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Analysis of Different Tool Path Strategies for Free Form Machining with Computer Aided Surface Milling Operations

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Abstract

Free form surfaces are commonly used to generate aesthetic parts. These parts can be manufactured directly by material removal techniques or indirectly with molding or forming techniques. In any case, these surfaces must be commonly machined with traditional processes, at least until certain degree of surface finishing, and the tool path must be generated with computer aided applications. In doing so, developers are implementing new theoretical strategy operations for controlling tool path and trajectories. These new options have so many combinations that it is difficult to know which is the best one to choose when defining the tool movements. Apart from the traditional strategies fixed angle method, principal axis method and multipoint machining, combined with tool orientation, there are many other strategies to explore due to machine tool and numerical control improvements. What is need now is a validation of these new strategies in computer aided applications regarding time minimizing and how the cutting parameters affects in the surface final result.

Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference

Keywords: 3DEXPERIENCE; aerospace materials; thermosetting materials; surface machining; simulation of machining processes; Industry 4.0.

1. Introduction

In the specific case of freeform surfaces machining, defining the toolpath strategy during the detailed manufacturing process planning is a critical task for parts manufacturing. Manufacturing Engineering Planners must meet very strict requirements in part and features design that determine the technical operations. For material removal, the tool

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selection and trajectory scheduling is a large and complex sequence with different stages or steps to achieve the required quality in the minimum time taking into account company's strategic indicators.

Freeform surfaces are commonly used to generate aesthetic parts. These parts can be manufactured directly by material removal techniques or indirectly with molding or forming techniques. In any case, these surfaces must be commonly machined with traditional processes, at least until certain degree of surface finishing, and the tool path must be generated with computer aided applications.

Recent research about the Artificial Neural Network (ANN), can help in the prediction of milling tool-path strategy and could be made in order to establish which milling path strategy or their sequence will show the best results [1]. The analysis of different finishing milling strategies of a complex geometry part containing concave and convex surfaces and the machining quality can be evaluated through the comparison of surface roughness, surface texture and dimensional control parameters [2]. Other interesting work is the 3D surface roughness parameter identification according to the machining strategy parameter and the surface description [3]. Surface topography is also a key element between process parameters and manufactured part performances [4]. The produced surface quality is affected from the selected milling strategy [5].

For that reason many developers are developing new theoretical movements strategies in machining operations for controlling tool path and trajectories. In doing so, manufacturing planners are trying to implement them in computer aided applications and test the theoretical advantages of the trajectories [6]. For example, a smaller scallop trajectory does not necessary mean that a better tool trajectory, because it implies longer machining time.

These new options in tool movements have so many combinations that it is difficult to know which is the best one to choose when defining the final tool path [7]. In the evaluation the roughness, the results show that the tool-surface contact had the greatest impact on the forces, because it can either be related to the effective tool diameter or with the tool tip on the cutting zone [8]. In recent researchers the effects of lead and tilt angles in 5-axis ball-end milling of flexible freeform aerospace parts by considering process mechanics and the effectiveness of the proposed strategy were validated by conducting experiments on 5-axis ball-end milling of flexible freeform structures [9].

Apart from the traditional strategies of isoplanar or isoparametric movements, it must be considered the combination with tool orientation, angle, principal axis and multipoint machining methods. This is a consequence of the rapid machine tool and numerical control improvements [10].

What is need now is a validation of these new strategies in computer aided applications [11] and how the cutting parameters affects in the surface final result [12]. The tool path planning consists of two main aspects: the path topology and the path parameters.

The first is defined by the pattern in which the cutter moves to produce the surface, and the last one is modeled by the passage of the tool side between the successive paths and the forward step of the tool in each path. Therefore, the challenge of toolpath generation is divided into the following three secondary problems for each specific and defined tool:

1. To specify the path pattern and the linking strategy
2. To specify the needed points on the surface
3. To check the local and global interference between tool and geometrical features of the part.

As every toolpath must be created through the selection of the appropriate topology and the parameters, in free form machining operations there is a need to stablish a methodological procedure for cutting location data (CL data) generation according to design requirements.

In order to reduce the total time operation, many investigations have focused on minimizing the total length of the path and the number of retractions of the tool. For freeform surfaces milling, parallel contour and direction paths are the most commonly used. The normal and parallel paths of the borders are suitable for cleaning machining operations.

In a direction parallel path, the segments of the path are parallel to a predefined line (Fig. 1.a). This line could be parallel or normal to the boundary of the surface or parallel to the axis of a specified coordinate system. An appropriate selection of the reference line affects directly to the length of the generated trajectory. A specific case of path parallel to the direction, *zigzag* path, is commonly used in commercial CAM systems for roughing.

A contour parallel path is constructed by the limit curves of the surface. Each route is a displacement of the surface boundary towards the center or in a reverse way (Fig. 1.b).

The distance between consecutive Cutting Contact (CC) points is called step forward designated by f, the distance between two adjacent paths is called the travel interval, indicated by w (Fig. 1).

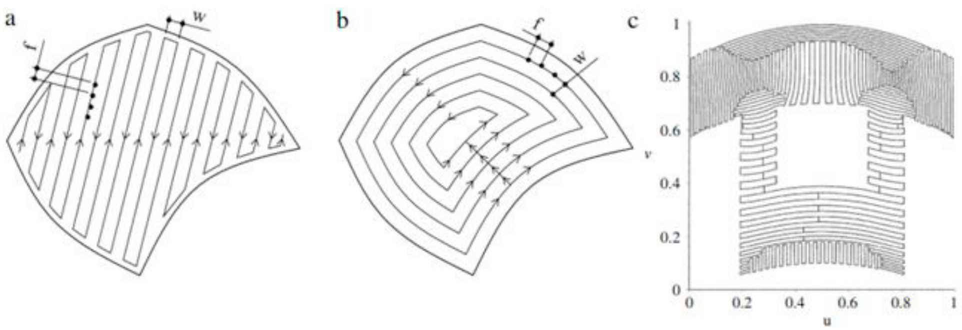


Fig. 1. Path topologies surface machining. (a) Direction parallel, (b) Contour parallel (c) Adaptive Curvilinear space filling curve (source: [13])

Two methods are often used to calculate the path parameters: circular adjustment of the approach arch and maximum chordal deviation. Although in most tool path generation methods, line segments are used to define the lengths of the step forward, interpolation of tool paths generated with polynomial curves has also been carried out. It is expected that this will reduce the machining time when the tool path is transformed into movement of the machine axis by the Numerical Control unit and will decrease the size of the memory required within the CNC controller.

For example, in more recent research about the manufacturing of spiral bevel gears, the machining strategy is fully defined with trajectories and after the manufacturing the final geometry is evaluated [14]

In order to help decision making for micro process planning in surface milling operations with 3 axis machines, this work contributes with an initial comparative analysis of different computer aided operation strategies, according to theoretical methodologies for generating free form surfaces commonly used in mold and die manufacturing. The set of experiments helped to validate the process plan and gave feedback about the expected results according to cutting parameters.

The aim of the work is to determine which is the appropriate machining strategy for 3 axis surface milling using computer aided applications through a comparative analysis and their corresponding experiments.

2. Methodological Analysis and Experimental Setup

2.1. Methodology for Machining Computer Aided Strategies Validation

The methodology followed for the analysis has four main stages.

1. To analyze the different theoretical strategies for toolpath generation in surface milling.
2. To define and to identify the indicators to be evaluated regarding to geometrical outputs and process metrics.
3. To evaluate the alternatives for surface machining offered by a commercial application (DELMIA from Dassault Systèmes).
4. To perform a set of theoretical and practical experiments to validate results.

For the development of the theoretical case studies two parts were designed. The material selected was AISI 1045 and inserts cutting tools for roughing and integral cutting tools for finishing were used. The set of experiments was done according to the combination of strategies and cutting parameters recommended by the tool manufacturer.

For this work, it was analyzed different options for tool path generation in surface milling, with all the possible combinations and simulations. Besides it was done a corresponding analysis with the theoretical strategies in order to have a mind map of free form machining which can add an extra in micro process planning.

It is expected that the results will help manufacturers to have a predictable output map from different surface milling strategies that could be useful when analyzing machining operations under different optimization criteria.

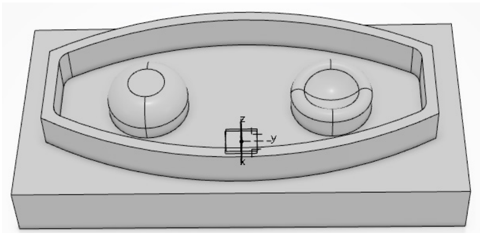
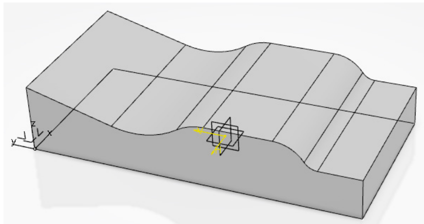
For the material removal operation, several cutting methods were used, with various strategies, simulating the part machining, that helped to compare different process variable results and to choose the best strategy.

2.2. Experiments Design.

In this work It was carried out the analysis of the manufacturing process plan of the designed models with a commercial CAx application (3DEXPERIENCE) In this case, it was defined two case study designs in order to test the different options for geometry generation and the machining of a free form surface, respectively, with the data obtained from the previous test. The machining process plan was developed specifically for the machining center Gentiger_GT_66V, a 4-axis machine with x-axis 720 mm, y-axis 500 mm and z-axis 400 mmm with a numerical control Sinumerik 840D from Siemens. Since there wasn't a digital twin of the machining resource, for the simulation analysis a standard machining center was used.

The tools selected to perform the experiments are moored with BT-40 standard and the simulation analysis was carried out considering the tool geometry and the cutting parameters. The first experimental part was used to test the different options for material removal in most common operations although the last two operations served to prepare the second experiment. The initial objective is to analyze strategies but not surface finishing which will be analyzed in later works (Table 1).

Table 1. Parts Designed for different operations machining strategies analysis

Experimental Design_01		**Experimental Design_02**	
			
Operations Sequence and Tools		**Operations Sequence and Tools**	
Face Milling	VPX300-063A06AR		
Profile Milling	VPX200R2003SA20S		
Pocket Milling	MSMHDD0400		
Roughing Surface Milling	 Ball Mill VQ4SVBR0600	**Surface Milling**	 Ball Mill VQ4SVBR0600
Finishing Milling Convex and Concave	 VQ4SVBR0300, r = 3 mm	**Finishing Milling**	 VQ4SVBR0300, r = 3 mm

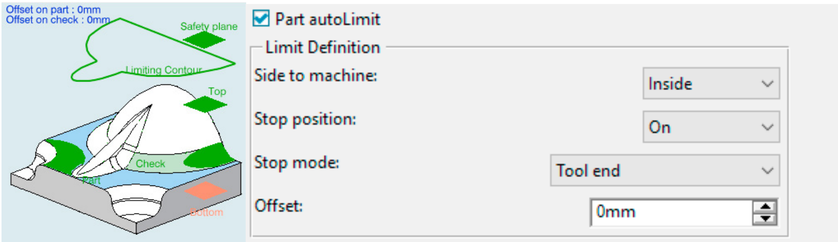
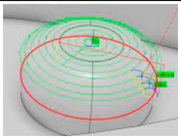
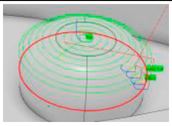
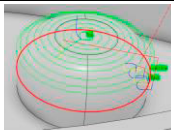
3. Experimental Results and Discussion.

The analysis of alternatives generated different strategies that can be applied for each operation. A sample of the results were selected for Experimental Design 01. Only finishing milling operations for the convex and concave geometries are described as they are directly related with Experimental Design 02. Then, for Experimental Design 02 three types of operations were analyzed: Roughing, Advanced Finishing and isoparameric Machining. The feed rate for all the analysis was fixed in 350 mm/min, the approach speed 100 mm/min and the retract speed in 100 mm/min. The spindle speed was fixed in 1700 rpm according to the tool manufacturer recommendations.

3.1. Analysis of finishing milling operations for the convex and concave Experimental Design 01.

Defining the finishing operation can be done with the same option of roughing milling with the CAM application. The difference is that the tool has a smaller diameter than the previous one and the material to remove is the 1 mm offset left earlier. The finishing parameters were defined with the Advanced Finishing option. The commercial tool used in this experiment was the Mitsubishi tool, carbide solid end mill coated with (Al,Cr)N with improved wear resistance, and the tool radius was 3 mm (VQ4SVBR0300). The parameters for convex surface are shown in Table 2.

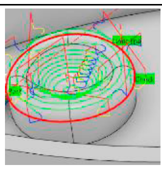
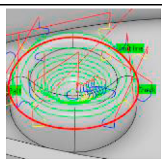
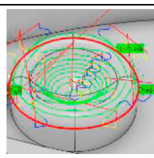
Table 2. Advanced Finishing Strategy for the convex surface in Experimental Design_01.

Advanced Finishing			
Tool parameters	Cutting Diameter DC= 6 mm; Tool Corner Radius RE= 3 mm; Maximum Axial Cutting Depth APMX= 9 mm; Flute Length LF= 15 mm; Total Tool Length OAL = 50 mm; Cutting Height Length LH= 18 mm		
Cutting mode	Conventional	Climb	Either
Zone	Maximum horizontal slope 15 deg. Axial depth a_p= 0.6 mm / Radial Depth a_e=1.2 mm		
Time (s)	24.7	24.7	24.7
Tool Trajectory			

From the results (Table 2), it is obvious that the cutting time is the same for every cutting mode. Therefore, no matter which strategy was selected it would be obtained the same cutting time for the finishing operation.

For the concave surface (Table 3), the three strategies for the finishing operation were repeated and the main cutting parameters had to be modified due to the interferences between surface geometry and tool geometry.

Table 3 Advanced Finishing Strategy for the conical surface in Experimental Design_01.

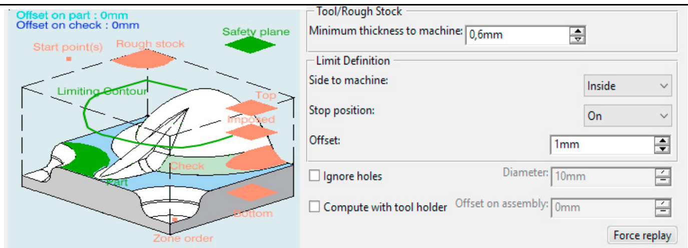
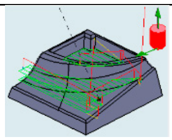
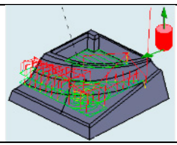
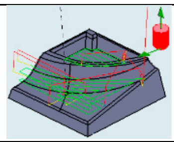
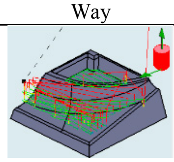
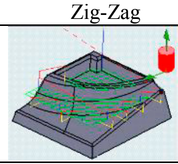
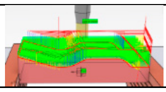
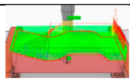
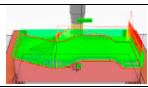
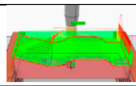
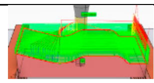
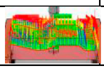
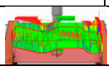
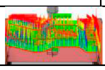
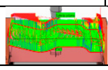
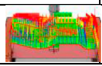
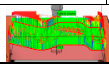
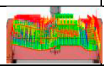
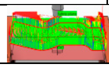
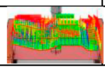
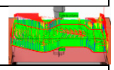
Advanced Finishing	Same as the finish of the convex surface		
Tool parameters	Same as the finish of the convex surface		
Cutting mode	Conventional	Climb	Either
Zone	Maximum horizontal slope 15 deg. Axial depth a_p= 0.2 mm / Radial Depth a_e=0.6 mm		
Time (s)	44	44	44
Tool Trajectory			

In the same way, it can be seen from the results in Table 3 that the cutting time was almost the same for each cutting mode. Again, the cutting strategy had no influence in the final operation time for this geometrical case. The analysis shown that the trajectories were almost the same due to the simplicity of surface and, therefore, of the operation.

3.2. Analysis of roughing milling operations for convex-concave combined surfaces. Experimental Design 02.

This experiment is focused to discover what happens when the part has a complex surface with the combination of convex and concave geometries. The work performed here has the objective to analyze the influence of the strategy in the machining operation total time. In this cases three trajectory styles where tested with their corresponding tool trajectory types (Table 4).

Table 4 Roughing Operation Strategy for Experimental Design 02

<table>
<tr><td>Roughing Operation Strategy</td><td colspan="10">
</td></tr>
<tr><td>Style in Pocketing</td><td colspan="10">Back and forth</td></tr>
<tr><td>Type of Trajectory</td><td colspan="2">Back and forth</td><td colspan="2">Concentric</td><td colspan="2">Helical</td><td colspan="2">Offset on part One-Way</td><td colspan="2">Offset on part Zig-Zag</td></tr>
<tr><td>Trajectory proposal</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Estimated Time (s)</td><td colspan="2">1 436.7</td><td colspan="2">1 482.0</td><td colspan="2">1 482.0</td><td colspan="2">1 482.0</td><td colspan="2">1 482.0</td></tr>
<tr><td>Proposed Path</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Style in Pocketing</td><td colspan="10">Concentric</td></tr>
<tr><td>Type of trajectory</td><td colspan="2">Back and forth</td><td colspan="2">Concentric</td><td colspan="2">Helical</td><td colspan="2">Offset on part One-Way</td><td colspan="2">Offset on part Zig-Zag</td></tr>
<tr><td>Moves</td><td>One-Way</td><td>Zig-Zag</td><td>One-Way</td><td>Zig-Zag</td><td>One-Way</td><td>Zig-Zag</td><td>One-Way</td><td>Zig-Zag</td><td>One-Way</td><td>Zig-Zag</td></tr>
<tr><td>Time (s)</td><td>3 973.0</td><td>2 464.0</td><td>3 973.0</td><td>2 464.0</td><td>3 793.0</td><td>2 464.0</td><td>3 793.0</td><td>2 464.0</td><td>3 793.0</td><td>2 464.0</td></tr>
<tr><td>Tool Trajectory</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Style in Pocketing</td><td colspan="10">Helical</td></tr>
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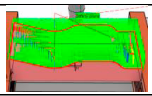
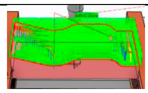
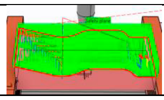
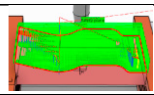
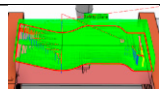
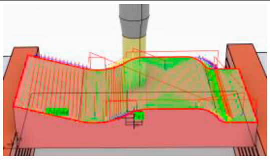
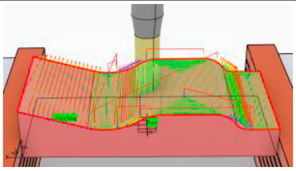
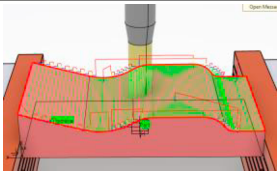
<tr><td>Helical Movement</td><td colspan="10">3 options: Inward, Outward, Both</td></tr>
<tr><td>Time (s)</td><td colspan="2">1 193.0</td><td colspan="2">1 193.0</td><td colspan="2">1 349.6</td><td colspan="2">1 193.0</td><td colspan="2">1 193.0</td></tr>
<tr><td>Tool Trajectory</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

In this case, there are many options to define the strategy, twenty options with this application, that outputs different results with this design. It will depend on the design and production objective the selected final strategy. It must be pointed out that, although there is a logic in the difference between one way and zig-zag movement, just one type of trajectory differs from the others.

3.3. Analysis of advanced finishing milling for convex-concave combined surfaces. Experimental Design 02.

To finish the process plan with the finishing operation two strategies were compared, an isoplanar machining and the isoparametric machining. The first one is denominated in the application as advanced finishing (Table 5).

Table 5 Operation Strategy Advanced finish for Experimental Design 02

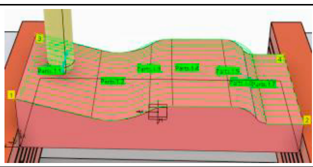
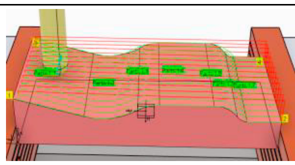
Cutting mode	Conventional	Climb	Either
Zone	Max horizontal slope 15 deg Vertical Zone. Distance between pass 0.2 mm Horizontal Zone. Distance between pass 0.6 mm		
Time (seg)	271.8	270	268
Tool trajectory			

According to the results of the simulation, there are not big differences between the three cutting modes so it will not be a critical decision in this case.

3.4. Analysis of isoparametric machining for convex-concave combined surfaces. Experimental Design 02.

The second finishing strategy tested, according to the fundamental theories, was the isoparametric Machining. In this case, it can be seen could see that in this experiment there is a slight difference of a 7% reduction in the operation time (Table 6). With this method, the machining is faster than with the previous method that is why it is more economical.

Table 6. Operation Strategy for isoparametric machining in Experimental Design 02

Tool path type	Zig-Zag	One-Way
Radial	Stepover: Scallop height; Scallop height: 0.6 mm; Distance between paths: 1.2 mm Number of paths: 25 mm; Skip paths none; Start extension = 0 mm; End extension = 0 mm	
Time (s)	70.7	65.8
Tool trajectory		

In this last analysis for the tool trajectory, it must be highlighted that one-way strategy output shows less total machining time than zig-zag trajectory. This could be due to the machine tool definition and the simulation environment adjustment that should be checked initially.

4. Conclusions and Future Work

In both simulated case studies, the material of the part and the selected topology of the surfaces conditioned the reduced axial and radial depths that resulted in a compacted toolpath with a high number of trajectories.

In roughing operations of convex and concave surfaces, from the individual operation analysis perspective, it is obvious that concentric toolpath style in pocketing is the most time consuming compared to helical and back forth trajectories. In a closer look, results show that in the toolpath there are many useless routes or trajectories due to the contour conditions imposed automatically to the tool movements.

However, when back and forth is used in the pocket strategy, the total operation time is being reduced and the operation time remains for the rest of the strategies with a 3% of time increasing.

When it is used a concentric strategy in pocketing, all the types of toolpaths have the same machining time when the concentric movement no matter if it is One-Way or Zig-Zag, however, the concentric movement with Zig-Zag is faster than One-Way which is reasonable.

When helical style in pocketing strategy is used in Experimental Design_02 roughing operation strategy, it is found that it is the longest one compared to the other style strategies. With this operation, the combination of back and forth style in pocketing strategy with back and forth type of trajectory is the most economical within all the combinations.

Paying attention to the finishing operations, it is confirmed that there is no difference in the operation time between the advanced finishing strategies while, in isoparametric strategies, it is shown that, on the contrary that is expected, the one-way strategy has less operation time than zig-zag. After reviewing the operation, it is verified that this is due to the machine tool definition, since new computer aided manufacturing applications consider many different cinematic and dynamic parameters that must be correctly defined.

Therefore, for future work, it is suggested that it must be defined all the machine tool features considering not only its geometry and cinematics, but also the dynamics of the different elements that will take into account not only speeds but also the accelerations and decelerations model in each axis. This issue implies that it is needed a correct definition of the digital twin model. More experiments must be also be designed in order to compare the operations strategies and select the most significant ones to translate then to the real machining experiments.

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