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Toolpath Strategy in Freeform Surface Milling

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Abstract
Milling, within the realm of mechanical engineering, stands as a favored machining technique. Diverging from conventional methods, the utilization of CNC (Computer Numerical Control) machines in milling enables the manipulation of intricate profiles with exceptional precision, meeting stringent technical, quality, and productivity demands. The parameters in the milling process are computed and selected based on various factors such as the workpiece material, tooling, and the machine's technological capabilities. These parameters significantly influence productivity and product quality. In this study, we address the process of determining the toolpath strategy in freeform surface milling with the aim of reducing machining time, consequently reducing power consumption and operational costs.
Keywords*: Milling, Toolpath, cutting parameter.*

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I. Introduction

Milling parameters refer to the various factors and settings that are adjusted and controlled during the milling machining process to achieve specific outcomes and desired results. These parameters play a crucial role in determining the quality, accuracy, and efficiency of the machining operation. Some common milling parameters include:

Cutting Speed (Surface Speed): This parameter represents the speed at which the cutting tool rotates and is usually measured in surface feet per minute (SFPM) or meters per minute (m/min). It determines the rate at which material is removed and directly impacts tool life and surface finish.

Feed Rate: The feed rate is the rate at which the cutting tool is moved through the workpiece. It is typically measured in inches per minute (IPM) or millimeters per minute (mm/min). Adjusting the feed rate controls the depth of the cut and the volume of material removed.

Depth of Cut: This parameter defines how deeply the cutting tool penetrates into the workpiece during each pass. It is usually specified in inches or millimeters and affects the material removal rate and tool wear.

Tool Diameter: The diameter of the milling cutter has a direct impact on the surface finish, tool life, and cutting forces. Larger diameter tools can remove material more quickly but may require more power.

Tool Path and Machining Strategy: The specific path that the cutting tool follows on the workpiece is determined by the tool path strategy. Different strategies, such as contouring, pocketing, or profiling, are selected based on the desired shape and features of the part. Cutting Tool Engagement (Radial and Axial Depth): Controlling how much of the cutting tool engages with the workpiece affects cutting forces, chip formation, and tool life. It's important to optimize these parameters for efficient machining.

1. Toolpath Generation in CAM

Optimizing milling parameters requires a balance between achieving the desired machining results, maximizing tool life, and minimizing production time and costs [1-4]. Skilled machinists and engineers carefully select and adjust these parameters based on the specific machining task, material, and machine capabilities. Advanced software, often integrated with Computer Numerical Control (CNC) machines, is used to generate these tool paths. These software programs use algorithms to calculate the most efficient tool path based on the input parameters, enabling precise and efficient milling operations. However, for each type of product, the software will also suggest a set of toolpath options, and the choice of the most suitable toolpath depends significantly on the programmer.

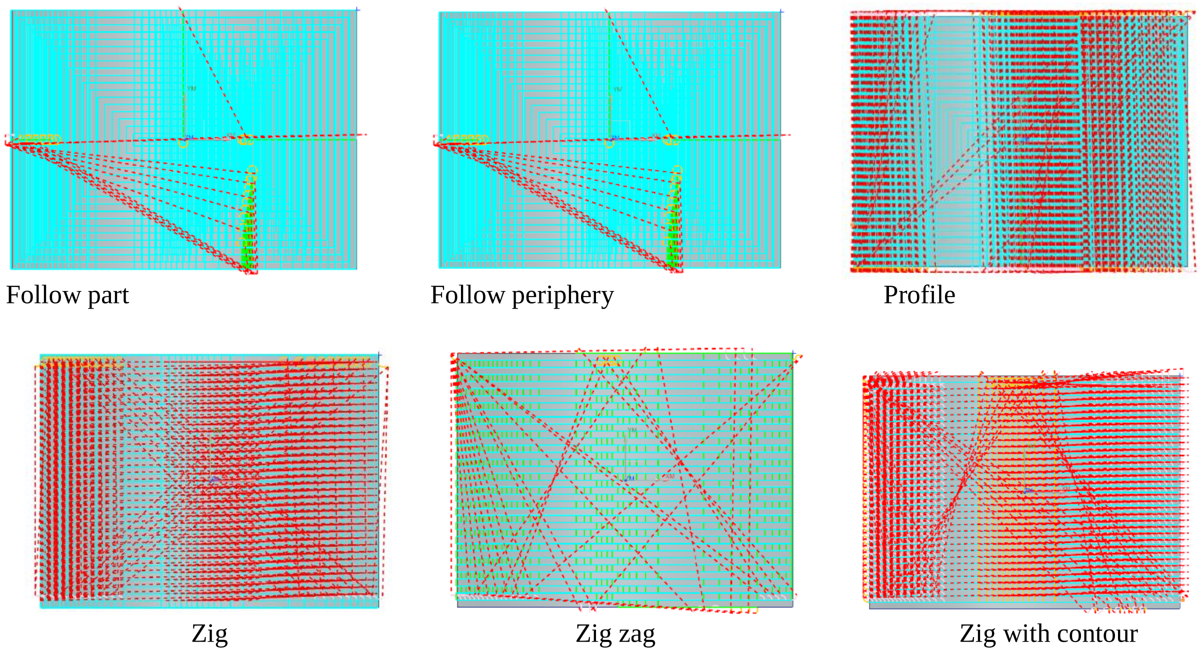

Fig 1. Several typical tool paths milling

In milling surface machining, especially for freeform surfaces, selecting the toolpath strategy is relatively straightforward because the part has open geometry and is not heavily constrained in the toolpath space. However, attention must also be paid to the engage and retract tool to ensure the desired efficiency.

To experiment with selecting an appropriate toolpath strategy, we simulate the process on a component with dimensions (Fig 1) and material properties (Table 1, 2) as listed below.

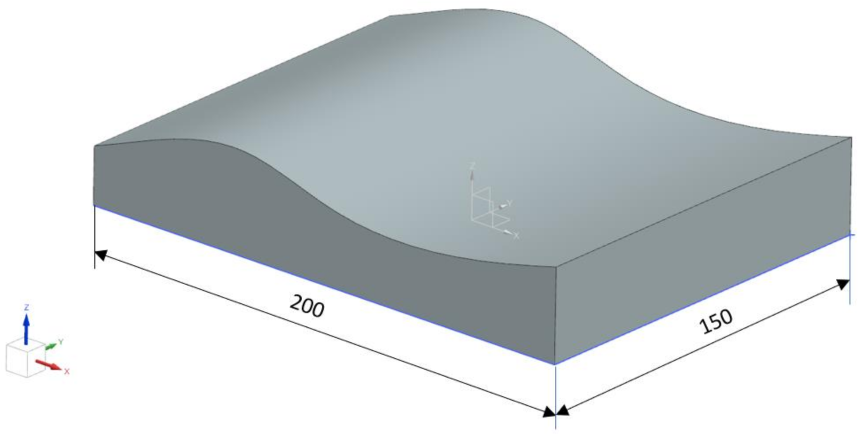

Fig 1. The dimension of part

Table 1. *Chemical composition of alloy steel En24* [4].

Element	Carbon	Silicon	Manganese	Phosphorus	Chromium	Molybdenum
Symbol	C	Si	Mn	P	Cr	Mo
Content%	0.36-0.44	0.11-0.31	0.45-0.71	0.036	1.02-1.47	0.23-0.34

Table 2. *Mechanical and physical properties of En24 alloy steel.*

Tensile Tension	855-1000 N/mm^2
Yield Stress	675 N/mm^2
Elongation	13.3%
Impact Strength	54 J
Hardness	Hardness
Elastic Modulus	207.3×109

In the technical workflow, the processing duration has a direct impact on process efficiency, making it a critical focus for optimization. Milling machining time is computed using the following formula

$$T = \frac{n.60.L}{f.N}$$

In that:
n = Number of cutting
L = Workpiece length + Tool approach distance + Tool retracts distance + Mandatory clearance distance
f = Feed rate
N = Cutting speed.
In CNC machining, as well as machining in general, machining time directly affects the efficient productivity of the machining process [5-7]. Machining time primarily determines the machine's power consumption, tool life, and wear, as well as the progress of the production process [8-10]. The selection of toolpath strategy, from approach to retract after machining, directly impacts the machining time. Depending on the characteristics of the machined part, the equipment provides users with several suitable options. Additionally, the toolpath must also be chosen to align with the current equipment's technological characteristics, the machined material, and the desired cutting mode.

II. Results

In the freeform surface milling process, various toolpath strategies are proposed for users. For enclosed freeform surface machining, like the part being used in this study, we often compare the machining times of different toolpath strategies under various cutting conditions.

Table 3. *Process variables and their Ranges.*

S1.No	Process Parameter		
	Cutting speed (RPM)	*Feed (mm/Min)*	*Depth of cut (mm)*
1	3800	320	1.0
2	5000	350	1.1
3	5500	350	1.2

The machining time for each cutting process is based on the simulation results.

S1.No 1

Toolpath	*Cutting time (mm:s)*
Follow part	33: 23
Follow periphery	32:05
Profile	42:03
Zig	39:07
Zig zag	35:05
Zig with contour	40:06

S1.No 2

Toolpath	*Cutting time (mm:s)*
Follow part	28: 36
Follow periphery	27:21
Profile	38:06
Zig	35:40
Zig zag	33:17
Zig with contour	36:42

S1.No 3

Toolpath	*Cutting time (mm:s)*
Follow part	26:18
Follow periphery	25:33
Profile	36:16
Zig	32:09
Zig zag	31:32
Zig with contour	33:31

Based on the outcomes of the machining process, it is evident that each toolpath strategy and cutting condition corresponds to a distinct machining duration. These findings enable us to assess that, in the context of freeform surface machining, the toolpath strategies known as 'Follow Part' and 'Follow Periphery' may be deemed more advantageous.

The 'Follow Part' strategy entails the cutting tool tracing the contours of the part or workpiece under machining. Typically, it involves machining along the part's edges or boundaries, faithfully following its outline. 'Follow Part' proves suitable for creating intricate shapes and profiles with precision, making it a preferred choice when exact dimensions and intricate features are critical. On the other hand, the 'Follow Periphery' approach prioritizes machining along the outer boundary or perimeter of the freeform surface or workpiece. Instead of navigating through the intricate interior contours of the part, this toolpath stays close to the exterior edges. This approach is often preferred when speed and material removal rate take precedence, as it can be faster than 'Follow Part' due to its simplified movements.

The selection between these two strategies hinges on specific machining requirements, including part geometry, material characteristics, desired surface finish, and machining time considerations. 'Follow Part' is typically employed for parts with intricate interior features, while 'Follow Periphery' is chosen when rapid material removal along the outer boundaries is the objective. In making this decision, machinists often find themselves balancing precision and efficiency, taking into account the inherent trade-offs associated with these toolpath strategies.

III. Discussion

The comparison results indicate that the optimal toolpath choice depends on factors such as part geometry, selected toolpath type, machine specifications, and cutting conditions. By employing similar methodologies and approaches, we can carry out assessments to identify the most suitable toolpath strategy for a given machining operation. It is worth noting that distinct technological circumstances and optimization goals may result in varying selection criteria. Nevertheless, the findings presented in this research paper can serve as valuable guidance for engineers and technologists in the decision-making process when selecting an appropriate toolpath strategy for enclosed freeform surface machining

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