# Multi-Objectives Optimization on Cutting Layers and Cutting Tools Selection for Sculptured-Dies Cavity Rough Machining: A State-of-the-Art Review

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## ABSTRACT

Sculptured-dies roughing (SDR) has some different objectives that maybe contradicting and therefore needs trade-off among them. Compared to prismatic and rotational shape machining, SDR is more complex considering the sculptured characteristics of machining surface. Layer-by layer approach applied in SDR requires multiple tools selection and determination of the depth of cut for each cutting layer. Those decisions need to be considered in SDR optimization problem. The trade-off between different objectives are required, such as machining residues/cut-off (or coverage) from the roughing process to be traded-off with the machining (roughing) time. This paper presents a state-of-the-art review on cutting layer and cutting tools selection (CLT) by multi-objective optimization for SDR and presents the needs for a trade-off between machining time and cut-off (residual volume) by minimizing machining Time per Volume Coefficient (TVC). The process is conducted simultaneously. A systematic literature review is presented to show the complexity of the geometric related problem, the optimization techniques that have been applied, and the different objectives in SDR, including some multi-objective coverage. Finally, some directions on algorithms for optimizing TVC in TLC problem is presented. Considering the combinatorial problem in CLT, this paper overviews the Multi-Objectives Dynamic Programming approach (MODP) and Metaheuristics Multiple Objective approaches (MOGA etc.) for CLT problem optimization. The results confirm that the optimum tools combination and cutting layer selection could increase SDR efficiency. The paper conclusion discussed recommended metaheuristic approach to trade-off between machining time and residual volume in more complex problem.

*Keywords:* *Sculptured-dies roughing (SDR), Tooling and Layering, Machining Time per Volume Coefficient (TVC), Multi-Objectives Dynamic Programming (MODP), Multiple Objective Genetic Algorithm approach (MOGA).*

## 1. INTRODUCTION

Sculptured-dies roughing (SDR) is part of a discussion in free-form surface machining (FSM) with special section on machining metal mould with sculptured walls [1-2]. Literature studies shows some topics of interest in SDR due to the complexity of the problems related to the sculptured characteristics of the machining cavity walls. In products with prismatic and rotational features, the machining time is linear with the tool path length, but on the sculpture surface, the machining time is not linear to the length of the machining surface as the consequence of the acceleration and deceleration of the feed rate [3-5] caused by changes in the surface contour of the sculpture and differences in critical distance (CD) in each layer so that it requires tools with different diameters for each cutting layer. Compared to the machining process for making cavities with prismatic or rotational shapes, the machining process for SDR with sculptured surface/ walls requires a different approach.

Latest update review about FFM, classified FFM into 5 domains [6] : (1) Investigation by experiments (2)

Analytical (3) tool-path generation (4) reconstruction of the surfaces, and (5) inspection process. Out of 168 papers reviewed in that studies, 89% make use of metal materials (Al and steel alloys), 56% studies about 3-axis machining.

This paper focuses on analytical studies for 3-axis roughing objectives. There are several research topics in FFM 3-axis milling machines objectives, such as energy savings [7-8], machining time [9-10], surface roughness and tool life [11]. Some other topics are related with the characteristics of sculptured surface that need to be considered in setting the FFM objectives, such as dynamic behaviour of machining and feedrate scheduling [5,11], subdivision of machining area and tool allocation [4,13-15], and prediction and evaluation of process parameters [6]. These topics arise because the geometric contours of the FFM are different from rotational and prismatic features [6].

FFM Roughing can take as much as 60% of total machining time [16]. Aggressive machining, which is the selections of largest-possible cutting tools, can be an alternative to minimize roughing time. On the other hand, minimizing roughing time, may increase finishing time [17].

Like FFM, SDR requires process planning with a high level of expertise and experience [13]. Due to the complexity of the problem, the time required for planning the machining process is often longer than its machining time [2].

Research in the field of SDR is becoming increasingly important, with the increasingly diverse forms of products made for consumers, with more diverse sculptured display designs, both in terms of aesthetics and functions, such as the appearance of electronic goods such as cell phones, household items such as cooking utensils, children toys, to products that require high technology / design such as turbine components, so more and more metal moulds are made with sculptured forms using the SDR process [1-2,4].

SDR is the process of making a metal cavity in the form of a mould through milling process which usually goes through two stages of the machining process, namely roughing and finishing. The finishing process requires a higher level of accuracy because it involves product specifications with a fairly high tolerance level [4]. The roughing process is the initial stage of the machining of a cavity so that most of the volume of the mould cavity is removed and leaves a portion of the volume called residual volume or un-cut volume. This

part requires a more precision process at the finishing stage.

The SDR process on a 3-axis CNC milling machine is conducted by using some selected flat-end mill tools with different diameters. Some considerations for tools selection are tool availability, machining time and geometrical limitations of the cavities or cutting layers to be machined [18]. About 80% of milling operations for the mechanical parts machining can be done by the movements of cutting tools only in the XY, YZ and ZX main Cartesian planes, or commonly called as 2.5-axis milling processes [18]. In SDR, the machining process can be carried out layer by layer in a horizontal direction (XY) with a depth that is adjusted to the tools parameters and geometric cavity boundaries [4]. This process is called layer-by- layer machining. Figure 1 shows the cavity which is cut by using flat-end-mill cutting tools. The figure represents the cutting operations in XY direction, layer-by-layer from A cutting layer to D.
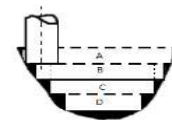


**Figure 1** Layer-by-layer die-cavity-machining

Table 1 shows some researches that have been carried out on the XY-single cutter and XY-multiple cutter. This paper focuses on the SDR process on a 3-axis CNC milling machine with layer-by-layer machining process, XY-single cutter.

Based on the direction of the machining axis and the number of tools used, the SDR process for single cavity on a 3-axis CNC milling machine can be divided into three groups, namely machining with single cutter [19-20], XY-Single cutter [12-13, 21-23] and XY-multiple cutter [27]. In the XY- single cutter, one tool is selected for each cutting layer, while for the XY-multiple cutter, several tools with different diameters are selected in order to expand the coverage area of the in feed in the cutting layer. The choice of the tools allocation also depends on the geometrical constraints and tools availability. In single cutter, only one cutter selected for the whole cavity. With advance technology in CNC machining with tools magazine and non-significant time of tools-change- over time [13], single cutter usage for the whole cavity, may be not efficient. On the other hands, the tools selection and sub-division of cutting area or layering becomes the challenge in multiple cutters usage.

**Table 1.** Tooling and area decomposition in SDR

| SDR – Single cavity | | | SDR – Multiple cavities |
|---|---|---|---|
| Layering and tooling | | Area sub-division and tooling | |
| Single cutter [19-20] | XY-Single cutter [12-13, 21-23] | XY-Multiple cutter [24-26] | [29] |

In XY-single cutter machining problem, the decision about tools selections and allocation for each cutting layer, and the determination of each cutting layer depth need to be optimized. There is still lack of research to optimize multiple cutters selection for aggressive roughing in CNC 3-axis machines [13], while no research yet to trade-off simultaneously between multi-objective in XY-single cutter machining.

## 2. FFM MULTI-OBJECTIVE OPTIMIZATION

In SDR with single cavity, there are 3 research groups on optimization as described in Table 1. The first one is optimization with single tool for the entire layers [19-20]. The second one is optimization with multiple cutting tools, one tool is allocated for each cutting layer, this is called XY-single cutter. Research about this was conducted by [12-13,21-23]. The third one, optimization with multiple cutting tools, more than one cutting tools are allocated for each cutting layer. This is called XY-multiple cutter. Research about this was conducted by [24-26]. In the optimization of single cavity, the focus of research is on the choice of tooling and layering strategies which partly neglecting non-cutting time [4], the time of moving the tool and the time of changing the tool.

In XY-single cutter, research regarding the sub-division of machining areas (roughing) and the selection/allocation of tools are still limited to single objective.

Machining optimization in multiple cavities was discussed in [13-14]. In multiple cavity problem, the focus of research is generally on the grouping of the XY area (sub-division) and generally covers

the total machining time including non-cutting time.

FFM has some different objectives that maybe contradicting and therefore needs trade-off among them. Compared to prismatic and rotational shape machining, FFM is more complex considering the characteristics of machining surface in FFM [4]. Table 2 presents some researches in FFM which discussed trade-off between machining variables [29-34]. This trade-off occurs because of the sculptured surface characteristics from which happen the start-stop and acceleration and deceleration of the feed of the tools, or it is known as dynamic behaviour of the machining tools in FFM [5].
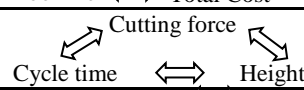
Tool life and machining cost can be traded of by setting optimum machining parameters i.e cutting speed and depth of cut [29]. While scallop height which is representing depth of cut, can be traded of with cutting force and cycle time [30]. In [31], machining time can be traded of with energy consumption. While energy consumption can be traded of with surface roughness [31], that means machining time can be traded of with surface roughness [32], and those 3 objectives which are surface roughness, energy consumption and machining time can be traded of altogether [33].

## 3. SYSTEMATIC LITERATURE REVIEW

This Systematic literature review is conducted based on the searching from Science Direct database year 2011-2020. Science Direct is one out of 14 academic search systems examined that are well-suited to evidence synthesis for systematic reviews since they met all necessary requirement [31].

The keywords used in searching process is 3-axis milling in sculptured surface machining with layer-by-layer approach (first keywords) and the additional keywords (second) based on the variables from the state-of-the-art of FFM multi-objective optimization presented in section 2 (Table 2). The result is presented in Table 3.

**Table 2.** Some multi-objectives research in Machining Optimizations

| Researcher | Trade-off variables | Methods |
|---|---|---|
| [28] | Tool life ⟺ Total Cost | Full-factorial 3 levels |
| [30] | Cutting force / Cycle time ⟺ Height of scallop | Weighted-objectives algorithm |
| [30] | Energy consumption ⟺ Surface Roughness | Principal component and surface |

| | | response method |
|---|---|---|
| [31] | Machining time ⟺ energy consumption | surface response method |
| [32] | Machining time ⟺ Surface roughness | Genetic algorithm |
| [33] | Surface roughness / Machining time ⟺ Energy consumption | Pareto analysis and Weighted signal-to-noise |

There are 57 articles discussed about machining time and toolpath, only 1 other article discuss machine time without discussing tool path

Related with dynamic behaviour of the machining tools in FFM mention by [5], there are 22 articles discuss about dynamic machining behaviour, 5 articles discuss about feed rate scheduling, and 2 out of those discuss both topics.

Related with tool cost mention by [29], there are 35 articles discuss tool life, 52 articles discuss about tool cost, and 28 out of those discuss both topics, which means there are more research discussing the relationship or trade-off between those objectives.

Related with energy consumption mention by [30-31, 33] and surface roughness mention by [30,32-33], out of 73 articles discussion about machining time, 14 of those are relating machining times with energy consumption and 37 articles are relating machining times with surface roughness. There are 9 articles discuss those 3 topics overall.

Related with number of cutters used, there are 19 articles discussed about multiple cutters, 16 of those discuss multiple and single cutters altogether, and only 6 articles discussed about single cutter alone. That means there are more research interest in discussing multiple cutters selection.

**Table 3.** Researches on FFM (3-axis CNC milling)

| Keywords (second) | | Total articles | |
|---|---|---|---|
| Toolpath, machining time | | 22 | 57 |
| Dynamic machining behavior | | | 2 |
| Feed rate scheduling | | 5 | 2 |
| Tool life | | 35 | 8 |
| Tool Cost | | 52 | 1 |
| Machining time | | 73 | 4 |
| Energy Consumption | | 15 | 38 |
| Surface Roughness | | | |
| Surface Roughness, | | | 37 |
| machining time | | | 9 |
| Surface Roughness, Machining time, energy consumption | | 19 | 1 |
| Multiple cutters | | | 6 |
| Single cutter | | 22 | 3 |
| Roughing time | | 44 | 0 |

| Keywords (second) | | Total articles | |
|---|---|---|---|
| Finishing time | | 47 | 22 |
| Multiple objectives | Multiple | | |
| Multiple objectives, | | | 9 |
| cutters, machining time | | | 27 |
| Genetic Algorithm | Genetic | | |
| Multi Objective | | | 20 |
| Algorithm | | | |

Related with processing steps in FFM miling, 44 articles discuss about roughing process, 30 of those discuss about finishing too. Only 14 articles focus on roughing.

Out of 73 articles which discuss machining time, and 22 articles which discuss about multiple objectives, only 9 articles are relating that topic to multiple cutters and machining time. Since there are technological development in CNC machining which support the use of multiple cutters [13], the more sculptured design of customer products, complex characteristics of FFM [4] which needs trade-off between two or more objectives [28- 33], the discussion about multiple objective for multiple cutter selection in FFM is an interesting research.

## 4. DISCUSSION AND FUTURE WORKS

### 4.1. Trade-off Between roughing time and residual volume (cut-off) by Multi-Objectives Dynamic Programming approach (MODP)

Inspired by some trade-off between variables in SSM [28-33], with the application of multi-objective optimization [7-8,28,34-35], the formula for calculating machining efficiency [17] which is proven scalable in SDR, the merging rules between hunting layers [12], the view of the tools selection as shortest path problem [22-23], the conflict between roughing time and residual volume (cut-off) [17,21], and the application of dynamic programming algorithm for multiple tools selection problem [12], this section discuss cutting layer and tooling strategy selection (CLT) for SDR and presents trade- off between machining time and residual volume by minimizing machining Time per Volume Coefficient (TVC) in order to optimize the two objective variables simultaneously by applying Multi-Objectives Dynamic Programming approach (MODP).

The object selected is die-cavity with certain depth and sculptured wall, with L hunting layers, maximum merged layers are M layers, total P flat end mills tools with certain diameters are selected as alternatives with minimum 1 and maximum P tools can be selected. Total sets of data is 22 from slightly different shapes of cavities, with 3 different scenarios of possible tooling (P), merging (M) and hunting layers (L). The setting of other cutting parameters are as per defaults set by the CAM software.

The optimization model and algorithm are developed in MATLAB software. The constraints are similar with the ones in [12,17], except for the residual volume since it become part of TVC objective function.

The input matrix is developed based on network rules for tool selections similar with [12,17] with limitation of P, L and M values. The objective values for each alternatives is TVC values.

The solution delivers better machining efficiency compared to the solution with single objective (machining time minimization). It shows 10% improvement in TVC values.

$$TVC_{k-1} \quad (j) = Min_{¿¿} \qquad (1)$$

$$i$$

$TVC_l{}^{p,m}$ is a function of machining time $T_l{}^p$, residual volume $R^m{}_l$, and total cavity volume to be machined $V^m{}_l$. Where l is representing hunting layer (l=1..L/A,B,C…), p is representing alternative tool (p=1..P), and m is representing number of merged layer (m=1..M). Equation 1. Shows the TVC formula. This formula was adapted from [17].

### 4.2. Multi-objective metaheuristic application for Trade-off Between roughing time and residual volume.

#### 4.2.1. The scalability problem

The studies presented in Table 2 are concerning the selection of machining parameters so that an experimental design approach is used, namely factorial design, principle component, response surface, pareto analysis and signal-to-noise ratio [28,30-31,33]. Two other studies [29,32] examined combinatorial decision sets. In a solution search algorithm, [29] used a weighting approach, while [32] apply genetic algorithm approach.

The objective weighted algorithm [29] applied since the effect of one decision variable with the other decision variables is proportional, so that the weight

given to each variable is relatively constant. This approach cannot be used for machining time and residual volume variables since there is scale problem that the proportion of residual volume to total volume will decrease with increasing cavity volume so that another approach is required to accommodate the non-linear nature of the volume proportion to the residual volume after roughing. Setting TVC as objective variable is the approach to overcome this problem.

FFM optimization problem is complex combinatorial problem [12,17,35] and therefore metaheuristic approach will help in finding the near-optimal solution for SDR problem optimization.

## 4. CONCLUSION

This paper introduced approach for a multi-objective CLT problem. The simulation is conducted to evaluate the TVC result and compare with single objective solution. The multi-objective approach has shown better TVC performance which will improve both roughing and finishing time.

Some metaheuristics approaches for the problem has been proposed. The studies has shown no clear winner, since it is conditional to the scenario. While two other metaheuristic approaches (VCO & MOGA) still need to be tested in this problem

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