Rough-Cut Machining an Impeller with 3-Axis and 5-Axis NC Machines

M.A. Suhaimi[1], Dong-Won Kim[2*], Jong-Yeong Lee[2], and Oscar Velasquez Arriaza[2]

[1]Department of Materials, Manufacturing and Industrial, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81200 Johor Bahru, Malaysia

[2]Department of Industrial and Information Systems Engineering, Chonbuk National University, Jeonju 561-756, South Korea

Abstract

This study presents an efficient rough-cutting strategy for machining a centrifugal impeller. Much of the machining time is consumed in rough cutting, where unnecessary stock materials are removed in between impeller blades. Thus, most of researchers focus on 5-axis rough machining of an impeller, controlling all the five axes simultaneously as fast as possible. In previous research, we introduced a 3-axis machining strategy that removes as much material as possible from the areas between blades. Thus, the main purpose of the research was to improve the machining efficiency by reducing the machining time. We achieved 19 percent of total machining time reduction by using the 3-axis rough machining. For further improvement, this paper will introduce an improved 3-axis machining strategy by applying feed-rate scheduling for more efficient rough cutting. There are two types of feed rate scheduling, namely, cutting force and material removal rate based scheduling. This research will focus on feed-rate scheduling based on cutting force to increase the feed-rate onto an allowable level. Current research in feed-rate scheduling applies cutting force calculations for each cutter-workpiece engagement, experimenting with different depth-of-cut layers. In this paper, we will calculate cutting force for each cutter-workpiece engagement by employing a finite element method. Cutting tool and workpiece geometry will be meshed and analyzed to find out best feed-rate scheduling. The rest of material that is left from the 3-axis machining will be removed by 5-axis machining. The result shows that by applying this hybrid roughing strategy, namely, 3-axis machining with feed-rate scheduling and 5-axis machining, total rough machining time can be reduced significantly up to 43 percent.

1. Introduction

An impeller is an advanced mechanical product used in the area of turbo-machinery. An impeller is capable of transforming fluid flow from axial to radial direction. In other words, it transforms mechanical energy into hydraulic energy by means of producing high pressure to create thrust force. Thus, an impeller is used in the automotive industries [2-4] for the turbo engines, aerospace and aircraft industries [2-15], and even a launch rocket [4]. Impellers consist of a single kind or two kinds of blades that revolve with equal distances through a hub surface. Each of its blades consists of ruled surface with twisted angle. Due to the impeller design complexity, 5-axis CNC machine is the most suitable for machining an impeller [2-4, 12, 13, 15-17]. A 5-axis machine has the flexibility of tool orientations, that is a necessary to machine the area between the twisted blades. Not like the 3-axis NC machine, serious collision will occur due to the tool movement that constraint only to translations movement [9, 12, 13, 15].

In order to produce high pressure to create the thrust force, impellers need to rotate with high rotational speed [10, 11, 18]. Thus, perfect balance of impeller's body weight, especially the blades are the most important factor. An imbalanced impeller with high rotational speed would result to blade breakage and fail during operation [4]. Hence, producing a high quality impeller is very important, and because of the complicated design, it makes more challenging. 5-axis machine is capable to produce a high quality impeller, but suffers from inefficient machining time issues. Generally, 5-axis machine capable of control and instruct all the axis of the cutter location (CL) simultaneously, which result for longer machining time and slower cutting speed. Concerning manufacturing perspective, longer machining time will increase the production lead-time, therefore, increase the production cost [8, 9, 14, 15, 19]. Thus, achieving optimum cutting speed is important in order to balance between maximum

* Corresponding author: Tel.: +82-63-270-2328; E-mail: dwkim@jbnu.ac.kr

production and minimum cost, as shown in Figure 1. Furthermore, inefficient machining operation, will also lead to bottleneck to the impeller production line due to machine heavy loaded.

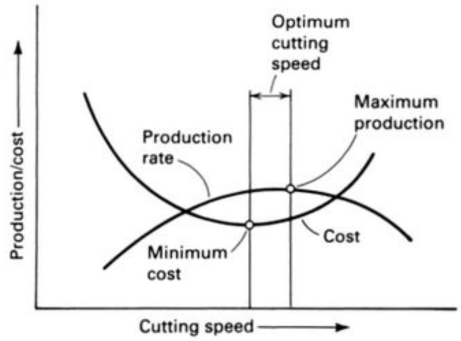


Figure 1. Chart for determining minimum cost, maximum production, and optimum cutting speed. [1]

Considering manufacturing cost, therefore, improving the machining time is vital. According to Ruolong et al. [16] almost 70 percent of unwanted materials has to be removed from the impeller blank during the rough-cutting operation. Besides, Heo et al. [11] believe that, roughing strategy takes more than 60 percent of the total machining time of an impeller. Nevertheless, commonly, 5-axis machining has weaker structural and dynamic characteristics, if compared to 3-axis machining. As the results, 5-axis machine capabilities such as machining speed and feed-rate are restricted to some pre-specified limit [11]. For that, this paper proposes an idea to improve the impeller roughing time by maximizing as much as possible 3-axis machining strategy for an impeller. By applying 3-axis strategy, almost 40 percent volume of the blank materials could be removed efficiently. In additions, by implementing feed-rate scheduling, roughing time will be more efficient. As the results, tool-path generations for 5-axis machining strategy could be reduced significantly. Moreover, proposed strategy gives an option to the small enterprise to use their 3-axis and 5-axis machine concurrently, instead, proposed method works perfectly with a single 5-axis machine. Besides that, proposed idea will helps to solve the bottleneck problem due to the heavy loaded of 5-axis machine in the production line by balancing the load using the 3-axis machine.

2. Previous Research

Numbers of study examined the capabilities the 5-axis machine for machining an impeller. Most of the researches were concerned towards improving the rough-cut machining time because it relates linearly with the manufacturing cost and production lead-time. K. Morishige and Y. Takeuchi [20] proposed to reduce the machining time by creating a reciprocating path and eliminate the tool retraction. On the other hand, Tsay et al. [13] developed a flank milling strategy by applying B-spline curve interpolation, ruled surface construction and coordinate transformation. With the same sense, Young et al. [14, 15] proposed a module using C++ programming, which able to automatically generate efficient tool-path. Later, Chuang and Young [8] improved Young et al. [14, 15] method by introduced a different approach of flank milling strategy which linked with a zig-zag style. Heo et al. [11] proposed an approach that the area between the impeller blades should be partitioned into several unit machining regions (UMRs). The authors aim to eliminate the cutter locations that need to be controlled by the 5-axis machine controller, so that, by applying UMR cutter location and machining strategy can be done using 3-axis strategy. Later on, Kim et al. [18] improved the method proposed by Heo et al. [11] by taking into considerations the surface roughness of the roughing strategies which would affect the finishing operations. The authors proposed a hybrid rough-cut machining plan that results with acceptable surface quality for the finish-cut operation. With a different approach, Cai et al. [2] developed a specific design of impeller cutting tool, named drum-taper cutter which able to minimize the tool-path length, hence reduced the machining time. As a result of 5-axis machine's flexibility in tool orientations, creates a higher probability for tool collisions and undercuts to occur. Thus, most researchers also focused onto generating roughing strategy concerning tool collision, and undercuts avoidance [5-8, 11, 14-18, 20-23]. Therefore, this study introduce 3-axis machining strategy which aims to minimize the tool-path for 5-axis machining strategy. The proposed idea is relevant in order to avoid tool collisions and undercuts. However, from all the researches mentioned concerning on improving the machining time, there are no proof and discussions revealed for supporting their proposed method. No evidence presented concerning the improvement that they had achieved in contrast to the conventional method. Thus, in this paper, experiments will be carried out and comparison between the conventional and the proposed method towards improving the machining time will clearly be shown.

3. IMPELLER MACHINING STRATEGIES

3.1. IMPELLER

An impeller consists of numbers of similar blades revolving at 360 degrees onto a hub surface. Each of the blades is ruled surface and twisted from the leading edge to the trailing edge. The blades consist of suction surface, pressure surface, leading edge, trailing edge and shroud surface. Besides that, the size of the impeller depends on its outer diameter, inner diameter, height, and amount of blade. Due to the blades are revolve onto equal distance on a hub surface, thus the blade angle can be calculated by division of 360 degrees with the total number of blades. Figure 2 shows the details view of a splitter-type impeller.

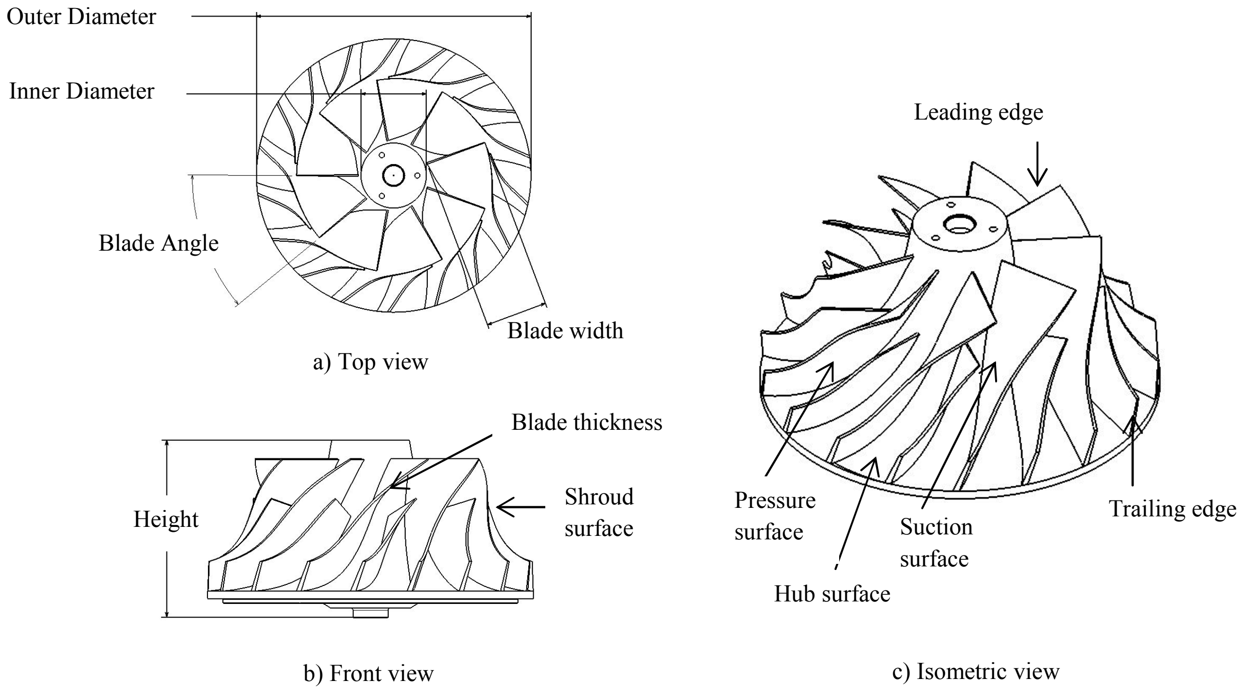
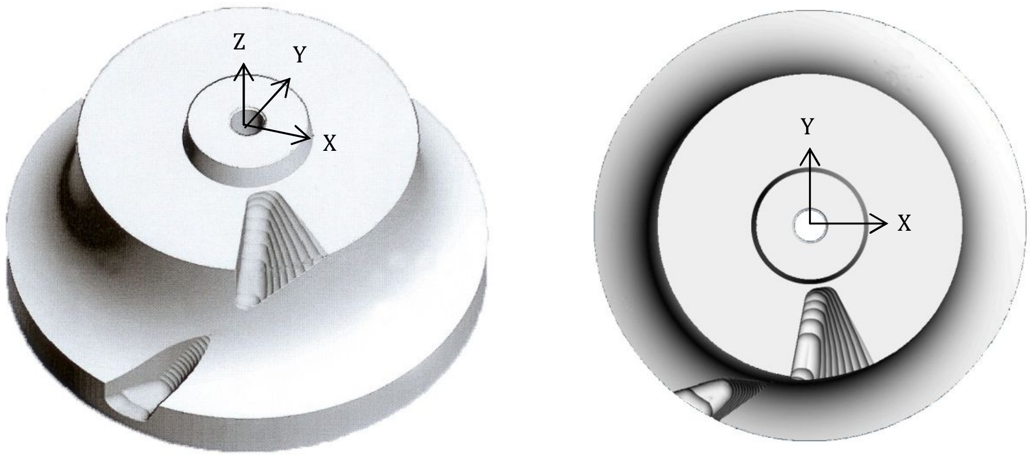


Figure 2. Geometrical view of an impeller; (a) Top view (b) Front view (c) Isometric view.

3.2. 3-AXIS MACHINING STRATEGY

The main objective of roughing strategy is to efficiently remove the unwanted materials as much as possible. Recently, several researchers agreed that applying 3-axis strategy is impossible for impeller machining [8, 9, 12, 14, 15]. They agreed that, 3-axis strategy would cause tool collisions while machining the area between the blades. Through a different sense, this research will introduce the 3-axis strategy that, only for roughing at the area between the leading edge, and the area between the trailing edge of the blades. The machining strategy only focuses on the tool engagement of translational motions in X, Y and Z-axes without requiring movement of the machine table ((A, C) = (0, 0)). Figure 3 shows the details about 3-axis roughing strategy for a single region of an impeller blade.



(a) Isometric View (b) Top View

Figure 3. 3-axis roughing strategy; (a) Isometric View and (b) Top View.

3.2.1. FEED-RATE SCHEDULING

In this research, feed-rate scheduling based on the cutting force will be implemented. Based on this method, cutting force for the 3-axis machining strategy can be predicted. Predicting cutting force for any machining strategy is most helpful as its supply additional information for selecting the appropriate value of the machining parameters [24, 25]. Even though, nowadays the existing of CAD/CAM systems provide advantages such as reduced time in designing and generating the NC code. However, selecting the appropriate machining parameters such as feed-rate, spindle speed, and depth of cut, etc., are still depending on the experience of skilled machinists [24, 26, 27]. Thus, this research will find the best feed-rate for impeller 3-axis cutting strategy, which results in improved machining time.

Predicted cutting force will be used as a reference to increase the feed-rate to an optimum level. In this sense, conventionally, cutting tool geometry will be divided into several discs and a slot-cutting experiments will be carried out which based on the depth of cut equal to the interval length of the divided disc. The slot-cutting experiment helps to detect the cutting constants, K, as it varies based on the cutter/workpiece material combination. Equation (1) shows cutting force that act on differential chip load in each cutter/workpiece engagement domains.

$$\begin{aligned} dF_r &= K_{rc} dA_c + K_{re} dz \ , \\ dF_\psi &= K_{\psi c} dA_c + K_{\psi e} dz \ , \\ dF_t &= K_{tc} dA_c + K_{te} dz \end{aligned} \tag{1}$$

where dA_c is the differential chip load, dF_r, dF_ψ, and dF_t, are the differential cutting forces for radial, axial and tangential, respectively. Whereas, K_{rc}, $K_{\psi c}$, and K_{tc} are the radial, axial and tangential cutting constants, and K_{re}, $K_{\psi e}$ and K_{te} are the related edge coefficients, respectively. Once dF_r, dF_ψ, and dF_t were obtained, these cutting force components will be transformed into the X-Y-Z global coordinate systems and the resultant value of the cutting force is used as the reference force.

With the same sense, in this study, the reference force that generated from the X-Y-Z global coordinates will be obtained by applying the finite element method (FEM). The slot - cutting experiment will be simulated through FEM software. Both cutting tool and workpiece will be meshed. For better accuracy, each tool/workpiece engagement region will have finer mesh, which consists of one-mesh elements within the feed per tooth of the cutter contact as shown in Figure 4.

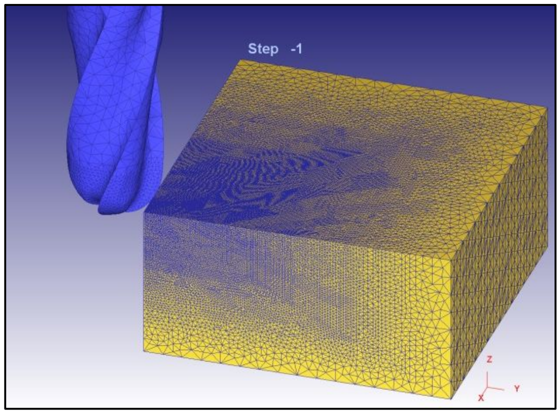
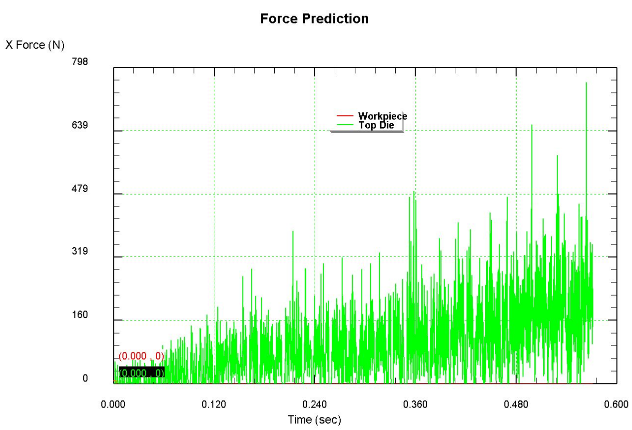
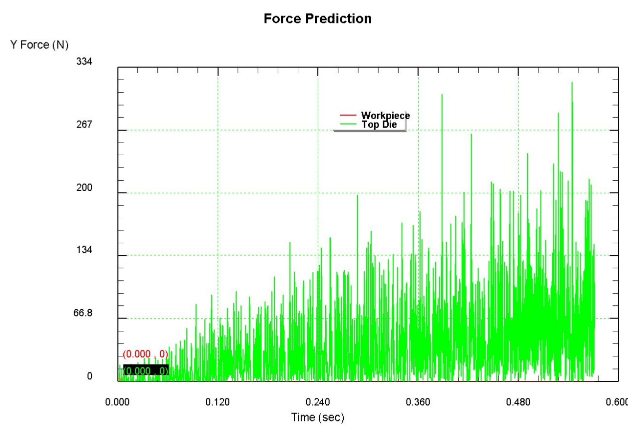


Figure 4. Finer mesh for tool/workpiece engagement regions.

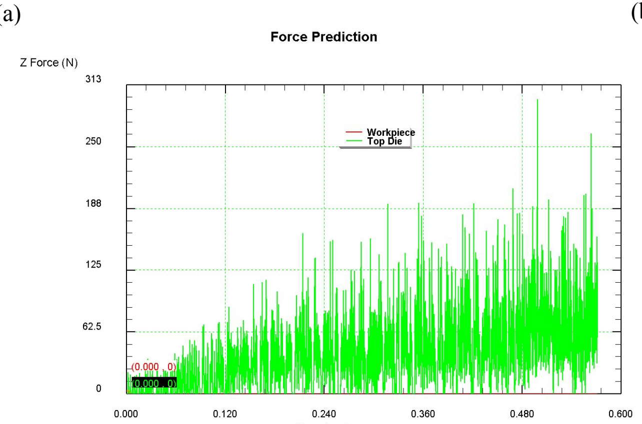
A set of simulations of the slot-cutting experiments were run at the cutting tool optimal condition, suggested by the tool manufacturer. The slot-cutting experiment, conventionally, runs at 5,600 rpm, feed-rate of 460 mm/min and the maximum depth of cut is 1.8 mm, which are recommended by a tool maker. The cutting tool was carbide ball-end mill with a diameter of 6 mm, nominal helix angle of 35 degrees, 4-flutes, and coated with AlTiN. The workpiece material was aluminium AL-7075. Finer mesh for cutter/workpiece engagement regions, which consist of 0.07 mm/element, same as the value of the feed per tooth of the cutter configurations. Cutting force calculations were performed for 3000 times (every 0.08 degrees of cutter rotation) for the cutting length of 4 mm long and 1.8 mm of depth of cut. Figure 5 shows the results of the predicted forces of the slot-cutting experiments acting on the tool/workpiece engagement for each axis, X, Y and Z.



(a)



(b)



(c)

Figure 5. Predicted forces for: (a) X axis, (b) Y axis, and (c) Z axis.

3.3. 5-AXIS MACHINING STRATEGY

This research aims to improve the machining time through minimizing the tool-path strategy of the 5-axis tool movement. Research proved that, 5-axis machining strategy suffer from several limitations such as having weaker structural and dynamic characteristics [11], and introduce higher probability to tool collisions either with the workpiece or worktable [7, 11, 15-18, 20], compared to 3-axis machining strategy. Thus, in this research, 5-axis machining strategy will only focus on the area between the blades, which required cutting tool orientations movement as shown in Figure 6.

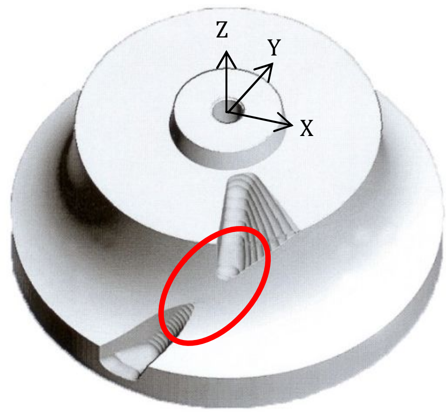


Figure 6. Area required 5-axis machining strategy.

4. SIMULATIONS AND EXPERIMENTAL VALIDATIONS

This section shows the machining time comparison via applying two different approaches for impeller machining, which are fully 5-axis machining strategy, and proposed method, 3+5 axis machining strategy. In this comparison, both strategies will be conducted using the same machining parameters and settings as shown in Table 1. Splitter-type impeller with outer, inner diameter and height of 120 mm, 32 mm and 53 mm, respectively, will be machined using both approaches. The impeller consists of 9 main blades and 9 splitter blades with blade angle of 20°. CSCAM-M52 5-axis machine will be used for the machining activities. The cutting tools are 4 mm diameter ball end-mill for both 5-axis strategies and 6 mm ball end-mill for the 3-axis strategy. The stock material is aluminium AL-7075. From the FEM simulation, the optimum force was obtained from the cutting conditions that recommended by the tool manufacturer as shown in Figure 5. Table 2 shows the details of the maximum force acting on each axis X, Y and Z, the instantaneous resultant forced which based on the optimal cutting conditions and the increased feed rates.

For improving the machining time, the experiments for 3-axis machining were carried out with a smaller depth of cut, however the feed rates were increased on condition that the instantaneous cutting force is not more than the reference force that obtained from the optimal cutting conditions. For example, from Table 2, experiment number 1 exceeded the reference force obtained from the optimum cutting conditions, thus, cutting conditions with feed rate 3,500 mm/min will theoretically increase the tool wear or breaks the tool rapidly. Whereas, experiment 2 will have a sound machining condition even though the feed rate is 3,000 mm/min, due to the instantaneous cutting force is still below the reference cutting force. Figure 7 shows the impeller machining experiments for the proposed 3+5 axis machining strategy.

Table 1. Impeller machining setting parameters for two different strategies.

Machining strategy	3-axis configurations			5-axis configurations			Total volume (cm^3)	Volume removed		Total machining time (hh:mm:ss)
	Feed rate (mm/min)	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/min)	Spindle speed (rpm)	Depth of cut (mm)		3-axis	5-axis	
Fully 5-axis	Not applicable			800	12000	1.5	185	-	185	9:32:24
3+5 axis	3000	14000	1.5	800	12000	1.5		75 (41%)	110 (59%)	5:27:15

Table 2. Instantaneous cutting force based on the optimum cutting condition and increased feed rates.

Experiments	Cutting conditions			Maximum instantaneous cutting force (N)			Instantaneous resultant force (N)
	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	X- axis	Y-axis	Z-axis	
1*	5,600	460	1.8	760.4	182	263.3	825
2	14,000	3,500	1.5	850.7	237.1	336.1	944.9
3	14,000	3,000	1.5	729.5	218.7	294	816.4
4	14,000	2,500	1.5	630.5	139.4	284.5	705.6
5	14,000	2,000	1.5	627	215.7	132.3	676.1
6	14,000	1,500	1.5	609.2	66.2	200.4	644.8
7	14,000	1,000	1.5	613.1	34.8	59.6	617
8	14,000	800	1.5	489.3	234.1	148.3	562.3

* Cutting conditions recommended by a tool manufacturer.

a) 3-axis machining startegy b) 5-axis machining startegy

Figure 7. Impeller machining experiments for the proposed strategy, 3+5 axis.

5. Conclusions

This study has presented a novel approach towards improving the machining time of an impeller. Tool-path generations by 3-axis machining strategy help to improve the machining time and able to remove the unwanted blank materials efficiently, which is up to 40 percent. Additionally, by analyzing the instantaneous cutting force acting on tool/workpiece engagements, suitable feed-rates can be applied, which boost the machining activity and at the same time, keeping the tool life under a sound condition. Machining experiments have been successfully conducted in order to compare the proposed method against the conventional method. From the experiments, it proved that the proposed method is more efficient than the conventional method. The 3+5 axis machining strategy able to improve the machining time up to 43 percent from the conventional method. Moreover, our proposed method gives an option to the small enterprise to use their 3-axis and 5-axis machines concurrently, instead, the proposed method works perfectly with a single 5-axis machine. Thus, the introductions of this new method pave the way for a new technique to produce impellers, which able to shorten the lead-time of manufacturing hence reduce the total manufacturing cost.

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