined Taguchi-Grey relation analysis technique.

2. Numerical Procedures

In order to evaluate which machining strategies, affect the machining cost in pocket milling, a number of experiments have been, numerically, realized. In the present work, cutting parameters values adopted in the literature [6].

2.1. Material and Milling tool

The workpiece material used in our experiments is ASTM A36 Steel which is a low carbon steel. The example part is represented Figure 1. The initial shape of the block is 200mm×120mm×20mm with a simple geometry pocket: a rectangle of 150mm×70mm×10mm with 4 fillets of 20mm radius and a width of cut 1mm. We assumed that this pocket is machined with a cylindrical tool of 10mm diameter, two flutes and engaged at 75%. The tool material used for the part is carbide. Solidworks® is then used to create different tool paths.

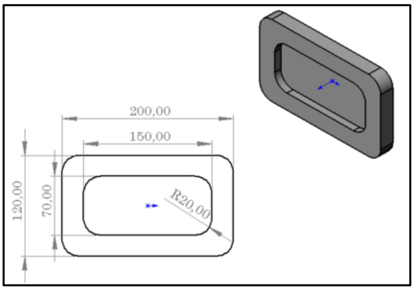

Figure 1. The example part

The operator's rate is assumed to be 28,320 Dinars per hour and the machine rate of a machining centre is assumed to be 14,160 dinars per hour. In addition, it is assumed that low carbon steel costs about 5.390 dinars per kg and the factory expense is 2,270 dinars per each part. Estimated set-up time per part is 1.2 min. All these values are taken from the literature [7].

2.2. Design of experiments

Four quantitative input factors, i.e., cutting speed, feed rate, depth of cut and stepover, and one qualitative factor which is tool strategy are adopted as input parameters, to measure the cutting energy consumption and the machining cost as output parameters. The four levels of input factors are shown in Table 1.

Table 1. Factors and levels of the pocket milling

Factors		Levels			
		1	**2**	**3**	**4**
Quantitative Input factors	**Cutting speed (m/min)**	17	19	21	23
	Feed Rate (mm/min)	120	180	240	300
	Depth of cut (mm)	0.2	0.4	0.6	0.8
	Stepover (mm)	2	3	4	5
Qualitative Input factors	**Toolpath strategy**	Contour	Zigzag	Zig	Spiral

Four toolpath strategies (Contour, Zigzag, Zig, Spiral) were generated using Solidworks® software. In order to reduce the machining time, energy and costs the Taguchi method is applicated. In this study, the experiments are realized with Minitab 19 software. The output responses are represented in Table 2.

2.3. Calculation of machining cost

Manufacturing cost calculation is essentially based on machining time and material cost [8]. Machining time is composed of set-up time T_{setup}, operation time T_O and non-operational time T_{NO} . Set-up time is the waiting period of a machine-tool for part configuration when two consecutive operations are not performed on the same machine and tool configuration (or change) when two adjacent operations use different cutting tools. It is proportional to the number of settings per batch. The operational time is the cutting time and the non-operational time is the air cutting time.

Manufacturing cost is given by Eq. (1):

$$C_{manufacturing} = (C_{labor} + C_{machine})(\frac{T_{setup}}{Q} \times T_O + T_{NO}) + C_{material} + C_{F.Ex} \qquad (1)$$

Where C_{labor} is the direct labor ($/hour), $C_{machine}$ is the machine rate ($/hour), Q iq the batch size, $C_{material}$ is material cost and $C_{F.Ex}$ is the factor expenses.

2.4. Material Removal Rate MRR

The material removal rate is given by Eq. (2):

$$MRR = V_f \times a_e \times ap \quad (2)$$

Where a_e is the width of cut (mm), a_p is the depth of cut (mm) and V_f is the feed rate (mm/min).

2.5. Cutting energy consumption

The cutting energy is the energy used for cutting the workpiece removing workpiece material into the form of chip. It is given by Eq. (3):

$$E_{cutting} = P_{cutting} \times t_{cutting} = k \times MRR \times t_{cutting}$$
(3)

Where k is the specific cutting energy which depends on types of workpiece material and reflect the machinability of the workpiece. In this study, the specific cutting energy k was evaluated to be 5,1175 J/mm^3.

Table 2. Output responses

Exp.N°	Machining strategy level					Responses		
	Cutting speed	**Feed Rate**	**Depth of cut**	**StepOver**	**Toolpath strategy**	**Cutting Energy (Wh)**	**MRR (mm^3/min)**	**Cost (Dinars)**
1	17	120	0.2	2	Contour	1.306	24	30,9390
2	17	180	0.4	3	Zigzag	3.750	72	29,7736
3	17	240	0.6	4	Zig	4.900	144	20,7664
4	17	300	0.8	5	Spiral	7.488	240	19,3702
5	19	120	0.4	4	Spiral	4.525	48	50,7885
6	19	180	0.2	5	Zig	0.667	36	13,0641
7	19	240	0.8	2	Zigzag	10.593	192	31,3092
8	19	300	0.6	3	Contour	5.530	180	19,1302
9	21	120	0.6	5	Zigzag	3.741	72	29,7127
10	21	180	0.8	4	Contour	6.002	144	24,5896
11	21	240	0.2	3	Spiral	1.488	48	19,2697
12	21	300	0.4	2	Zig	6.004	120	28,7505
13	23	120	0.8	3	Zig	7.850	96	44,5595
14	23	180	0.6	2	Spiral	13.114	108	64,3091
15	23	240	0.4	5	Contour	2.444	96	16,5085
16	23	300	0.2	4	Zigzag	0.745	60	10,0133

3. Results and discussions

Taguchi method is unable to solve multi-response optimization problems. So, to overcome this problem, we combined the Taguchi method and grey relation analysis. This combination is able to convert the multi-objective optimization problem to a single objective problem.

3.1. Application of Grey Relation Analysis

To achieve the maximum material removal rate with minimum cutting time, and minimum cutting energy “the-higher-the-better” and “the-lower-the-better” conditions are chosen respectively. Then, we calculated the different grey relation coefficients (GRC) as it shown in Table 3. The max of average value of GRC (GRG) indicate the closest combination of input parameters to the optimum solution. In this study, the best input parameters correspond to experiment N°16: A4B4C1D3E2, i.e., cutting speed =23m/min, feed rate=300 mm/min, depth of cut = 0.2 mm, stepover= 4mm and zigzag toolpath strategy.

Table 3. Calculated grey relational coefficient and GRG

Exp.N°	Grey Relation Coefficient GRC			Average	Rank
	MRR	Machining Cost	Cutting energy		
1	0,33333333	0,56471602	0,90690841	0,60165259	8
2	0,39130435	0,57874559	0,66872319	0,54625771	11
3	0,52941176	0,71628450	0,59538240	0,61369289	7
4	1,00000000	0,74367975	0,47708603	0,74025526	3
5	0,36000000	0,39968625	0,61731115	0,45899913	14
6	0,34615385	0,89897664	1,00000000	0,74837683	2
7	0,69230769	0,56039957	0,38536907	0,54602544	12
8	0,64285714	0,74860166	0,56139039	0,65094973	6
9	0,39130435	0,57949780	0,66935626	0,54671947	10
10	0,52941176	0,65065117	0,53844383	0,57283559	9
11	0,36000000	0,74573354	0,88351019	0,66308124	5
12	0,47368421	0,59164937	0,53834531	0,53455963	13
13	0,42857143	0,44004085	0,46420983	0,44427404	15
14	0,45000000	0,33333333	0,33333333	0,37222222	16
15	0,42857143	0,80693835	0,77794457	0,67115145	4
16	**0,37500000**	**1,00000000**	**0,98770118**	**0,78756706**	**1**

3.2. Determination of optimal machining strategies

Table 5 represents the average values of GRG (A-GRG). The maximum value of A-GRG indicates the best performance of input factors. As it is shown in Table 4, the best performance corresponds to the cutting speed at level (4), the feed rate at level (1), the depth of cut at level (1), the stepover at level (4) and finally the toolpath at level (1) (i.e., A1B4C1D4E1). The difference between the max and the min of each factor has been also calculated. This difference indicates the degree of influence of each factor on the output respond. In our case, the feed rate has the most significant influence while the cutting speed has the least influence.

Table 4. A-GRG at different levels and determination of the optimized input factors

	Level 1	Level 2	Level 3	Level 4	Difference	Influence
Cutting speed	**0,625464613**	0,601087784	0,579298983	0,568803692	0,056660921	5
Feed rate	0,512911307	0,559923087	0,623487756	**0,678332921**	0,165421614	1
Depth of cut	**0,70016943**	0,552741981	0,545896078	0,557834629	0,154273353	3
Stepover	0,513614971	0,528153031	0,608273667	**0,676625752**	0,16301078	2
Toolpath	**0,624147339**	0,606642421	0,585225846	0,558639465	0,065507874	4
Optimized Input sequence		*A1B4C1D4E1*				
		Cutting speed = 17 m/min, Feed rate= 300mm/min, Depth of cut= 0.2mm, Stepover= 5mm, Toolpath= contour				

3.3. Verification of optimum levels of Input factors

Table 6 presents the experimental confirmation of the optimum process factors. As it is indicated in Table 5, we note that is an improvement about 2% from the predict results.

Table 5. Comparison of predicted results and the experimental results

Factors / Responses	Optimal machining strategy	
	Predicted results	**Experimental results**
	A4B4C1D3E2	A1B4C1D4E1
Machining Cost (Dinars)	8.93	10.013
Cutting energy (Wh)	0.614	0.745
MRR	60	60
GRG	0.7722	0.7875
The % improvement = 2%		

4. Conclusions

For the ASTM A36 cavity machining process, perform a multi-objective optimization problem to optimize cutting energy, machining cost, and material removal rate. This study examines the effects of different machining strategies, which include a quantitative parameter: cutting speed, feed rate, depth of cut and feed, and a qualitative parameter, the toolpath strategy. A series of numerical experiments were performed using the Taguchi method. A summary of this stream is as follows:

- Feed rate has become the main factor. After stepover, the depth of cut, then the toolpath strategy, and finally the cutting speed.
- Best machining performance was obtained with a cutting speed of 17 m/min, a feed rate of 300 mm/min, a depth of cut of 0.2 mm, a stepover of 5 mm and a contour toolpath. The best combination was verified by confirmatory testing.

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